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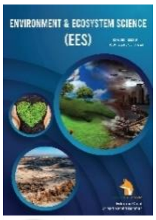

RESEARCH ARTICLE

THE ROLE OF BIOGAS TECHNOLOGY IN FOREST CONSERVATION AND REDUCING ENERGY EXPENDITURE: A CASE IN ALETA-WONDO DISTRICT

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ABSTRACT

This study investigates the perceptions of rural households in Aleta-Wondo District, Ethiopia, regarding domestic biogas technology and its potential to reduce deforestation and dependence on biomass for energy. Domestic biogas is a renewable energy solution that can decrease reliance on traditional fuels like firewood, charcoal, and kerosene, which contribute to deforestation and environmental degradation. However, biogas adoption remains limited in the region. A survey of 191 households (90 adopters and 101 non-adopters) was conducted using multistage sampling, with data analyzed through descriptive statistics and regression models to determine adoption patterns. Biogas adoption significantly reduced traditional fuel use: firewood consumption decreased by 83.33%, charcoal by 66.67%, and kerosene costs for cooking were eliminated. This shift reduced deforestation and promoted forest regeneration. Adopters also experienced notable time and financial savings, including an 81.82% reduction in monthly firewood use, an 80% decrease in firewood collection trips, and a weekly time savings of 8 hours (72.7%). Key factors influencing adoption, identified through binary logistic regression ($p < 0.01$; pseudo $R2 = 49\%$), included household head's sex and education, income, water access, livestock ownership, and credit availability. The study highlights biogas as a sustainable, cost-effective solution to reduce energy problem, conserve forests, and improve rural livelihoods. However, adoption barriers such as financial constraints, technical expertise gaps, and limited credit access must be addressed. Targeted government support, including financial incentives, technical assistance, and capacity-building, is essential to scale up adoption and maximize its benefits.

KEYWORDS

Biogas, Biomass Dependency, Energy, Rural Households, Forest conservation

1. INTRODUCTION

Globally, energy access remains a significant challenge, with approximately 1.06 billion people lacking electricity and 2.8 billion without clean cooking facilities, predominantly in rural sub-Saharan Africa and developing Asia (Sawin et al., 2018; Hoque and Das, 2013). In rural Ethiopia, this issue is acute, as about 80% of the population relies on biomass fuels such as wood and charcoal (Wassie and Adaramola, 2021). The dependence on these traditional energy sources contributes to deforestation, greenhouse gas emissions, and severe health issues due to indoor air pollution (Wassie and Adaramola, 2020; Kan et al., 2023). The total coverage of the forest resources in Ethiopia is being reduced at an alarming rate over time due to different factors. One of the main reasons is the unwise utilization of the forests for fuel wood consumption which is around twenty times greater than the combined demand for other forest products (EFAP, 1993). Fuel wood collection for cooking is the main driving force for forest degradation in those countries (Skutsch et al., 2011). Renewable energy solutions like biogas technology present a sustainable alternative, offering the potential to reduce household expenditures, improve health conditions, and provide environmental benefits (Gielen et al., 2018; Zheng, 2012). Biogas can be produced from organic materials, including human and animal waste, and used for cooking and lighting (Arthur et al., 2011). Despite its benefits, the adoption of biogas in Ethiopia has been limited by technical challenges, lack of information, and infrastructure issues (Lakew, 2008; Tiruye et al., 2021). In Ethiopia, traditional biomass fuels account for about 92% of energy consumption, with rural households heavily reliant on these sources (Power, 2013; UNION, 2008). This reliance not only exacerbates deforestation but also results in inefficient energy use, as traditional cooking methods transfer only 5-10% of the fuel's energy to the pot (Francisco et al 2014). The bio-slurry is a high quality organic fertilizer used for increasing agricultural production and ensuring food security (Figure 1). The first biogas installation in Ethiopia dates back to 1962, yet adoption has remained slow due to various barriers (Eshete et al., 2006; Kamp, 2016). Addressing these barriers is crucial for reducing deforestation and energy expenditures. This study focuses on rural households' perceptions of biogas technology in the Aleta-Wondo District, aiming to identify adoption barriers and assess the potential impact on deforestation reduction and energy expenditures. By understanding these factors, the research seeks to inform policies and promote renewable energy use, ultimately reducing dependence on traditional biomass fuels which contributes significantly to forest resource degradation.

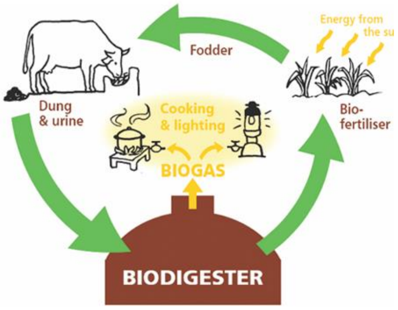

Figure 1: Biogas technology energy operating system, sourced from: https://www.bing.com/images/search

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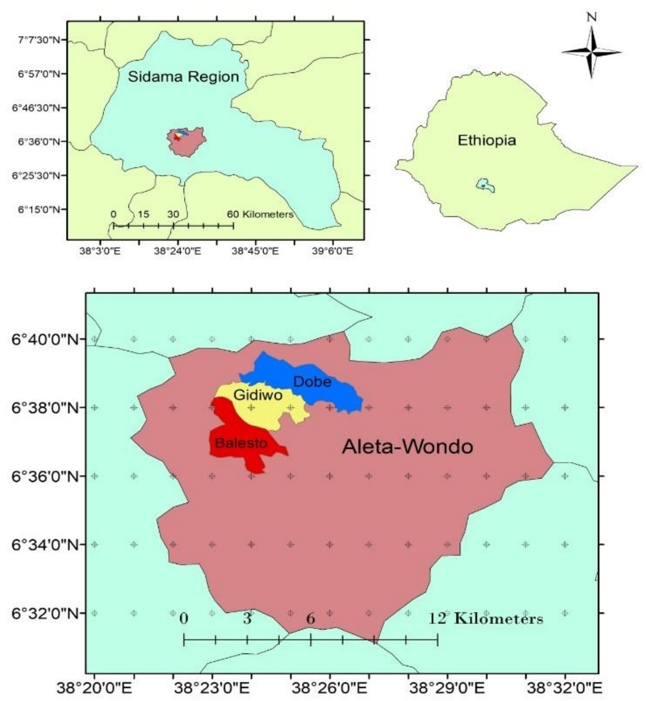
2. Methods and Materials

2.1 Description of the Study Area



The research was conducted in Aleta-Wondo Woreda, located in the Sidama Regional State of Ethiopia, approximately 64 km and 337 km away from the regional capital city of Hawassa and the national capital city of Addis Ababa, respectively. The woreda covers an area of 27,823 hectares and is divided into 27 administrative Kebeles ("Kebele" is the smallest administrative unit of Ethiopia, similar to a ward, a neighborhood, or a localized and delimited group of people). Its geographic location ranging between 60°25'N and 60°45'N latitude and 38°015'N and 38°45'N longitudes (CSA, 2008/09). It has a flat area of 640 km2 with a population of 191,592 of whom 97,364 are males and 94,228 are females while more than 90% are urban population (CSA 2014). The annual rainfall in the area varies from 900 to 1400 mm, while the mean minimum and maximum temperatures range from approximately 10°C to 24°C (Woreda report, 2013/14). The Woreda has two agro ecologies, namely highland medium 'Dega' (14.9%) and most 'WoyinaDega' (85.1%). It experiences two rainy seasons, Belg and Maher Belgst, with the short rainy season lasting from March to May.

2.2 Sampling Design and Sample Size.

A multistage sampling technique was utilized to select households for the survey. Initially, the Aleta Wondo district was purposively selected, due to largest number of biogas installations. Secondly, three kebeles (Gidiwo, Dobe, and Balesto) were again selected purposively from the 27 rural kebeles based on the availability of biogas plants and the number of potential biogas-adopting households. Thirdly, households in the selected kebeles were stratified based on their adoption characteristics into two groups: adopters and non-adopters of biogas technology. Finally, 191 household heads, including 90 adopters and 101 non-adopter households, were selected for the study using random sampling techniques. The sample size for non-user respondents was determined using formula, where n represents the sample size, N represents the population, and e represents the level of precision, which was set at 7% (0.07) (Yamane, 1967).

$n = N/ [1+N (e)^2] = 3200/1+3200*(0.07)^2 = 3200/16.68=191$ Where, n=sample size, N= population, e= level of precision

2.3 Data Collection techniques

To effectively assess the contribution of domestic biogas technology on deforestation and energy expenditures, a mixed-methods approach was employed, integrating both qualitative and quantitative data collection methods. The quantitative method involved a structured household survey using semi-structured questionnaires. This survey targeted both adopters and non-adopters of biogas technology, focusing on households' demographics characteristics, types of energy sources used consumption patterns, costs, and perceptions of biogas benefits. The survey also gathered data on the relationship between biogas adoption and reduced reliance on traditional biomass fuels, particularly fuel wood and financial implications of adopting biogas technology. Key Informant Interviews and Focus Group discussion with selected biogas adopters, Woreda water resource and energy office experts, and kebele administration leaders

were done. The study used primary data directly from household surveys and secondary data from relevant stakeholders and recent studies, ensuring the reliability and accuracy of the information.

2.4 Methods of Data Analysis

The study used both descriptive statistics and regression analysis to analyze data. Descriptive analysis included means, standard deviation, relative frequencies, and percentages to interpret the data. Statistical Package for Social Sciences (SPSS), STATA, and Microsoft Excel were used for quantitative analysis and data arrays. Qualitative data were coded, clustered into common themes, and interpreted. The Probit model was applied to analyse the factors influencing adoption of biogas technology.

2.5 Model Specification

The dependent variable in this study was the adoption of Biogas technology, represented by a dichotomous variable where "1" indicated a household owning a biogas plant and "0" indicated otherwise. Binary logit model is appropriate for adoption studies with dichotomous dependent variables and any type of independent variables (Maddala, 1986). The Logit model used in the study was as follows:

$$\mathbf{Y_i=\beta_0+\sum\beta_j x_{ij}+\varepsilon_i}$$

Where Y_i is the adoption of biogas technology, βo is the constant term, β_j ($\beta_1+\cdots+\beta_{11}$) is the coefficient of estimated parameters corresponding to each explanatory variable, X_{ij} ($B_1+\cdots+B_{11}$) is the set of explanatory variables, and ε_i is the error term of the regression. The explanatory variables included X_1 (sex of household head: Dummy), X_2 (age of household head), X_3 (education: Category), X_4 (total livestock holding), X_5 (household size), X_6 (marital status: Category), X_7 (availability of water: Dummy), X_8 (Income: continuous) X_9 (Awareness on Env't: Dummy), and X_{10} (access to credit), X_{11} (Extension service: Dummy) and X_{11}(Ease to use: Dummy variable).

2.6 Variables explaining biogas technology adoption

According to the study, technology adoption involves a series of steps, including becoming aware of the technology, gathering information, developing interest, evaluating the technology's characteristics, and making a decision to adopt or reject it (Rogers, 2010). However, studies like the present one aim not only to understand these processes but also to identify the underlying factors that influence households' decisions to use or not use the technology. Previous studies in Kenya, Uganda, China, Bangladesh, and Pakistan have identified various socio-economic, personal, institutional, economic, and social factors that influence the adoption of biogas technology. For example, (Walekhwa et al., 2009; Kabir et al., 2013) found that farmers' socio-economic status significantly determines their decisions to adopt the technology. Further studies in Pakistan have identified factors such as education level, daily electricity deficit, female labor, awareness of the technology, socio-economic status, and cost analysis as important determinants of biogas technology adoption (Jan and Akram, 2018; Amigun and Blottnitz, 2010). The present study considers a range of explanatory variables beyond socio-economic factors alone, recognizing that households may have a variety of concerns in the adoption process (Table 1).

Table 1: Description of variables and hypothesized relationship

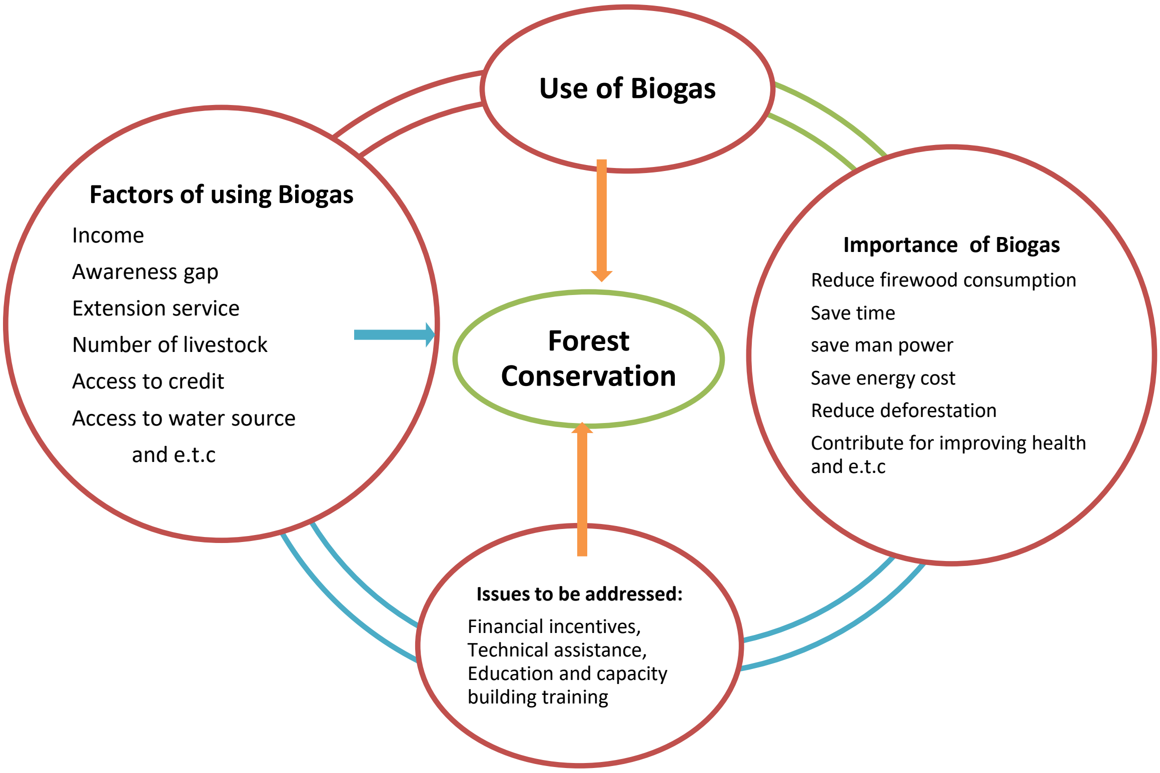
Variable	Type	Description	Expected Effect
Sex	Dummy	Gender of the household head (1 = male, 2 = female)	±
Age	Continuous	Age of the household head	±
Family size	Continuous	Size of the household	±
Marital status	Category	Relationship status of the household head	±
Education level	Category	Education level of the household head (1 = illiterate, 2 = grade 1-8, 3 = grade 9-12, 4 = Diploma and above)	+

Table 1 (cont): Description of variables and hypothesized relationship

Number of livestock	Continuous	Number of cattle owned by the household	+
Accessibility of water source	Category	Walking distance to water source from home (1 = less than 30 minutes, 0 = greater than 30)	+
Accessibility of credit	Category	Access to credit for initial investment (0 = no access, 1 = access)	+
Extension Services	Category	Availability of training and extension services	+
Perceived Ease of Use	Category	Households' perceptions regarding the complexity of installation and maintenance	+
Knowledge on Env'tal Impact	Category	Awareness on the benefits of biogas to reduce deforestation and improve sanitation	+
Income Level	Continuous	Household income level	+

Notes: Positive (+): Indicates that an increase in the variable is expected to positively influence biogas technology adoption. **Negative (-)**: Indicates that an increase in the variable is expected to negatively influence adoption. **Mixed Effect (±)**: Indicates uncertainty or variability in the effect direction based on context or other interacting factors.

2.7 Conceptual Framework for the role Biogas to forest contribution



Use of Biogas

Factors of using Biogas

Income

Awareness gap

Extension service

Number of livestock

Access to credit

Access to water source

and e.t.c

Forest Conservation

Importance of Biogas

Reduce firewood consumption

Save time

save man power

Save energy cost

Reduce deforestation

Contribute for improving health and e.t.c

Issues to be addressed:

Financial incentives,
Technical assistance,
Education and capacity building training

Figure 2: Conceptual Framework about the role Biogas to forest contribution by researcher

This conceptual framework outlines the key factors influencing the adoption of biogas technology in rural areas, the needs required for successful implementation, the importance of biogas for local communities, and its ultimate contribution to forest conservation.

3. RESULTS AND DISCUSSION

3.1 Socio-economic characteristics of respondents

The socio-demographic characteristics of households in Aleta-Wondo District, Ethiopia, have implications for the adoption of domestic biogas technology. The Table shows that Male households are more likely to have adopted the technology than Female households, indicating potential barriers to adoption for Women.

Table 2: Mean value of socio-economic characteristics of respondent

Variable Description	Category	Adopters	Non-Adopters	Total
Gender	Male	68	69	137
	Female	22	32	54
Marital Status	Married	76	99	175
	Widow	9	1	10
	Divorced	5	1	6
Age Group	18-35 years old	31	53	84
	36-64 years old	56	22	78
	Above 65 years	3	16	19

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Table 2 (cont): Mean value of socio-economic characteristics of respondent

Family Size	Less than 6	38	59	97
	Greater than 6	52	42	94
Educational Status	Illiterate	29	43	72
	Primary School	34	47	81
	High School	18	10	28
	Diploma and Above	9	1	10
Number of Livestock	0-2	25	60	85
	3-5	45	30	75
	6 or more	20	11	31
Income Level	Low	20	50	70
	Medium	50	40	90
	High	20	11	31

3.2 Perception and Attitudes towards Adoption of Domestic Biogas among Adopters and Non-adopters

The findings of this study reveal a significant disparity in awareness of biogas technology between adopters and non-adopters. Approximately 94.7% of adopters reported having awareness of biogas technology, compared to only 4% of non-adopters. This suggests that nearly all adopters have better access to information regarding biogas, while a substantial majority of non-adopters—96%—lack knowledge about the technology. This knowledge gap indicates that many non-adopters are unable to access detailed information about biogas, which is crucial for understanding its benefits. Respondents rated their levels of agreement, neutrality, or disagreement with these statements using a Likert scale, further emphasizing the importance of perception in influencing the adoption of biogas technology among households.

Table 3: The Role of Biogas Technology in Forest Conservation

Perception Statement	Adopters						Non-adopters					
	1	**2**	**3**	**4**	**5**	**Mean score**	**1**	**2**	**3**	**4**	**5**	**Mean score**
Biogas technology reduces the need to cut down trees for firewood.	0	5	4	42	39	4.28	13	20	8	39	21	3.35
Biogas adoption has contributed to the regeneration of nearby forests.	0	3	3	45	41	4.35	6	9	13	40	33	3.84
Biogas technology plays an essential role in reducing deforestation in our community.	0	0	1	36	53	4.58	2	5	9	60	25	4.00
Since adopting biogas, my household has significantly decreased reliance on firewood.	0	0	3	52	35	4.36	0	0	0	0	0	1.00
The use of Biogas will reduce the frequency of firewood collection trips.	0	1	2	43	44	4.44	8	21	13	37	22	3.44
The use of biogas helps preserve biodiversity within forested areas.	0	0	1	56	33	4.36	7	13	14	41	26	3.65
Biogas technology is an effective and sustainable alternative to firewood.	1	1	3	37	48	4.43	5	12	26	34	23	3.58
The availability of biogas technology encourages households to reduce their dependence on firewood.	3	8	12	50	17	3.78	6	16	14	40	25	3.61

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Table 3 (cont): The Role of Biogas Technology in Forest Conservation

The promotion of biogas technology is critical for long-term forest conservation in the study district.	3	4	10	47	26	3.99	6	12	13	40	30	3.75
Reduce energy expenditure	3	11	5	40	31	3.94	14	18	12	40	17	3.27
Save time	2	7	3	43	35	4.13	15	19	16	37	14	3.16
Save man power	6	11	7	37	29	3.8	13	10	21	42	15	3.35
Reduce work load	4	18	4	40	24	3.69	13	23	18	36	11	3.09

1 =Strongly Disagree): Respondents completely disagree with the statement.2 =Disagree): Respondents somewhat disagree with the statement.3 =Neutral): Respondents neither agree nor disagree (undecided or indifferent). 4 =Agree): Respondents somewhat agree with the statement. 5 =Strongly Agree): Respondents completely agree with the statement.

Biogas adoption is strongly linked to positive perceptions of its role in forest conservation, as adopters consistently report higher agreement across various benefits compared to non-adopters. Adopters emphasize reduced reliance on firewood (mean score: 4.36) and a significant decrease in firewood collection frequency (4.44), while non-adopters score lower (1.00 and 3.44, respectively) due to their lack of direct experience. This reduced firewood dependency enables forest regeneration (adopters: 4.35, non-adopters: 3.84) and contributes to biodiversity preservation (4.36, 4.05) and deforestation reduction (4.58, 4.00), with adopters directly witnessing these environmental improvements. Both groups, however, recognize biogas as a sustainable alternative to firewood (adopters: 4.43, non-adopters: 3.58), and its critical role in long-term forest conservation (non-adopters: 4.25, adopters: 3.99). Overall, the findings underscore that biogas adoption is central to reducing deforestation, promoting forest regeneration, and enhancing biodiversity, thereby playing a crucial role in community-driven forest conservation efforts (Table 3). The graphical representation of mean score between adopters and non-adopters is presented below in the chart.

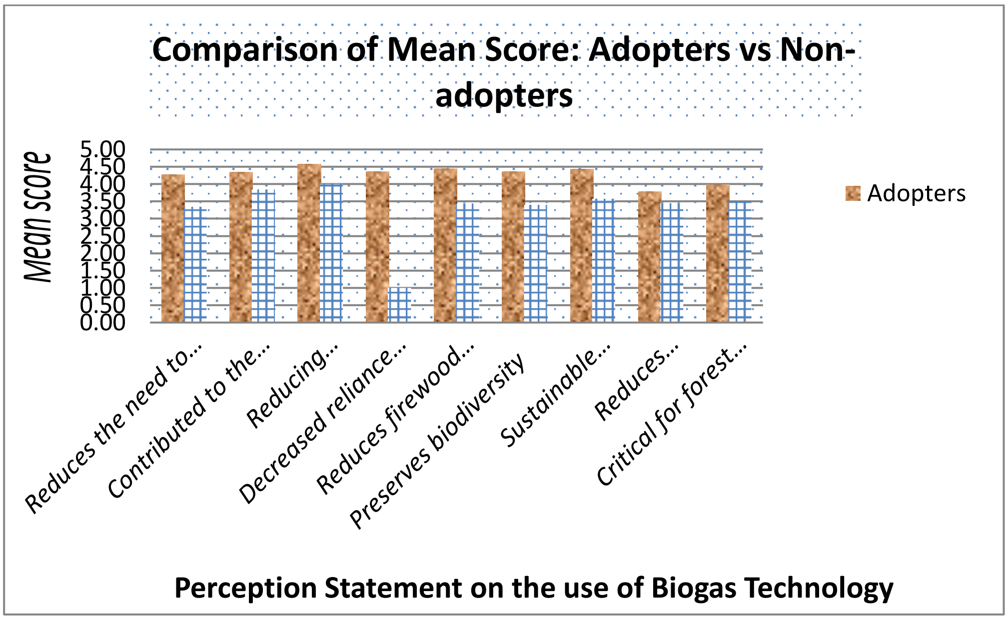

Figure 3: Comparison of mean scores: Adopters vs. Non-adopters

Increasing awareness and accessibility of biogas could further strengthen its adoption and amplify its positive impact on forest ecosystems.

3.3 Fuel Source mix before and after Biogas adoption

The adoption of biogas drastically reduces reliance on traditional fuel sources. Firewood usage for cooking drops by 83.33% and for lighting by 90%, with charcoal use also decreasing by 66.67% for cooking (Table 4). Kerosene consumption is eliminated entirely for cooking (100% reduction) and significantly reduced for lighting (75% reduction). Biogas emerges as the primary fuel source post-adoption, replacing traditional fuels, but no reductions are applicable to biogas itself as it is introduced as a new, sustainable alternative.

Table 4: Fuel source for different purpose before and after biogas adoption

Fuel Source	Cooking Before	Lighting Before	Cooking After	Lighting After	% Reduction Cooking	% Reduction Lighting
Firewood	90	20	15	2	83.33%	90%
Charcoal	9	0	3	0	66.67%	0%
Kerosene	1	80	0	20	100%	75%
Biogas	N/A	N/A	82	78	N/A	N/A

3.4 Firewood Consumption Comparison Table

Adopters of biogas experience a significant reduction in firewood usage. Their average monthly firewood consumption decreases by 81.82% (*from 22 shekim to 4 shekim),* while the number of firewood collection trips drops by 80% (from 5 trips per week to 1). In contrast, non-adopters maintain high firewood consumption levels (*22 shekim/month and 5 trips/week*), highlighting the transformative impact of biogas adoption in reducing firewood dependency and associated labor.

Table 5: Firewood collection trips and average consumption

Parameter	Adopters (Pre-Biogas)	Adopters (Post-Biogas)	Non-Adopters	% Reduction in Adopters
Average Monthly Firewood Usage (shekim[1])	22	4	22	-81.82
Firewood Collection Trips per Week	5	1	5	-80

[1] *Shekim is equivalent to one Man load*

3.5 Firewood Consumption Before and After Adoption of Biogas Technology

Table 6 below illustrates the weekly firewood consumption patterns among rural households in the Aleta-Wondo district before and after the adoption of biogas technology. Prior to adoption, the majority of households (60.2%) consumed 3–5 bundles of firewood per week, while 27.2% consumed 6–7 bundles, and 12.6% consumed 8–9 bundles. In contrast, after adopting biogas technology, firewood consumption significantly decreased. A large proportion of households (80.6%) reduced their consumption to 1–2 bundles per week, 17.27% consumed 3–4 bundles, and only 2.13% consumed 5–6 bundles.

Table 6: Firewood Consumption Before and After Adoption of Biogas

Before Adoption			After Adoption		
Number of bundle/week	**Frequency**	**Percentage**	**Number of bundle/week**	**Frequency**	**Percentage**
3–5	115	60.2	1–2	154	80.6
6-7	52	27.2	3–4	33	17.27
8–9	24	12.6	5–6	4	2.13
Total	191	100	Total	191	100
How much is the price of one bundle in your local market (ETB) on average?	Price=65				

3.6 Analysis and estimation of time requirement for traditional fuel collection

The data on the time required for households to collect firewood per week before and after the installation of biogas plants is provided (Table 7). Before the adoption of biogas technology, the average time spent collecting firewood was **11 hours per week**. A majority of households (81.1%) spent 7–11 hours per week, while 18.9% spent as much as 14 hours per week. This translates to an average of **572 hours per household per year** for firewood collection.

Table 7: Time requirement for traditional fuel collection

Time requirement	Hour per week	Frequency	Percent
How long does it take you to collect firewood before biogas plant installation? *Average=11hours/week*	7	80	41.8
	10.5	75	39.3
	14	36	18.9
How long does it take you to collect firewood after biogas plant installation? *Average=3 hours/week*	1	123	64.4
	3	52	27.2
	5	16	8.4

3.7 Respondents average annual energy expenditure pre and post installation of biogas

The important information on the role of biogas adoption on energy expenditures in rural households is presented (Table 8). The data shows that before biogas installation, adopter households had slightly higher expenditure on both fuel wood and naphtha compared to non-adopter households. This may be due to the fact that adopter households may have had larger families or more energy-intensive cooking and heating practices. However, after biogas installation, the expenditure on fuel wood and naphtha in adopter households significantly decreased, indicating the positive impact of biogas adoption on reducing energy expenditures. In contrast, non-adopter households continued to spend on fuel wood and naphtha even after biogas installation, suggesting that these households may face barriers to biogas adoption or may not have sufficient access to biogas technology.

Table 8: The role of adopting Biogas technology in reducing energy expenditures

No.	Expenditure	Adopters (n=90)	Non-adopters(n=101)
1	The average annual expenditure on fuel wood for cooking and heating before biogas installation	1703.35	1673.25
2	The average annual expenditure on naphtha for cooking and heating before biogas installation	393.80	390.55
3	The average annual expenditure on fuel wood for cooking and heating after biogas installation	340.65	1673.25
4	The average annual expenditure on naphtha for cooking and heating after biogas installation	269.25	390.55

3.8 Factors influencing Biogas technology adoption

The results of the binary logistic regression model show that the estimated values fit the observed data reasonably well. The study examined social and cultural factors that influence the adoption of biogas technology in the study area, including all expected variables. The results indicate that five of these variables were statistically significant ($p < 0.01$) in influencing the adoption of biogas technology by households in the study area. These variables included and presented in (Table 9) below.

Table 9: Result of the Binary logistic regression model

Biogas Adoption	Odds Ratio	Coefficient Value	Std.err	p-value	95%conf. Interval	
Sex	3.309568	1.199	1.819726	0.030*	1.126545	9.722863
Age	1.006029	0.006	0.0239607	0.801	0.9601457	1.054104
Marital	1.38698	0.325	0.5193161	0.382	0.6658269	2.889209
Educ	3.146506	1.148	0.8796922	0.000*	1.81908	5.442586
Family	0.9157637	-0.090	0.1312502	0.539	0.691491	1.212775
AW	7.830406	2.057	3.764443	0.000*	3.05191	20.09078
AC	11.96988	2.484	5.98262	0.000*	4.494214	31.88054
TLU	1.29886	0.258	0.1120941	0.002*	1.096736	1.538235
Extension	1.36896	1.005	3.6864931	0.102	0.543261	1.321557
Income	1.000066	0.983	1.5418626	0.0032	1.53908	5.3654721
Ease of Use	2.35789	0.453	1.6210027	0.203	1.45608	5.4578901
Constant	0.0003049	-8.098	0.0004796	0.000*	0.000014	0.006651

Sex: The results showed the statistically significant ($p < 0.01$) and positive relationship between the sex of the household head and the probability of adopting biogas technology at the household level. Male headed households are more likely to adopt biogas technology than female headed, with an odds ratio of 3.309568.

Educational level (Educ): The level of education of the household head is an important factor that influences the adoption of biogas technology. The results of this study demonstrate a statistically significant ($p < 0.01$) and positive relationship between the level of education and adoption of biogas technology.

Income: The study sought to determine whether household's income levels influence the adoption of biogas technology. The respondents were requested to indicate the sources of their income and the range of their annual income. Binary logistic regression result revealed that, it was found to be statistically significant and positive association between the total annual income and adoption of biogas technology at (0.01)

Access to water (AW): The result of the regression analysis reveals that, a positive relationship between access to water and the probability of adopting biogas technology, with an odds ratio of 7.83.

Access to credit (AC): The statistical analysis in this study indicates that access to credit is a significant ($p<0.01$) and positive factor in the adoption of biogas technology. The study found that access to credit is expected to increase households' decision to adopt biogas technology by a factor of 11.96.

Number of livestock (TLU**):** The results show a statistically significant ($p < 0.01$) and positive correlation between the two variables, indicating that households with a higher number of livestock is more likely to adopt the technology.

4. DISCUSSION

Married households are more likely to have adopted the technology, suggesting that stable and reliable sources of income may be needed to invest in the technology. Households in the age group of 36-64 are more likely to have adopted the technology, indicating that specific outreach efforts may be needed to promote adoption among younger and older households. Larger households are more likely to have adopted the technology, suggesting that households with smaller family sizes may need to be incentivized to invest in the technology. Households with higher levels of education are more likely to have adopted the technology, indicating a need to provide clear and accessible information to less educated households to encourage adoption. Overall, understanding the socio-demographic characteristics of households can help identify potential barriers to adoption and inform targeted outreach and education efforts to promote adoption of domestic biogas technology. Result revealed that, a large proportion of households (80.6%) reduced their consumption to 1–2 bundles per week after the adoption of biogas technology. This shift highlights the substantial reduction in firewood dependency following the adoption of biogas technology, which contributes to decreased deforestation and labor associated with firewood collection. Additionally, as the average price of one firewood bundle is 65 ETB in the local market, the reduction in consumption translates into notable financial savings for households, further emphasizing the economic benefits of adopting biogas technology. The data underscores the potential of biogas technology to alleviate pressure on forest while reducing household energy expenditures. After the adoption of biogas technology, the time required for firewood collection decreased significantly, with the average time dropping to 3 hours per week. About 91.6% of households reported spending only 1–3 hours per week, while 8.4% spent 5 hours per week. This reduction equates to an average of 156 hours per household per year. The adoption of biogas technology allowed households to save an average of 8 hours per week on firewood collection, which is a reduction of approximately 72.7%. This substantial decrease not only alleviates the labor burden, particularly for women and children, but also provides households with more time for other productive activities. The data underscores the significant time-saving benefits of adopting biogas technology. The data shows that before biogas installation, adopter households had slightly higher expenditure on both fuel wood and naphtha compared to non-adopter households. This may be due to the fact that adopter households may have had larger families or more energy-intensive cooking and heating practices. However, after biogas installation, the expenditure on fuel wood and naphtha in adopter households significantly decreased, indicating the positive impact of biogas adoption on reducing energy expenditures. The data also highlights the potential for biogas adoption to provide significant financial savings for rural households. By reducing the reliance on expensive and unsustainable sources of energy, households can redirect their resources towards other important expenditures, such as education, healthcare, and livelihoods. Overall, the result underscores the importance of promoting sustainable energy solutions, such as biogas, in rural areas to improve the livelihoods of households and contribute to sustainable development. The results of the binary logistic regression model show that the estimated values fit the observed data reasonably well.

The results showed that sex was statistically significant at ($p < 0.01$) and positive relationship between the sex of the household head and the probability of adopting biogas technology at the household level. Male headed households are more likely to adopt biogas technology than female headed, with an odds ratio of 3.309568. This finding is unexpected when the burden of using traditional three stone stove for preparing meals, by collecting fuel wood. However it can be due to the greater control over household resources and decision-making processes. This can occur in societies where patriarchal norms and gender inequalities limit women's access to resources and decision-making power. In contrast, a study found that female-headed households had more favorable biogas technology adoption behaviors than male-headed households (Kabir et al., 2013). Overall, the relationship between the sex of the household head and the adoption of biogas technology is complex and dependent on various cultural, social, and economic factors.

The level of education on the other hand is an important factor that influences the adoption of biogas technology. The results of this study demonstrate a statistically significant ($p < 0.01$) and positive relationship between the level of education and adoption of biogas technology. An increase in the household head's level of education by one grade is associated with a 3.146 times higher the probability of adopting biogas technology. Educated individuals are more likely to be aware of the environmental impact of uncontrolled biomass utilization on their health and the environment and may be more willing to try new technologies that can help reduce greenhouse gas emissions. This finding is consistent with previous studies, which also found a positive association between the level of education and adoption of biogas technology (Kabir et al., 2013; Mengistu et al., 2016). Lack of education can limit the spread of biogas technology and to successfully promote its adoption, it is essential to educate potential beneficiaries about the health, environmental, and socio-economic benefits that the technology can provide. Overall, the level of education of the household head is an important factor in the adoption of biogas technology, and promoting education can help facilitate the spread of the technology.

Binary logistic regression result revealed that, Income of the household head was found to be statistically significant and positive association between the total annual income and adoption of biogas technology at (0.01). This suggests that higher-income households are more likely to adopt biogas technology. This could be because higher income increases the household's ability to afford the initial investment and maintenance costs associated with biogas systems. Additionally, wealthier households may have greater access to information and resources, further facilitating adoption. The positive relationship between access to water and the probability of adopting biogas technology, with an odds ratio of 7.83 was the other finding of the study. This means that households with access to water are 7.83 times more likely to adopt biogas technology compared to households without access to water. This finding is consistent with the feasibility study report on the national program for domestic biogas in Ethiopia (Eshete et al., 2006). The result also indicates that accessibility to water within the compound where the biogas digesters are located is crucial. Water is a critical component for the proper functioning of biogas digesters, and it was expected to be a significant factor influencing the adoption of the technology at the household level in the study area. The statistical analysis in this study indicates that access to credit is a significant at ($p<0.01$) and positive factor in the adoption of biogas technology. Access to credit is particularly important for poor households who may not have the financial resources to invest in the technology. The study found that access to credit is expected to increase households' decision to adopt biogas technology by a factor of 11.96. This suggests that providing credit services is essential for accelerating the dissemination of the technology. The result of this study is consistent with the findings of previous studies, who also reported that access to credit is a significant factor in the adoption of biogas technology (Mengistu et al., 2016). Both studies found that access to credit can ease financial constraints associated with managing biogas plants in rural areas. This finding is also consistent with the work who argued that credit services can help in managing biogas technology in sub-Saharan African countries (Parawira, 2009). Overall, access to credit is an important variable in the adoption of biogas technology and can help empower poor households interested in adopting the technology.

Number of livestock in **TLU** shows a statistically significant at ($p < 0.01$) and positive correlation between the two variables, indicating that households with a higher number of livestock is more likely to adopt the technology. Specifically, an increase in the number of cattle owned by one unit is associated with a 1.29 times higher chance of adopting biogas technology. This finding is consistent with previous studies which also found a significant relationship between livestock ownership and adoption of biogas technology (Walekhwa et al., 2009; Kabir et al., 2013; Mengistu et al., 2016). The size of livestock population in general and cattle population in particular is one of the most important factors that determine the availability of sufficient dung for the successful operation of biogas plants. As cow dung is the primary substrate used in biogas digesters, households with a higher number of livestock have a greater potential to produce the necessary input for the technology. The National Biogas Programme of Ethiopia has set a minimum requirement of four heads of cattle for households to be targeted for biogas technology adoption. This is because four heads of cattle can produce a minimum of 20 kg dung daily input required to operate the minimum size biogas digester (EREDPC and SNV 2008). The average number of livestock owned by adopters and non-adopters in the study area is 9.2 and 6.1, respectively, which is considered suitable for the production of substrate for the technology at the household level.

5. CONCLUSION

The study highlights the transformative role of biogas technology in forest conservation and reducing energy expenditures among rural households in the Aleta-Wondo district. Biogas adoption significantly reduces reliance on traditional fuels, with firewood usage dropping by 83.33%, charcoal by 66.67%, and kerosene for cooking entirely eliminated. This shift alleviates pressure on forests, reduces deforestation, promotes forest regeneration, and enhances biodiversity, thereby supporting community-driven forest conservation efforts. Additionally, biogas adoption reduces firewood collection trips by 80%, saving households an average of 8 hours weekly (a 72.7% reduction), which translates into substantial labor and time savings. These reductions also result in financial savings, as households spend 22.1% less on energy, allowing greater resource allocation to essential needs such as education and healthcare, thereby improving overall quality of life. Beyond its environmental and economic benefits, biogas mitigates indoor air pollution, reducing critical health hazards, and promotes toilet construction by utilizing organic waste, which improves sanitation and reduces open defecation. Results from the qualitative data from Focus Group Discussion supported most of the results obtained from the survey. For instance, the use of biogas technology reduces the cost of kerosene for lighting, time for collecting fire wood from the forest, the amount of firewood being collected from individual plantation and communal forests, which in turn reduces deforestation. Moreover, the result from FGD and KII assures that the use of biogas also reduces the exposure to indoor air pollution and promotes toilet construction; because toilets provide organic wastes for feeding biogas plants and avoids field defecation. However, despite its benefits, the adoption rate remains low (12%), primarily due to high initial investment costs, limited technical expertise, and inadequate access to credit. The study identifies key factors influencing adoption, including education level, awareness, income, livestock ownership, and access to credit, emphasizing the need for targeted interventions to address these barriers. Government support in the form of financial incentives, technical assistance, and capacity building is essential to scale up adoption and unlock biogas technology's full potential. Overall, biogas technology emerges as a practical, sustainable, and cost-effective solution for reducing energy poverty, conserving forests, and improving rural livelihoods. By addressing barriers and promoting its benefits, stakeholders can foster widespread adoption, contributing to environmental sustainability, socio-economic resilience, and a more equitable future for rural communities.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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