Research article

The potential of biogas technology in fuelwood saving and carbon emission reduction in Central Rift Valley, Ethiopia

Tamiru Kefalew [*], Boja Tilinti, Mulugeta Betemariyam

Forestry, Madda Walabu University, Bale Robe, Oromia, P.O.Box: 247, Ethiopia

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H I G H L I G H T

- Data were collected from 68 biogas adopters and 124 non-adopters of biogas technology.
- Fuelwood, biogas, animal dung, agricultural residue, and charcoal were the most common energy source for heating and cooking.
- The annual fuelwood savings of biogas adopters per household per year was 1.86 tons.
- About 2.75 t CO_2e was reduced per biogas plant per year.

A B S T R A C T

The rapid rate of deforestation, combined with Ethiopia's rapid population growth, has resulted in increased energy scarcity, high greenhouse gas (GHG) emissions, and climate change. Biogas technology has recently been described as one of the most promising solutions to the problems of deforestation, energy supply, and climate change. Therefore, this study was aimed to investigate the potential of biogas technology in fuelwood saving and carbon emission reduction in the Central Rift Valley of Ethiopia. A multi-stage sampling procedure was employed to select a sample of 192 households (HH) (68 biogas adopters and 124 non-adopters). To conduct the Kitchen efficiency test, 25 test subjects were chosen at random from each category. The data were analyzed using descriptive statistics and an independent-sample t-test. The energy source for cooking and heating were fuelwood, biogas, animal dung, agricultural residue, and charcoal were the most common energy source for domestic use, accounting for 46.9%, 35.4%, 9.4 %, 5.2 %, and 3.1%, respectively. Kerosene lamps, battery cells, and tiny solar panels were utilized by 35 %, 32.4 %, and 18 % of respondents, respectively, for lighting. The most widely used woody plants for domestic energy usage were *Eucalyptus camaldulensis* and *Eucalyptus saligna*, according to the findings. The digester size of 6m^3 was used in 93 (56.5%) of the 165 biogas plants, while 8m^3 and 10m^3 digesters were used in 69 (43.5%) and 3 (1.8%) of the plants, respectively. Hence, the annual fuelwood savings from using biogas technology per household was calculated to be 1856.78 kg per year, with an annual Carbon dioxide (CO_2) emission reduction capacity of 2.75 tons per biogas plant. Consequently, it was projected that all functional biogas plants (111) would save around 305.25 tons of CO_2e per year. Generally, Biogas has been proven to be a viable technique for reducing reliance on forest resources and mitigating climate change in general. As a result, the country's energy sector should encourage families to embrace biogas technology to enhance fuelwood availability and reduce carbon emissions.

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1. Introduction

1.1. Background and justification

In the last two decades, forests have changed dramatically. The global forest area was estimated to be about 4.13 billion hectares (ha) in 1990.

In addition, the world's forests store an estimated 296 Gigaton (GT) of carbon in both aboveground and belowground biomass [1]. However, by 2015, the area had shrunk to 3.99 billion hectares [1]. Hence, between 1990 and 2015, approximately 129 million hectares of natural and cultivated forests were lost. Over the past 25 years, it has also lead to a reduction of 697 million megatons of emissions per year, or around 2.5
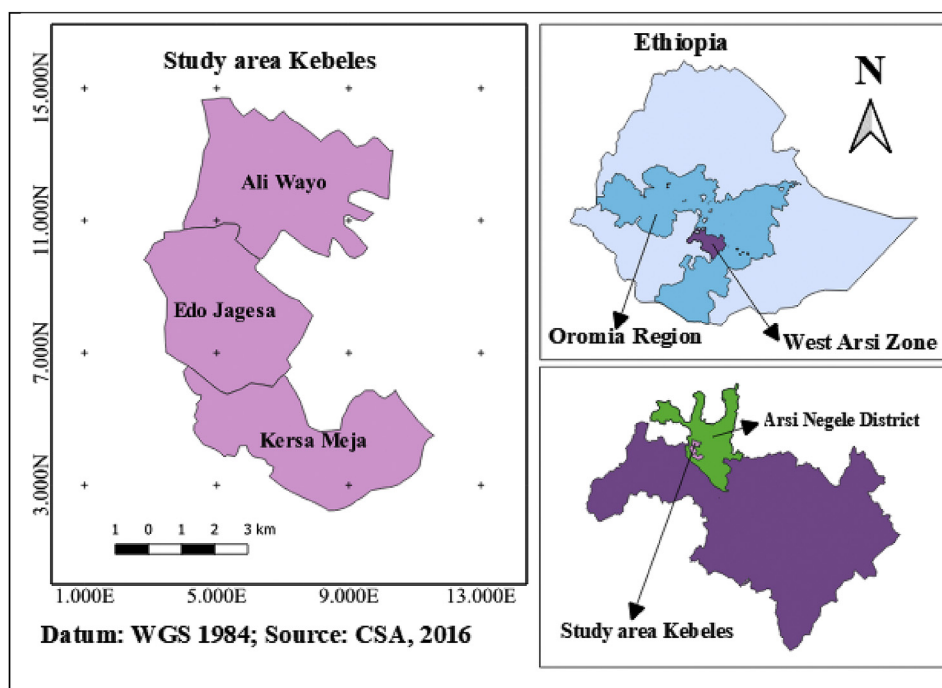

Figure 1. Location map of the study area.

GT of CO_2 [1]. Around 3.9 billion m^3 of fuelwood was produced globally, with 2.3 billion m^3 (58.9%) being used for various purposes. More than 43% of the world's population relies on firewood for cooking [2]. As a result, about 60% of the world's forest has been cleared for energy purposes. More than 64% of the world's forest has been cleared for human use in developing countries [3]. Fuelwood is used as a source of energy by more than 70% of Africa's population [4].

Fuelwood is the most common source of energy in Ethiopia, accounting for 78 % of total energy consumption, followed by animal dung (12 %) and crop residue (9 %). Fuelwood is used for cooking, heating, and lighting in Ethiopia's rural and urban areas. The natural forest environment provided the majority of firewood, with a few exceptions from plantation forests, home gardens, and woodlands woody plants [3, 5]. It leads to deforestation and a reduction in associated ecosystem services including carbon emissions, resulting in air pollution that contributes to climate change [6, 7]. Furthermore, under a conventional development path, greenhouse gas (GHG) emissions will rise from 150 to 400 Mt CO_2e (2010-2030). Hence, environmentally friendly energy sources have gotten a lot of attention [8, 9], particularly when they have the potential to alleviate energy poverty in areas with minimal or no access to modern energy infrastructure [10].

A biogas digester is one renewable energy option that has the potential to provide low-cost energy without the need to harvest wood [11, 12]. Biogas is a renewable energy source produced in domestic bio-digesters that uses anaerobic digestion to turn waste from animals and humans into biogas for cooking and lighting [13]. It produces 60–70 percent methane (CH4) and 30–40 % carbon dioxide (CO_2), as well as 1–5% hydrogen and trace amounts of nitrogen, hydrogen sulfide, oxygen, water vapor, and slurry [14]. The National Biogas Program (NBP) in Ethiopia has planned 14,500 biogas plants for the first phase (2009–2013) and 20,000 biogas plants for the second phase (2014–2017) in 163 districts, including the study region. In the first and second phases, however, only 8,063 and 1762 biogas plants were installed, respectively [15, 16]. It is a low-cost, environmentally friendly technology [17] that improves energy protection while lowering pollution and greenhouse gas emissions [18].

The World Development Indicators [19] and many other studies [20, 21] indicated that the national energy balance is dominated by a heavy dependence on firewood, crop residues, and dung (biomass accounts for 91% of the energy consumed). Traditional biomass energy sources are highly important to the majority of local communities in Arsi Negele (e.g. about 69.38 kg/day of wood fuel were used per household in the town). Particularly, 87.3 % of the population relies on the distillation of Katikala/Arake[1] to sustain their lives, and wood fuel was the primary source of energy for distillation. In addition to this, selling fuelwood is a coping strategy for vulnerable households who are low on cash, property, or food as a result of the harsh weather (e.g. drought, erratic rainfall, and political instability) [22]. Furthermore, a large area of forestland has been changed to other land-use types due to over-harvesting of the forests [23, 24]. This situation has caused a scarcity of fuelwood sources and forced for other options (e.g. biogas technology) [22]. investigated the effect of Katikala/Arake production on vegetation and greenhouse gas emissions in the study area, while [25] investigated the status of biogas and factors influencing biogas technology adoption Therefore, this study aimed to look into the potential of biogas technology in saving fuelwood and reducing carbon emissions in Ethiopia's Arsi Negele District.

2. Materials and methods

2.1. Description of study area

The research was carried out in the Arsi Negele district of Ethiopia's central Rift Valley, about 225 km south of Addis Ababa. The study site is

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[1] **Arake** is local alcoholic beverage produced by distillation process. Ground gesho (common name of Rhamnus prinoides used in making local alcoholic beverage in Ethiopia) leaves and water are kept for three to four days and after that a kita (refers to baked bread made of whole-grain flour) made up of *Eragrostis teff* or other cereals and germinated barley or wheat are added. The mixture is allowed to ferment for five to six days and then distilled. In the villages distillation is carried out with primitive equipment made of gourds and wood. The local beer tella can also be distilled to produce arake. The arake can be redistilled and will then have higher alcohol content. The average alcohol content of Arake lammataa is around 45%. The term lammataa in Afaan Oromoo refers to "second time" and indicates that it is distilled a second time …"

situated between 1° 00′ and 13° 00′ east and 3° 00′ and 18° 00′ north latitude (Figure 1). The annual temperature in Arsi Negele district ranges from 10 to 25 °C, with annual rainfall ranging from 500 to 1000 mm. The mainstays of their livelihoods are rain-fed crop production and livestock rearing. The study area's natural vegetation is a dry Afromontane evergreen forest, with *Afrocarpus falcatus* and *Croton macrostachys* as the dominant tree species. In Arsi Negele, society has faced major challenges such as irregular rainfall, periodic droughts, population growth, deforestation, soil depletion, and decreasing crop productivity. The total population of Arsi Negele district was 137,228 in 1994 (c), 198,307 in 2005 (p), 260,129 in 2007 (c), and 338,967 in 2016 (p), according to Ethiopian Central Statistical Agency (CSA) estimates (c and p indicating censuses and projections, respectively). According to these statistics, the district's population grew by more than double between 1994 and 2016.

The domestic energy in this study is biomass energy sources such as firewood and charcoal [22]. In addition, renewable energy technologies such as improved stoves and biogas technologies have been promoted in the area. In this research field, a fixed dome model of biogas digester (local name-'SINIDU') with various volumes of 6m³, 8m³, and 10m³ was mounted.

2.2. Methodology

2.2.1. Data sources

For this study, both primary and secondary data sources were used. A sample Household survey, Focus Group Discussions (FGD), Key Informant Interview (KII), and Field Observation were used to gather primary data. Secondary data was gathered from the district's office of water, minerals, and energy, kebele administration offices, and other published books, papers, and studies.

2.2.2. Sampling techniques and sample size

This study fuelwood sources of households commonly used fuelwood species for domestic energy, the basic design of digester, the status of biogas plants, digester size and feedstock types, fuel consumption, and role of biogas in carbon dioxide emissions reduction. The biogas plant used in this study was installed by National Biogas Programme (2014–2017).

Biogas adopters and non-adopters households were chosen using a multi-stage sampling technique. Arsi Negele was purposefully chosen from the West Arsi zone in the first stage due to the existence of relatively higher domestication of biogas technology and its functionality. Three kebeles were chosen for the study based on their degree of biogas adoption. The district and Kebele (the smallest administrative division in Ethiopia) administration offices were contacted for a list of biogas technology adopters and non-adopter household heads in the selected kebeles. Hence, the overall number of sample households for both biogas adopter and non-adopter members of the target population was calculated using the simplified formula given by [26] at a 92% confidence level and 0.08 (8%) level of precision:

$$n = \frac{N}{1 + N(e)^2}$$
Equation (1)

Table 1. Distribution of sample sizes in each selected kebele.

Kebeles	Total number of households		Sample size taken	
	Biogas Adopters	Non-adopters	Biogas Adopters	Non-adopters
Edo Jigesa	56	1179	23	38
Ali Woyo	61	1395	25	46
Kersa Meja	48	1218	20	40
Total	**165**	**3792**	**68**	**124**

where: n is the sample size, N is the population size (3957), and e is the level of precision at 92 % significance level. A total of 150 samples was determined for both biogas adopters and non-adopters. However, the analysis included 68 biogas adopters and 124 non-adopter household heads (Table 1). The number of sample households from each of the chosen kebele was calculated in the third stage using the Probability Proportional to Size (PPS) sampling technique (Table 1). Finally, sample households from the three kebele were chosen using a simple random sampling technique.

Based on the household interviews (192 respondents) the average fuelwood sources and types of woody species used for domestic energy use were collected. Furthermore, direct field observations were made to assess digester size, each biogas plant's functional status, failed digester sections, and the feedstock form used in biogas plants. Open-ended and closed-ended questionnaires were developed, translated into the participants' first language, and interviewed. Open and close-ended questions were designed to solicit information relating to fuel sources, commonly used species and factor affects the functioning of the biogas plant. In each selected kebele, a total of six Focus Group Discussions (FGD) with ten participants and 12 KII were used to discuss the basic design of the digester, as well as the problem they faced with biogas production [27]. Key Informants in the study area were chosen using snowball sampling. This research was performed following the laws, guidelines, and ethical standards of Ethiopia, where the research was performed.

2.2.3. Kitchen performance test procedure (KPT)

The Kitchen Performance Test (KPT) is the principal field-based procedure to measure household fuel consumption. The KPT is a type of performance test used to determine how much fuel is saved by the use of biogas technology as compared with traditional three-stone fire stoves [28]. For cross-sectional analysis, an equal number of biogas adopters (25) and non-adopters (25) of biogas technology was chosen at random.

As a rule of thumb, In a small target population, usually less than 200 families, the number of families who may participate in the initial survey should not be less than 20 [28]. During high variance in the fuel used and saved, which is common in KPT, the sample size should be as large as possible.

According to [28], a minimum of three days of continuous testing is expected. Accordingly, the amount of fuelwood used and left was weighed continuously for ten days in the study area. Before the KPT have to be carried out, one-day visits were done to each selected household. This was done to arrange or to order households to be ready for the next day's KPT. Then the uniform firewood from similar tree species was supplied for each biogas adopter and non-adopter household. The provision of uniform fuelwood was to fulfill the want of the researcher and to make all selected households use fuel woods from similar tree species. The test subjects were informed households to cook normally as the usual cooking manner and ordered to use fuelwood only from a designated stock during the tests.

The mass of wood for each sample household was pre-weighed at the start of the day and the remaining wood was weighed at the end of the day to conduct KPT. Since more wood is needed for cooking, festivals and holidays were not considered. During the testing period, test subjects were told to cook normally. The aim was to capture their typical kitchen activity. They were also told to only use fuel from pre-weighed stock, and they were visited at least once a day to ensure that they were only using fuel from the pre-weighed stock. Finally, a statistical analysis of the mean fuel savings estimation was conducted on the test results. Then, the precision for a sample of size n is determined using the formula as follow;

$$\text{Precision} = 1.67 \times \frac{\text{SEy}}{\overline{\text{y}}} \times 100$$
Equation (2)

Where; $\overline{y}$ is the estimate of mean fuel savings; **SEy** is the standard error of the estimate, 1.67 is used as an approximation to the critical

value $t_{0.95,-1}$ which will vary between 1.75 and 1.64 as the sample size n increases from 15 to very large. In this KPT, the Coefficient of Variation (CV) for biogas technology adopters and non-adopters' daily fuelwood intake was 0.29 and 0.31, respectively. Furthermore, the accuracy achieved was 20.4 percent. This means the sample size adheres to the 90/30 rule. Endpoints of the 90 percent confidence interval lie within +/- 30% of the approximate mean when sample sizes are broad enough to fulfill the 90/30 law. Hence, there was no need for a larger sample size for KPT [28].

Estimation of minimum sample sizes in simple random sampling was conducted using (Equation 4). Since the project (biogas adopter) and baseline (non-adopter) samples are independent, then the standard error of the estimate (SE_Y) is:

$$SE_y = \sqrt{\frac{s_{b^2}}{n_b} + \frac{s_{p^2}}{n_p}}$$

Equation (3)

where; s_b is the standard deviation of the ith sample of baseline (non-adopters); s_p is the standard deviation of the ith sample of the project (adopters); n_b is the sample size for non-adopters and n_p is the sample size of biogas adopters. According to [28], the minimum required sample size ($\tilde{n}$) to accomplish "90/x" precision with two independent samples is approximately equal to:

$$\tilde{n} \geq \left(\frac{\sqrt{S_{b^2} + S_{p^2}}}{Y_B - Y_P} * \frac{1.67}{X/100} \right)^2 ; \ \tilde{n} \geq 10$$

Equation (4)

As a result, the total sample size needed in this case is 20 test subjects. All of the tested subjects (25 households from each group) were considered for this analysis to minimize bias and make the samples more representative.

Fuelwood consumed by households in both adopter and non-adopter can be measured by recording daily fuelwood consumption and dividing the amount by the number of adult equivalent served.

$$F_{Saved} = \frac{\text{fuelwood consumed by non} - \text{adopter}}{\text{Number of adults served}} - \frac{\text{fuelwood consumed by adopter}}{\text{Number of adults served}}$$

Where F_{saved} is saved amount of fuelwood.

A regular KPT survey was used to monitor the number of people served on meals cooked during each day of the KPT. In addition, to measure Standard Adult Equivalents (SAE), weighting factors were used. Keith Openshaw's guidelines for wood fuel surveys for the Food and Agricultural Organization (FAO) were used to calculate the SAE, as cited in [29]. Finally, per capita, SAE was used to calculate fuelwood usage and savings (Table 2).

Livestock size in the study area was calculated based on Tropical Livestock Unit (TLU) (Table 3).

2.2.4. Emission reduction potential determination

UNEP [31] reported that about 55.3 GtCO2e of greenhouse gases (GHGs) were emitted into the atmosphere per year. Deforestation and degradation of forests have a huge contribution to GHGs in many developing countries [32]. Hence, the impact of climate change is significant in poor people in developing countries [33]. Therefore,

Table 2. Standard adult equivalence factors.

Gender and Age	Fraction of standard adult
Child: 0–14 years	0.5
Female: over 14 years	0.8
Male: 15-59	1
Male: over 59 years	0.8

Table 3. Conversion factors used to estimate tropical livestock units (TLU).

Animal Category	Conversion factor
Calf	0.25
Donkey (young)	0.35
Weaned Calf	0.34
Camel	1.25
Heifer	1.75
Sheep and goat (adult)	0.13
Cow and Ox	1.00
Sheep and goat (young)	0.06
Horse	1.10
Chicken	0.0013
Donkey (adult)	0.70

Source [30].

Table 4. Parameters for calculating carbon emission.

Parameter	Value	Source
Annual wood saving per biogas	KPT	Field survey
The emission factor of fuelwood	112 CO2t/Tt	[35]
The net calorific value of fuelwood (wet basis)	15 MJ/kg	[35]
Conversion CO_2/C	3.667	The ratio of molecular weights
Fraction of non-renewable fuel wood	88%	[36]

estimating the amount of CO_2 emission from fuelwood and emission reduction potential of biogas will provide vital information for the Ministry of forest, Environment and Climate change, and the Ministry of Energy. Thus, the amount of carbon dioxide emitted was calculated by calculating the total amount of fuelwood saved by biogas plants (Table 4). As indicated by [34], it was calculated based on default net calorific values, emission factors, and carbon storage in forests by using the formula below.

$$ERy = By, \ savings \times fNRBY \times NCVbiomass \times EFprojected - fossil \ fuel$$

Equation (5)

Where:

ERy is emission reduction during the year in tons of carbon dioxide equivalent (tCO2e).

By, savings is the quantity of woody biomass that is saved in tones or kilogram per biogas plant.

fNRBY is the fraction of woody biomass saved during the year that can be established as non-renewable biomass.

NCV biomass is the net calorific value of non-renewable biomass.

EF projected-fossil fuel is an emission factor for the substitution of the non-renewable woody biomass by similar consumers.

Finally, the CO2e was converted to carbon using a conversion factor of 3.667 (ratio of molecular weights of CO_2 and C).

2.3. Data analysis

Statistical Package for the Social Sciences (SPPS) Version 20 was used to analyze the collected data. At a 5% significance level, the disparity between biogas adopter and non-adopter sample households was tested using an independent t-test. On other hand, qualitative data were analyzed based on content analysis. The analyzed data was presented using tables, figures, maps, and pie charts.
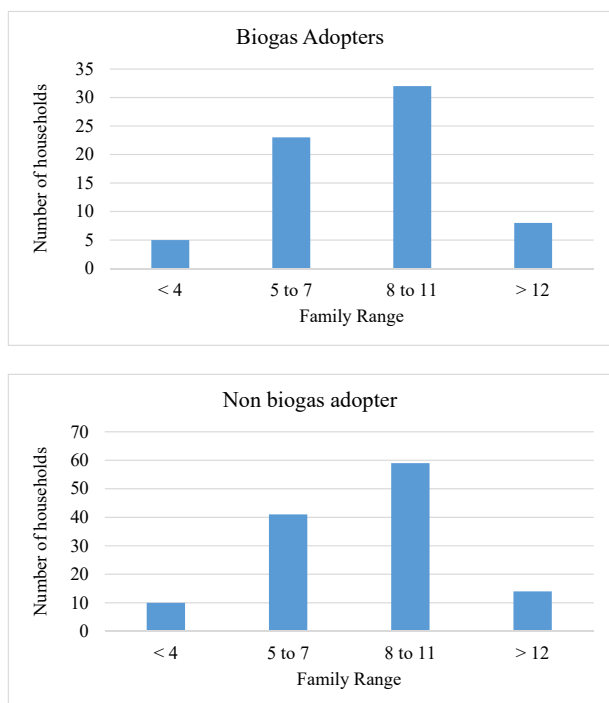
Figure 2. Family size distribution of biogas adopters and non-adopters respondents.

3. Results

3.1. Socioeconomic and demographic characteristics of households

In the study area, the households with family sizes of 5–7 and 8–11 members in biogas adopters households account for 33.8% and 47.1% respectively. While 33.1% and 47.6% in non-biogas adopters (Figure 2). This implies that there is a need for more energy and adequate household labor for running biogas systems.

Biogas adopters' average age and family size were 42.3 and 8.07, while non-adopters average age and family size were 41.56 and 7.97, respectively. There is no statistically significant difference between the two categories in terms of age and family size (p 0.05). This may mean that the biogas adopters and non-adopter household heads have almost similar demographic characteristics unless other factors are affecting the adoption of biogas in the study area. It agrees with the findings of [29], who researched Ethiopia's south-eastern central highlands. In contrast, the household survey showed that the average farm size and Tropical Livestock Unit (TLU) of biogas adopter households' were around 1.88 ha

and 9.88, respectively, while non-adopter households' average farm size and TLU were 1.34 and 5.3, respectively, and were significantly different at (p 0.05). This implies the livestock waste used as a substrate for biogas digester and larger grazing land for cattle could be among the factors that influence the adoption of biogas in the study area. Hence, a significant difference in economic characteristics between the two groups may be one of the factors influencing biogas adoption in the study area (Table 5).

Our findings also revealed that the biogas adopter's average family size and standard adult equivalents were 7.96 and 5.02, respectively. Non-adopters' average family size and standard adult equivalents were 7.72 and 4.90, respectively, and the difference between biogas adopters and non-adopters was statistically insignificant at (p 0.05) (Table 5). This may be related to the fact that both adopter and non-adopter sample households were taken from the area having almost similar demographic characteristics.

However, the average annual incomes of the adopter (1395.68 USD) were significantly higher than non-adopter households (978 USD) (Table 6). The annual income of non-adopters ranges from 500 – 1600 USD, while 850–1955 USD for biogas adopters. Moreover, the annual income of non-adopters of (<500 USD), (500–1000 USD) and (1001–1500 USD) accounts 6%, 64% and 32%, respectively, while, (<500 USD), (1001–1500 USD) and (>1500 USD) accounts 12%, 40% and 48% respectively. This result suggests that annual income was among the factors that affect the adoption of the technology. More annual revenue, according to many academics, could provide more economic capacity and legibility for the installation and maintenance of a biogas plant [13, 25, 37]. Household heads with higher annual income and livestock have a higher likelihood of adopting biogas technology, according to research conducted by [25, 38]. This relates to a budget for biogas plant construction, maintenance, and a sustainable feedstock (livestock waste) for biogas plant activity.

3.2. Types of energy source and current status of energy utilization

Our findings revealed that, out of 192 respondents, about 46.9% of the respondents used fuelwood for cooking and heating purposes. Particularly fuelwood were collected from plantation forests (homestead trees, public plantation, and *Eucalyptus* planted individually) account for 58% and 42 % of biomass collected illegally from the surrounding natural forest. It agrees with [39], who discovered that fuelwood obtained from plantations and natural woods was a significant source of fuel. About 5.2% of them have used agricultural crop residue for heating and to bake bread and Injera. Animal dung has been utilized for cooking and heating by about 9.4% of people. Besides, 35.4 % of respondents have utilized biogas as a source of energy, while the remaining 3.1 % have used charcoal for heating and cooking (Figure 3). This means that traditional biomass fuels were used by a greater proportion of the households in the study. Furthermore, individuals who have adopted biogas technology have relied on alternative energy sources to support their livelihood. The findings of this study are confirmed by those of [40, 41], who found that the majority of families cook and heat using firewood and agricultural

Table 5. Distribution of respondents by household characteristics.

Variables	Biogas adopters (n = 68) Mean ± SD	Non adopters (n = 124) Mean ± SD	P value
Age (Year)	42.3 ± 9.77	41.56 ± 7.08	0.537
Family size (Number)	8.07 ± 2.72	7.97 ± 2.71	0.852
Farm size (ha)	1.88 ± 0.58	1.34 ± 0.94	0.001*
Livestock (TLU)	9.88 ± 4.3	5.3 ± 2.19	0.001*
Variables	**Adopters (n = 25) Mean ± SD**	**Non adopters (n = 25) Mean ± SD**	**P value**
Annual income (USD)	1395.68 ± 289.2	978 ± 312.93	0.001*
Family size (Number)	7.96 ± 2.49	7.72 ± 2.41	0.731
Standard adult equivalents (Number)	5.02 ± 1.14	4.89 ± 1.28	0.719

Note: * represent statistically significant mean differences between adopters and non-adopters at p < 0.05.

Table 6. Household's daily and per capita fuelwood consumption (kg).

Variables	N	Ave. AME served	Average fuelwood used	Per capita fuelwood
		(per HH/day)	(Kg/HH/day)	used (kg/AME/day)
Non-adopters	25	5.07 ± 1.47	10.5 ± 3.83	1.98 ± 0.58
Biogas Adopters	25	5.26 ± 1.32	4.42 ± 1.38	0.92 ± 0.29
P-value		0.644;	<0.001*	<0.001*

Note: * represent statistically significant mean differences between biogas adopters and non-adopters at p < 0.05.
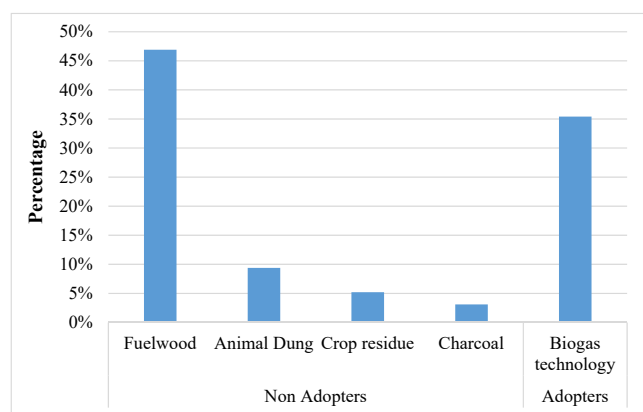**Source:** KPT survey, 2019

Figure 3. Types of energy used by households for cooking and heating in the study area.

leftovers. According to [42], the annual biomass intake in Ethiopia accounts for 77% of fuelwood which is followed by animal dung and agricultural residue, respectively.

According to the International Energy Agency (IEA), 93 % of Ethiopians relied on conventional biomass fuel for cooking in 2009. Fuelwood demand was projected to be 77 million m^3 in 2009, but the sustainable supply was only 9.3 million m^3 [43]. Thus, in conditions of unaffordable and escalating prices of imported oils, inaccessibility of electricity and increasing scarcity of wood fuel, the majority of the population will turn to animal dung and crop residues for energy [44]. have stated that less developed countries' heavy reliance on fuelwood is a source of air pollution and deforestation, as well as a significant source of greenhouse gas emissions. As a consequence, enhancing energy quality and using technological solutions such as biogas are among the options for addressing energy-related issues. Hence, biogas technology has been described as one of the most promising approaches to reversing deforestation and related issues.

Kerosene lamps, battery cells, and tiny solar panels were utilized by 35 %, 32.4 %, and 18 % of respondents, respectively, for lighting. Furthermore, the results revealed that 13.2 percent of the respondents have used biogas energy for lighting. Almost 1% of the families in the study utilized electricity to illuminate their homes (Figure 4). This conclusion is consistent with that of [40, 41], who found that the majority of respondents utilized kerosene lamps and battery cells for illumination, with only a few families using tiny solar panels and biogas.

3.3. Commonly used woody species for domestic energy use

Eucalyptus camaldulensis (18.2%), *Eucalyptus saligna* (14.6%), *Acacia tortillis* (13%), *Acacia etbaica* (10.4%), and *Balanites aegyptica* (8.3%) ranked first through fifth among woody species used for fuelwood in the study area. *Croton macrostachyus* (2.6%) and *Ficus elastic* (2.1%) were two
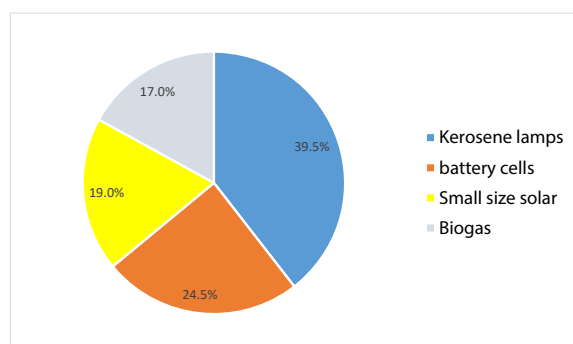
of the least commonly used species in the study field (Figure 4). This result is consistent with a previous study that found that many Ethiopians depend on the *Eucalyptus* species as a source of fuelwood [45]. 75 % of respondents revealed households prefer *Eucalyptus* species because of their accessibility, expense, availability, and fast-growing rates compared to other tree species in the area, according to KII and FGD. *Eucalyptus* is the most common tree species planted in the homestead, according to [39]. Many woody plants take a long time to mature, and native trees mature at a slower rate.

The study area's people relied on rain-fed agricultural cultivation and animal husbandry for their survival. During droughts, erratic rainfall, and political instability, the majority of fuelwood species were utilized as a coping mechanism for vulnerable households that were short on cash, property, or food as a result of the severe weather, according to Focus Group Discussants and Key Informants. *Afrocarpus falcatus* and *Ficus* species, according to the Ethiopian Biodiversity Institute, are endangered tree species in Ethiopia that have received special conservation attention. *Acacia* species were planted in their field to improve agricultural output and productivity. *Acacia* species' main stems were only utilized when they were old/easily damaged by winds. Moreover, *Cupressus lustanica, Juniperus procera,* and *Croton machrostachyus* were used majorly for construction purposes (poles and lumber). During the difficult conditions, the majority of respondents (85%) said they were unlawfully utilized for fuelwood.

3.4. The basic design of the digester

Fixed dome biogas digesters were used in the studied area. It is made up of six major elements, including a digester with a permanent, non-movable gas holder (Figure 5). The feedstock enters the inlet chamber, passes through the inlet pipe to the digester chamber, and after digestion, the produced gas accumulates in the upper part of the chamber (in the gas holder), and the digested slurry exits the digester outlet tank and flows out to the compost pits through the outlet tank's overflow opening. The gas is then piped into the kitchen, where it is used for cooking and lighting with appliances such as a gas stove and a gas lamp [46] (see Figure 6).

Due to the lack of moving components and rusting steel parts, fixed dome digesters have very cheap construction costs as compared with Floating Drum Digester. Fixed dome plants may live for a long time if they are well-built [46]. FGD and Key Informants revealed the plant's design necessitates technical expertise, and fluctuations in gas pressure might pose problems for consumers. The gas-tightness of the brickwork gas holder is a common concern (a small crack in the upper brickwork can cause heavy losses of biogas).

The required time the specific amount of dung to produce (80–85 %) of total gas is affected by the ambient temperature and the quantity of
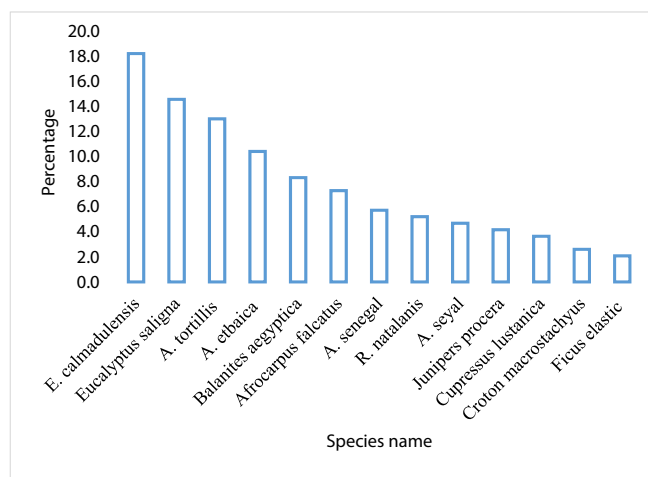

Figure 4. Types of energy used for lighting in the study area.

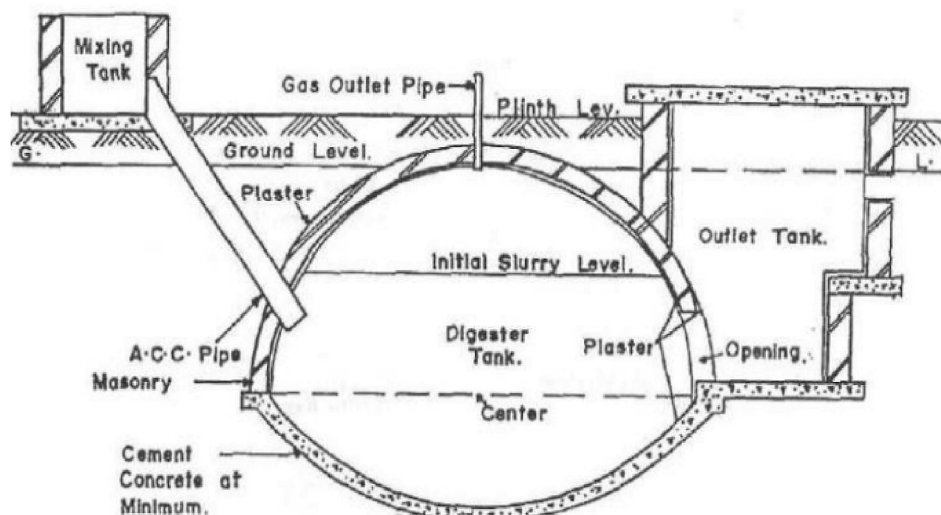**Figure 5.** Most commonly used tree species for domestic energy use.

Figure 6. Fixed dome biogas digester [46].

organic material in the bio-digester, according to FGD and Key Informants. Because they were tiny digesters, it took less than five days. The shorter the retention period, the higher the degradability of the organic substance, with an optimal value. If the period is too short, bacteria will not have enough time to break down organic material. If the process takes too long, the bacteria will starve, and methane output will decline after the optimum is reached. This also explains why temperature is so important since it influences the rate of degradation of organic molecules.

3.5. Functional status of biogas plants

Out of 165 installed biogas plants in the study area, 111 (67.3%) were providing energy for the biogas adopters, while, 54 (32.7%) were non-functional The percentage of non-functional biogas plants is lower than that found by [47], who found that about 47% of installed biogas plants were non-functional. This suggests that almost half of all biogas adopters aren't reaping the rewards of their investments. Furthermore, respondents (78%) stated that gas lamps and gas holders (Dome) are frequently failing and non-functioning parts of the biogas digester. Furthermore, Key Informants and discussants in focus groups observed that there is sometimes a problem with supplying repair service and spare parts. Furthermore, technical issues (water stuck in piping, unprotected piping damaged by cattle, broken stoves, leaky gas hose, broken digester, and input pipes, lack of technical backup services) hampered the biogas technology's operation. Water problem (longer distance to the water source), a decrease in the amount of dung and the number of cows owned, a shift in stock-keeping practices, and clumsy operation-related issues were also factors affecting biogas plant efficiency. Generally, the failure of the bio-digester in the study area was attributed to a lack of technical expertise for installation and maintenance, poor institutional control (e.g. weak linkage between distributer and final user and a gap in improving the skills of users in repairing the biogas plants), and insufficient and expensive maintenance service, according to the majority of biogas adopters (80%). This is consistent with [48]. Key Informants and Focus Group Discussion reported about 54 installed biogas plants were unable to provide a service due to one or more of these factors. This result is consistent with the results of [49]. FGD also indicated even after biogas technology was introduced to the study area, all of the households continued to use firewood, crop residue, and animal dung. The communities' continued reliance on firewood and charcoal necessitates a focus on tree-planting programs to help mitigate the lack of fuel-wood sources in rural areas. As a result, deforestation and land loss in the study areas remain unresolved issues. FGD and Key Informants also revealed there is a gap in cooperation between National Biogas Plan and other sectors (Ministry of Agriculture, Ministry of resources and energy,

Forestry and Environmental experts). The energy need and the number of livestock of the households were considered as a sufficient requirement for installation of biogas digester, without considering others (e.g. grazing land, climate change, maintenance cost). In general, there is weak cooperation between stakeholders and a gap to identify and establishing sustainable energy sources in the study area.

3.6. Digester size and feedstock types of biogas plants

The digester size of 6m^3 was used in 93 (56.5%) of the 165 biogas plants, while 8m^3 and 10m^3 digesters were used in 69 (43.5%) and 3 (1.8%) of the plants, respectively. In Ethiopia [48], also found that digester sizes of 6 m3 cover 37% of the population, followed by 10 m^3 (29%) and 8 m^3 (26%). This indicates that biogas plant distribution, especially with larger digester sizes, is insufficient in the study area. The number of livestock held by household heads affected the digester size of biogas adoption, according to more than 62 % of respondents. This is primarily related to the amount of digester substrate made. Dung is increasingly being used as a household fuel for baking Injera and bread in the study area. According to 25% of respondents, the soil structure and fertility have been negatively impacted as a result of the lack of natural fertilizer-dung, forcing them to use smaller digester sizes.

Renewable energy for the 21st century (2013) reported developed countries to focus dominantly on large-scale biogas installations for combined heat and power generation whereas the primary focus of developing countries is on the construction of small-scale biogas digesters that particularly generate heat for cooking. Bio-digester service, on the other hand, necessitates regular physical labor for dung processing, water fetching, feedstock preparation, and bio-digester feeding. Even in cases where households have sufficient livestock, the existence of grazing systems such as nomadic, semi-nomadic, and free grazing has made it difficult to collect manure and feed biogas digesters in many parts of Sub-Saharan Africa [50]. also reported smaller bio-digesters were enough to fulfill the cooking fuel needs of a small family. Small-scale biogas digesters, according to [51], have a lot of potentials to contribute to sustainable development by providing a wide range of socio-economic benefits, such as energy diversification, improved regional and rural development opportunities, and the formation of domestic industry and job opportunities. The amount of available substrate, necessary resources, water supply, family size, cost of construction materials, maintenance and spare parts, and the degree of expert commitment to operate and maintain the bio-digester were among the factors that determined the bio-digester size requirements in the study area.

About 60.5 % of respondents said their major bio-digester feedstocks were a mix of cow dung and toilet. Cow dung and latrine waste were used

by 38.2 percent and 1.3 percent of households, respectively. The usage of household waste is unusual in the study area. According to interviews with respondents and focus group discussants, combining latrine with livestock dung is an effective way to boost the amount of energy provided by biogas technology when compared to using only animal dung. The lack of cow dung can be compensated for by using a latrine. According to [29], 79.63 percent of respondents combined cow dung and latrine usage. Only cow dung was used by 18.52 % of households, while latrines and household wastes were used by 1.85 % and 0 % of households, respectively. According to a previous study conducted in Ethiopia by [52], 59 (64.9%) of the 91 institutions visited have linked their digester to the toilets. On the other hand, 26 households (28.6%) have only fed cattle dung to their digester, while 24 (26.4%) have mixed cattle dung with human, kitchen, and other animal wastes.

3.7. Household's daily fuelwood consumption

The average adult means equivalents (AME) served from cooked meals within 24 h for biogas adopter and non-adopter tested subjects were 5.26 and 5.07, respectively. It reveals the average adult means served from cooked meals in both categories is almost similar in the study area. Biogas adopter and non-adopter households consumed 0.92 and 1.98 kg of fuelwood per capita, respectively. Furthermore, the average daily per household fuelwood intake was found to be 4.42 kg for the biogas adopter and 10.5 kg for the non-adopter-tested subjects (Table 6). The difference between biogas adopters' and non-adopters average daily and per capita, fuelwood intake was found to be statistically significant (Table 6). This implies that biogas technology has the potential to reduce pressure on the surrounding forest and related land uses used as a source of fuelwood. The annual per capita fuelwood consumption was 723.2 kg for non-adopter households and 336.03 kg for biogas adopter households. The average annual fuelwood consumption per household was 3543.66 kg for non-adopters and 1686.87 kg for biogas adopters. As a result, the annual fuelwood savings from implementing biogas technology per household per year was calculated to be 1856.78 kg, which justifies biogas technology adoption's fuelwood reduction potential (52.4 %). It also coincides with [53], who discovered that cooking in basic stoves and open flames had a conversion efficiency of 10–20 percent, resulting in significant primary energy use. Advanced wood burning and biogas stoves have the potential to reduce biomass fuel use by 60% or more [53].

Research conducted in southeastern Ethiopia recorded a nearly identical result to the current study, with an average annual fuel savings of 1423.06 kg (1.42 t) as compared to the conventional three-stone fire system [29]. According to a study conducted in Kenya, each biogas system saves an average of 1519.2 kg of fuelwood per year [54]. It also agrees with [55] report, which found that biogas saved 62.30 % of fuelwood. The construction of a biogas plant was projected to save 2,091.36 kg of fuelwood per household per year. Many authors have stated that biogas technologies can help rural livelihoods [56] by lowering energy costs and saving time from firewood harvesting [12]; limiting the use of fuelwoods from natural forests and helping to stabilize the natural environment [57].

However, the amount of fuelwood saved per household per year in this study is lower than that found in Northern Ethiopia, where 2,534.4 kg (70.47 %) of average fuelwood consumption was saved per household per year [58]. The difference may be due to differences in digester size, digester temperature, manure loading rate, and unaccounted for fuelwood consumption per capita SAE when calculating the amount of fuelwood saved by using biogas technology.

3.8. Role of biogas technology in carbon emission reduction

The annual fuelwood savings from implementing biogas technology per household per year was found to be 1856.78 kg (1.86 t) per year when compared to the conventional three-stone fire, according to the quantitative fuel consumption survey. The net calorific value of fuelwood (wet basis) (15 MJ/kg), the emission factor of fuelwood (112 tCO_2/TJ), and a fraction of non-renewable fuelwood were used to calculate the CO_2 emission reduction capacity of a biogas plant (88 %). In this way, around 2.75 t CO_2e was saved per year per biogas plant. As a result, a total of 305.25 tons of CO_2e emissions were reduced per year from the 111 operational biogas plants in the study area. As a result, these biogas plants in the area will save 8.24 tons of carbon per year. Moreover, if the biogas energy was used to bake bread and 'Injera,' the carbon emission reduction would be greater than the current value. The total amount of fuelwood saved by biogas plants was used to determine the amount of carbon dioxide released. The number of emissions from biogas plants, on the other hand, was not taken into account in this analysis.

This study's average GHG emission reduction was higher than a study conducted in south-eastern Ethiopia, which found that each biogas plant reduced about 2.1 t CO_2 e per year [29]. According to [59], the average amount of greenhouse gas emissions reduced per biogas installation is about 2.4 t per year. and a study conducted in the Afromontane forest revealed that each functionally improved cooking stove (ICS) reduced 2.145 tons of CO_2 emissions per ICS per year [60]. Furthermore, the current study's result is significantly higher than that of [61], who estimated that biogas technology will save 1.3 tons of GHG emissions per year on average.

Contrary to what [62] found, the average amount of greenhouse gas emissions reduction per domestic biogas installation was estimated to be about 5 t CO_2 equivalents per year. The study found that by reducing 65.10 percent of fuelwood consumption per household per year, greenhouse gas emissions were lowered by 3.82 tons of CO_2 equivalent per household per year in Nepal. Biogas has been discovered to play an important role in climate change mitigation by reducing greenhouse gas emissions [63]. The variance may be linked to the efficiency with which the biogas plants in request generate biogas energy.

4. Conclusion

This study investigated the role of biogas technology in fuelwood saving and carbon emission reduction in the Central Rift Valley of Ethiopia. In the study site, the majority of household heads use fuelwood as a primary source of energy for cooking. Switching to biogas, on the other hand, causes adopters of the technology to use less fuelwood. This resulting in less strain on the forest and lower greenhouse gas emissions. The average daily fuelwood use per family and the average daily fuelwood consumption per capita indicated a substantial difference between biogas technology adopters and non-adopters. Using household waste (including food waste) is not a widespread practice in the research area. This would significantly reduce the quantity of biogas generated. The digester's failure was blamed on a lack of technical knowledge for installation and maintenance, as well as weak institutional control and insufficient and costly maintenance service. Hence, stakeholders should consider training and equipping local masons and technicians to guarantee that maintenance and repair services are available without unreasonable costs or delays within a reasonable radius. Furthermore, biogas energy experts should collaborate with agricultural, forestry, and environmental experts on the adoption of sustainable biogas technology to minimize deforestation and mitigate climate change.

Declarations

Author contribution statement

Tamiru Kefalew: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Boja Tilinti, Mulugeta Betemariyam: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data associated with this study has been deposited at https://doi.org/10.17632/jxrgmngs7k.1.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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