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Original Research Article

The characteristics of bio-digester owners and effects of biogas utilization on woodfuel and emission reduction in Gambella, Oromia, southern nations and Somalia regions of Ethiopia

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ABSTRACT

Biogas is an environmentally friendly energy source produced from the anaerobic digestion of biodegradable biomass. In response to Sustainable Development Goal 7 (SDG7), a biogas programme and a biogas scale-up project were implemented in Ethiopia. In this study, a multi-stage sampling procedure was employed to select well-functioning bio-digesters that supply cooking energy and bio-slurry from bio-digesters constructed in April 2017 to April 2020 in the National Biogas Scale-Up Project (NBPE+) of Ethiopia. Then qualitative and quantitative data were collected through interviews with 59 households, 10 focus groups, and 20 key informants in 22 woredas in the Gambella, Oromia, SNNP, and Somalia regions. The type of digester was a dome-type one constructed underground. Qualitative data were narrated and summarized, and quantitative data were analysed for means of variance. Utilization of biogas energy reduced the wood fuel collection and consumption time by 38% in Gambella, by 50% in Oromia, SNNP, and by 55% in the Somalia region. The use of biogas reduced the amount of carbon emissions from woodfuel combustion by 7.28 tCO_2^e in Oromia to 2.78 tCO_2^e in Gambella. Although the households were highly interested in biogas technology, the cost of biodigester construction became unaffordable, and only 15% of the households requested credit. About 69.49% of the households constructed a 6-m^3 biodigester. Overall, 16.95% of the households had four cattle, and 10.17% of them had nine cattle. In Gambella, the available feedstock was sufficient to feed only a 3.7 m^3 bio-digester, while the mean size of the installed bio-digester was 6 m^3 and as a result, only 61.7% of the size of the bio-digesters was filled by the available feedstock. The dung's total solids and volatile solids were different among the regions that affected the amount of biogas production. The biogas production ranged from 0.01 to 1.75 m^3, which was sufficient for cooking for 0.03 to 4.38 h. The highest mean amount of biogas and corresponding cooking hours were obtained in Somalia, about 0.51 ± 0.11 m^3 and 1.27 ± 0.27 h based on the number of available cattle; however, there was a lack of water. Therefore, zero grazing, home feeding, and watering of cattle should be practiced for the sustainability of biogas production.

Keywords: cooking energy; emission; bio-digester; cattle dung; water

1. Introduction

Biogas is a combustible gas produced from the anaerobic digestion of biomass wastes, including the dung and excreta of cattle, pigs, chickens, and humans, and food remained. Biogas contains 60%–70% methane (CH_4), 30%–40% carbon dioxide (CO_2), and 1%–5% hydrogen (H_2) and traces amounts of nitrogen (N_2),

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hydrogen sulphide (H_2S), ammonia (NH_3), oxygen (O_2), water vapour (H_2O), and slurry and has a calorific value of 21 MJ m^{-3}–24 MJ m^{-3}[1,2]. Methane from anaerobic digestion of manure or biomass residue can be burned to generate electricity or heat so as to reduce its global warming potential as a greenhouse gas (GHG). Methane is a renewable source of electricity that can power farm equipment or be sold to the electricity distribution grid[3]. Biogas is an environmentally friendly technology that improves energy production with low indoor pollution and reduced greenhouse gas emissions[4]. Burning one ton of methane is removal of about 24 tons of carbon dioxide[5].

Ethiopia's energy sector is highly dependent on biomass (firewood, charcoal, crop residues, and animal dung). Then the bulk of the national energy consumption is met from biomass sources, accounting for over 90% in 2010, of which 81.2% is supplied by woody biomass, 9.1% from dung cakes, and 8.1% from crop residue[6]. Moreover, at the household level, 98.6% of the energy is supplied by biomass[7].

In Ethiopia, the use of fuelwood is mostly on traditional inefficient stoves that accelerate deforestation, thus increasing carbon dioxide (CO_2) emissions, which are associated with a smoky environment that has adverse health impacts on women and children who spend long hours in the kitchen. In rural areas, where firewood is scarce, over 70% of households collect firewood, and about 25% travel at least 5 km. Exposure to indoor air pollution from solid fuels leads to diseases related to the lungs and heart and premature deaths. In Ethiopia, 56,460 deaths per year were directly attributable to indoor air pollution from the use of solid fuels; more than 90% of them were children under five years of age. Due to their reproductive role, women and girls are often in charge of providing the household with thermal and mechanical energy sources (e.g., collecting solid fuels, performing domestic tasks using their physical strength and efforts, etc.), which adds to their domestic and unpaid work burden. While in urban settings, 41% of energy is obtained from purchased firewood, in rural households, 76% of their energy sources come from collected firewood[8]. Then cooking, which is designated as a female task, is highly detrimental to the health of women and children.

A National Biogas Programme of Ethiopia (NBPE) was developed as a strategic response to the challenges of using solid biomass energy sources. The programme was implemented originally in eight regions: Afar, Amhara, Benishangul-Gumuz, Gambella, Oromia, SNPPR, Somalia, and Tigray. The institutional arrangement for the implementation of the programme provided a participatory and decentralised approach. The main implementing partners were SNV, the National Biogas Programme Steering Committee, the Ministry of Water, Irrigation, and Energy (MoWIE), Regional Energy Bureaus, Woreda (District) Energy Offices, and private sector actors. The private sector actors include individual masons, biogas construction enterprises, and metal workshops or fabricators. Micro-financial institutions, the private sector, and government agencies cooperate with biogas users at the district level. The ambitious energy plan of the country was in line with the Global Sustainable Development Goal 7 (SDG 7) of reducing emissions and attaining a clean energy future[9].

In Ethiopia, biogas was introduced through Ambo Agricultural College in 1957 for welding agricultural tools. During the last two decades, over 32,000 household bio-digesters were installed throughout the country ranging from 2.5 to 200 m^3 volume for households, communities and institutions[10] by including NBPE Phases 1, 2, and NBPE+ by December 2020. In Ethiopia, more than 3 million households are eligible for dung-based bio-digester installation, out of which 5% are in rural areas and 1% are in urban areas, but only less than 1% of the potential of biogas production has been used since its introduction in 1979. In urban areas, there are few people who have cattle to install biodigesters. Then over one million households in rural areas and 0.1 million in urban areas were planned to own biogas stoves in 2030. There is also a large stock of biomass in Ethiopia for biogas production, ranging from 214.3 kt of coffee residue, 89 kt of cotton stalk residue, 6.61 kt of chat residue, and 25 kt of sawmill residue to 27.2 million metric tons of cattle dung per annum[11].

The Ethiopian Growth and Transformation Plan (GTP) (2015–2020) advocates expanding electricity generation from renewable sources of energy and commits to expanding bio-based gaseous and liquid biomass energy, thereby reducing firewood consumption and deforestation. Renewable energy, such as biogas, is believed to support a country's growth and reduce emissions of greenhouse gases that cause climate change[9]. The GTP had a target of installing 31,400 biodigesters in the country. The use of biogas in Ethiopia was supposed to have a gross GHG abatement potential of 2.3 $MtCO_2^e$ in 2030.

Biogas as cooking energy and light

Biogas is an environmentally sustainable energy source, and its production serves to reduce firewood consumption, deforestation, indoor air pollution, provide clean energy and organic fertiliser (bio-slurry), and serve as a waste disposal method. The transition from the use of biomass fuel into cleaner technologies such as biogas in rural areas would improve the standard of living, health, and the environment.

Indoor air pollution (IAP) caused the deaths of women and their young children[12,13]. In addressing these energy-related problems, biogas technologies are one of the solutions to energy development. The burning of dung as fuel instead of using it as a soil conditioner has led to a reduction of 550,000 tonnes of grain production per year. When utilised, the co-product of biogas, bio-slurry, is high-value organic manure, better than dung[14].

Generally, limiting global warming to 1.5 °C requires rapid, deep, and sustained reductions in global greenhouse gas emissions of 43% by 2030 relative to the 2019 level. Therefore, efforts are required to accelerate the development, deployment, and dissemination of technologies and the adoption of policies to transition towards low-emission energy systems, including by rapidly scaling up the deployment of clean power generation and energy efficiency measures and the phase-out of inefficient fossil fuel subsidies. Actions are needed to reduce non-carbon dioxide greenhouse gas emissions by 2030, including methane from wood consumption and dung decomposition. Accordingly, huge capital needs to be invested in renewable energy, such as biogas, until 2030 to be able to reach net zero emissions by 2050[15]. Although Ethiopia has a high potential for hydroelectric power, the pace of distribution and access to electricity from the central grid system to rural areas was very slow. Moreover, the water levels for hydroelectric power generation are liable to fluctuate because of the climate dependence of water bodies; therefore, a mix of renewable energy sources is crucial for the sustainability of rural development. Biogas is a potential source of renewable energy in rural households that have cattle, decomposable waste, water as feedstock, and some income sources to purchase and install bio-digesters. In a country with an important cattle industry and overexploited biomass resources, biogas is a renewable and clean energy option for rural areas and small towns where family dairy farming is often practised. Ethiopia has the largest number of cattle on the African continent, and its moderate to hot temperature throughout the year makes the country suitable for bio-digester technology. Therefore, it is important to study the characteristics of bio-digesters and the roles of biogas so as to understand the limitations in households that have non-functioning bio-digesters for further improvement of the technology.

2. Material and methods

2.1. Description of the study area

The study was conducted in two woreda kebeles' of Gambella region (Abobo-Mender 7, and Gambella-Kebele 01), 12 woreda kebeles of Oromia region (Bele Gesger-Koshimo, Lode Hetosa-Ligaba 01, Munesa-Doba Ashe, Seru-Jida Jiru, Shirka-Hela Mekana, Gera-Bore Gogo, Gumay-G/Dege, Abichu-A/Goro, Gerar Jarso-Banshe, Dodola-K/Bereda, Kofale-W/Alkeso, and Wondo-B/Gugisa), five woreda kebeles of Southern Nations and Nationalities People (SNNP) region (Enamor-Mekana, Ezha-Weradeba, Wondo Genet-Wetera

Ketchma, Shebedino-Morecho Negesha and Offa-Galuka), and three woreda kebeles of Somalia region (Gursum-Degahle, Owbarre-Lafa-ise, and Tulli-guled-Warabaley) (**Figure 1**).

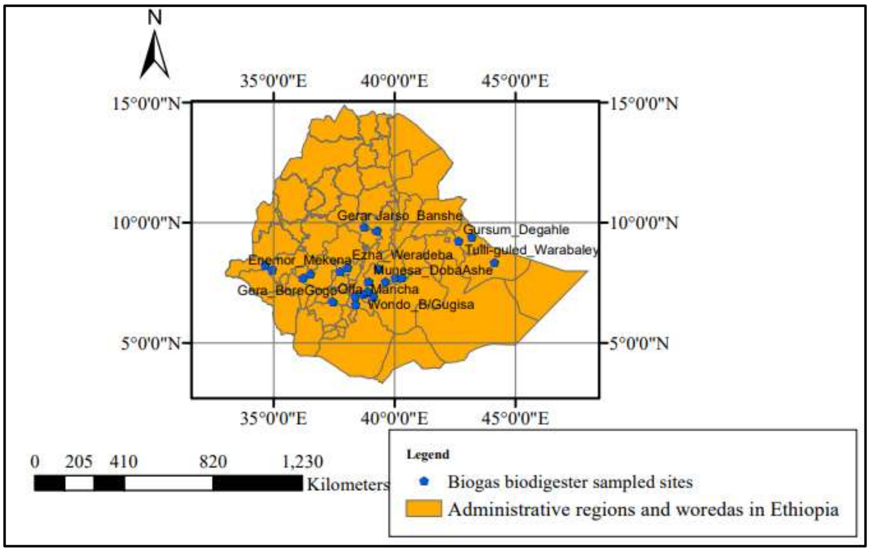

Figure 1. Location of the sampled study areas (own sketch from field GPS readings).

2.2. Description of bio-digesters

The type of digester used was fixed dome digesters, built underground. The size of the digester depends on the location, family size in a household, and the amount of dung feedstock available for daily feeding. The feedstock is put in to the digester through inlet (14 and 11) and the bio-slurry is removed via the outlet (1) (**Figure 2**).

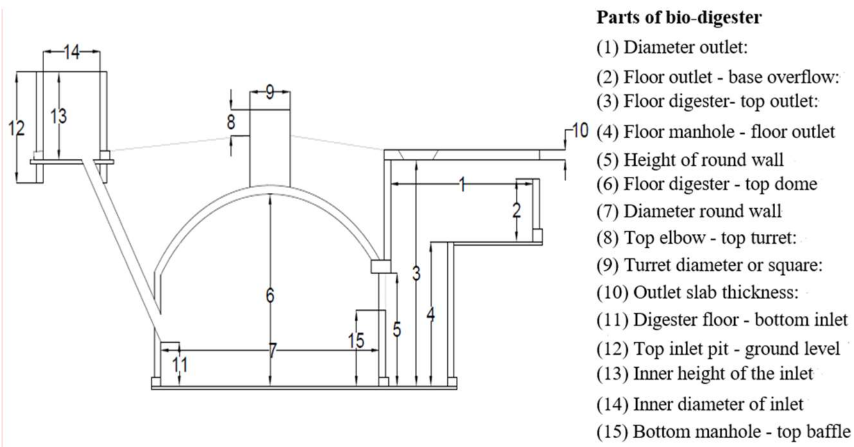

Figure 2. Design of fixed dome bio-digester used for biogas generation[16].

2.3. Methods of data collection and analysis

A multi-stage sampling procedure was employed to select from a number of biodigesters constructed in Ethiopia. Well-functioning and accessible bio-digesters that supply cooking energy and bio-slurry were sampled in a long field visit of bio-digesters. Then a mix of qualitative and quantitative data was collected through interviews with household heads and observations of bio-digester plants in 22 woredas that spread to four regions. Although at least 30 bio-digesters are needed for statistical validity of samples, the current 59 bio-digesters were sampled based on the proper supply of electricity and bio-slurry from the bio-digesters constructed in April 2017 to April 2020 by the Ethiopian National Biogas Scale Up Project (NBPE+).

The amount of wood consumed was measured by a graduated balance with the known moisture content of the wood. Key informant interviews (KII) and focus group discussions (FGD) were held in each region for hot season (April to May) and cold season (July to August) data. KIIs were conducted with office representatives from the Energy Office, Regional Biogas Programme Coordination Units (RBPCUs), Agriculture Office, Technical, Vocational, and Educational Trainings (TVET), Rural Technology Office, Women and Children's Affairs Office, Environmental Protection Office, Microfinance Institutes (MFI), and Mason. A total of 1 FGD, and 3 KII in Gambella, 4 FGD, and 7 KII in Oromia, 2 FGD and 4 KII in SNNP, and 3 FGD and 6 KII in Somalia were interviewed about the biogas uses in selected woredas of survey regions. The collected qualitative data were analysed by narration and summarization and the quantitative data by means variance and correlation using SPSS version 22.

2.3.1. Assumptions in biogas production

The daily manure produced by a cow ranged from 8 to 10 kg per 100 kg of animal body weight in a zero grazing condition[17]. However, in the studied areas in the four regions of Ethiopia, the cattle and cows were in a free-grazing range system where dung was collected only during the night. Then it was assumed that only 50% of the dung was available for biogas production. The number of cows in each household was different. Cow dung was mixed with water at a ratio of 1:1 to form a bio-slurry of a specific density of 1.089 g/cm^3. Since all the areas studied were in the in the tropics, where the average ambient temperature was 25–30 °C, the common reaction time was about 30 days. The size of the dung and water mixture containing part of the bio-digester was 75% by volume, while the gas holder was 25% by volume of the whole bio-digester. The amount of biogas obtained from a biomass feedstock was determined by the feedstock quality, mainly its total solids, volatile solids, and Organic Loading Rate (OLR), where OLR below 2 kg is preferable. Total Solid (TS) content is 20% of the cow dung. Feedstock concentration, or volatile solids (VS) content, of dung is 80% of TS. Gas yield for one kg of cattle (cows and bullocks) per day was assumed to be about 0.023–0.040 m^3 (average 0.035 m^3). The average consumption of a biogas stove was 0.4 m^3/hour[18].

Calculation of the size of the digester and biogas: Digester size is the sum of the dung-water mixture (dung-water) size and the gas holder size. The amount of dung obtained is determined by the number of cows available each night (Equation (1)). Then dung and water were mixed in an equal proportion of 1 kg of dung with 1L tap water with a ratio of 1:1 (Equation (2)), which is multiplied by 30 in a month (Equation (3)). In the dung, it was assumed that there was a 20% solid and 80% liquid part (Equation (4)). From the solids, it was assumed that 80% are volatile solids (Equation (5)), which determines the quality of daily dung available (Equation (6)). The flow of the dung-water mixture is determined by the concentration of the dung, which is also called the organic loading rate (Equation (7)). The amount of biogas produced from the dung-water mixture for energy generation was determined by the assumed amount of biogas per unit mass of dung and OLR (Equation (8)). The length of time required for food cooking by using biogas depends on the amount of gas produced at a rate of 0.4 m^3/hour (Equation (9)).

$$\text{Amount of dung for biogas production (kg)} = \text{Number of cows} \times 50\% \text{ (10 kg/day)} \tag{1}$$

$$\text{Amount of dung-water mixture in 1:1 ratio} = 2 \times (1 \times (\text{Number of cows} \times 50\% \text{ (10kg/day)})) \tag{2}$$

$$\text{Volume of dung water mixture size (m}^3) = 2 \times (1 \times (\text{Number of cows} \times 50\% \text{(10kg/day)})) \times 30 \text{ Days} \tag{3}$$

$$\text{Total solids (kg)} = 0.2 \times \text{Daily amount of cow dung} \tag{4}$$

$$\text{Feedstock concentration or volatile solid (VS)/Day} = 0.8 \times \text{TS} \tag{5}$$

$$\text{Concentration of quality feedstock (VS/kg)} = \text{Volatile solids (VS)/daily feedstock} \tag{6}$$

$$\text{Organic loading rate (OLR) (kgVS/m}^3\text{/day)} = \text{Flow rate} \times \text{feedstock concentration/dung with water mixture volume} \quad (7)$$

$$\text{Amount of biogas(m}^3\text{)} = \text{Organic loading rate (OLR)} \times \text{(biogas yield from cow dung)} \times \text{(dung with water volume mix)} \quad (8)$$

$$\text{Gas sufficient for cooking hours (h)} = \text{Amount of gas/0.4} \quad (9)$$

3. Results

3.1. Characteristics of bio-digester owner households

The average family size of the studied biogas household owners' indicated that the Somalia region had the highest number of about 9.8 persons with the lowest education level of 4.8 grade, while the Gambella region had the lowest, about 6 persons per household with the highest education level of 7.5 grade. In terms of cattle, the highest number, about 12.4, was recorded in the Somalia region, while the lowest, about 6.2, was recorded in SNNP (**Table 1**). The water source point in the Somalia region was the farthest, about 60.3 min, to walk on foot by women, but in SNNP it was within a short distance of 3.2 min walk (**Table 1**). In most cases, the biogas owner household heads were males (M), although only five in Oromia and two in SNNP were female (F). The age group of the households that constructed biodigesters was 40 to 45 years old (**Table 1**).

Table 1. Characteristics of biogas owners' households in four regions.

Region		Gambella (N = 4)	Oromia (N = 28)	SNNPR (N = 9)	Somalia (N = 18)	Total (N = 59)
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
Number of persons in a household		6.0 ± 1.41	7.21 ± 0.42	7.00 ± 0.50	9.78 ± 0.44	7.88 ± 0.31
Average age of household head		44.25 ± 4.97	45.04 ± 2.04	41.44 ± 3.12	41.89 ± 3.06	43.475 ± 1.447
Household head sex	F	0	5	2	0	7
	M	4	23	7	18	52
Education grade level of household head		7.50 ± 2.47	6.00 ± 0.862	6.22 ± 1.176	1.61 ± 0.991	4.797 ± 0.618
Cattle number per households		9.25 ± 2.06	7.143 ± 0.621	6.222 ± 1.12	12.39 ± 1.27	8.746 ± 0.615
Water source point (minutes)		4.50 ± 2.02	17.214 ± 5.27	3.222 ± 1.3	60.33 ± 11.8	27.37 ± 5.225
Relative distance of feed source for free grazing (minutes)		Far	Nearby	Nearby	Very far	
Relative firewood availability		Abundantly available	Sufficiently available	Sufficiently available	Not available	

As shown in **Table 1**, the Somalia region had the greatest number of family members of 9.78 ± 0.44 persons and a cattle population of 12.39 ± 1.27 within a household; however, the number of educated people was very low, and the water source point was relatively far, taking more than an hour (**Table 1**). Therefore, the potential of the Somalia region's cattle population for biogas production was not fully utilized because of a lack of water supply. Then the energy scarcity of the Somalia region was very critical because of the lack of water supply that hampers the growth of feed for dung-providing cattle and the lack of firewood. The Gambella region had a lower human population, which reduced the ability to fetch sufficient water and feed the cattle; however, there was ample firewood supply. Therefore, these relatively dry regions of Somalia and Gambella did not properly benefit from biogas technology. While the two other regions, including Oromia and SNNPR, had nearby feed sources for free grazing and an average family size of seven people per household, this promoted the production of biogas.

3.2. Wood fuel reduction due to biogas utilization

Utilization of biogas energy reduced the woodfuel collection time by 38% in Gambella, by 50% in Oromia, SNNP, and by 55% in the Somalia region. The amount of wood fuel saved due to biogas energy was higher in the cold season than in the in the hot season. In the cold season, there was a shortage of wood fuel, so biogas was highly needed in place of wood fuel, which reduced wood fuel consumption more than in the hot season. The mean reduction in wood fuel consumption all year round was 40% in Gambella, 56% in Oromia and SNNP, and 58% in Somalia (**Table 2**).

Table 2. Wood fuel utilization reduction by biogas energy.

Region	Gambella (N = 4)	Oromia (N = 28)	SNNPR (N = 9)	Somalia (N = 18)	Total (N = 594)
Woodfuel amount per year (kg)	2865.00 ± 967.6	3434.14 ± 297.9	3114.67 ± 287.8	2489.33 ± 576.0	3058.58 ± 239.2
Woodfuel collection time saved by biogas (%)	38.00 ± 13.00	50.00 ± 0.00	50.00 ± 0.00	55.00 ± 1.00	51.00 ± 1.00
Woodfuel consumption and consumption time saved by biogas (%)	38.00 ± 13.00	56.00 ± 1.00	56.00 ± 0.00	58.00 ± 1.00	51.00 ± 1.00
Woodfuel amount saved by biogas hot season (%)	38.00 ± 13.00	49.00 ± 2.00	51.00 ± 1.00	52.00 ± 2.00	49.00 ± 2.00
Woodfuel saved by biogas cold season (%)	43.00 ± 14.00	64.00 ± 2.00	62.00 ± 2.00	66.00 ± 2.00	63.00 ± 2.00
Woodfuel money required per year ($USD) in April 2021	121.48 ± 5.33	213.36 ± 16.38	221.98 ± 29.43	198.68 ± 22.19	203.97 ± 11.46

3.3. Carbon emission reduction potential of biogas

The use of biogas reduced the amount of carbon emission of wood fuel combustion. The highest emission reduction, about 7.28 tCO_2^e was observed in Oromia region, while the lowest, about 2.78 tCO_2^e was observed in Gambella because of the amount of wood fuel utilized, more wood fuel utilized in Oromia than in Gambella (**Table 3**).

Table 3. Carbon emission reduction potential of household biogas in wood fuel annually.

Region	Emission reduction due to biogas per households per year (tCO_2^e) (mean ± SE)
Gambella (N = 4)	2.78 ± 0.93
Oromia (N = 28)	7.28 ± 0.80
SNNP (N = 9)	6.39 ± 0.56
Somalia (N = 18)	4.87 ± 1.01
Total (N = 59)	6.10 ± 0.53

3.4. Sources of HH income and contribution for bio-digester construction

The households were highly interested in the biogas technology because of the energy supplied for cooking and the bio-slurry used for soil fertility maintenance. However, the cost of bio-digester construction was so expensive that it reached $483 USD in Gambella and $425 USD in SNNP, which was higher than the annual income of $422 USD in SNNP and $136 USD in Somalia. Then a few people were constructing biodigesters. The key informant response revealed that the non-adoption of biogas technologies was partly caused by the ever-increasing cost of the biodigester since the construction cost was greater than the annual income of households studied. There was a fear of borrowing money by risk-averse poor rural people, and as a result, only about 15% of the households with bio-digesters requested credit from different finance organizations to construct bio-digesters based on cattle and food crop production (**Table 4**). Therefore, local respondents revealed that households with functioning bio-digester had the financial capacity to feed and water the bio-digester; non-functioning bio-digesters were limited by the resources of water and dung; and non-adopting households of bio-digesters were limited by finance.

Table 4. Income for household bio-digester construction.

Region	Source of household income	Annual household income ($USD) (mean ± SE)	Bio-digester construction costs ($USD) (mean ± SE)	Contribution of finance for bio-digester construction (%)	
				Credit source	Own source
Gambella	Cattle and food crop production	335.0 ± 51.0	483.2 ± 38.9	0.0	100.0
Oromia	Cattle and food crop production	415.7 ± 115.0	426.0 ± 31.1	4.0	96.0
SNNP	Cattle and food crop production	422.2 ± 12.0	425.0 ± 21.5	56.0	44.0
Somalia	Cattle and food crop production	136.1 ± 11.0	449.2 ± 17.0	0.0	100.0
Total	Cattle and food crop production	325.9 ± 57.0	436.7 ± 16.1	15.0	85.0

3.5. Volume of household bio-digesters

The design of bio-digester was fixed dome type in all households studied. The volume of bio-digesters constructed was dependent on the economic status and number of cattle owned by households. About 69.49% of the studied households constructed a bio-digester with 6 m^3. In Gambella, all the households had 6 m^3 bio-digesters. In Oromia, there were few households; about 7.1% had a 4 m^3 bio-digester, while 14% had an 8 m^3 bio-digesters, in SNNP, all had 6 m^3; and in Somalia, 67% had 8 m^3 bio-digester (**Table 5**).

Table 5. Volume of household bio-digesters.

Region	Bio-digester volume in households			Total
	4.00 m^3	6.00 m^3	8.00 m^3	
Gambella	0.0%	100.0%	0.0%	100.0%
Oromia	7.1%	79.0%	14.0%	100.0%
SNNPR	0.0%	100.0%	0.0%	100.0%
Somalia	0.0%	33.0%	67.0%	100.0%
Total	3.0%	69.0%	27.0%	100.0%

In Gambella, 25% of the households had 4–14 cattle; in Oromia, 18% of the households had 4–5 cattle; in SNNPR, 44% of the households had four cattle; and in Somalia, 11% of the households had 8–15 cattle. The lowest number of about 2–3 cattle was observed in 4% of the households in Oromia. Overall, 16.95% of the households had four cattle; 10.17% of the households had nine cattle; and 1.69% of the households had 20–25 cattle (**Figure 3**). Proportionally, the increase in the number of family members in a household also significantly increased ($P < 0.01$) the bio-digester volume and cattle number. The amount of household income was negatively correlated with the biodigester volume (**Table 6**). Therefore, larger-sized bio-digesters were constructed in larger families and in areas where the water source point was longer in distance. There was a strong correlation (r = 0.34–0.42) of the bio-digester volume with family size and the number of cattle in households ($P < 0.01$). The cost of bio-digester construction was also highly correlated with the distance of water source points (**Table 6**).

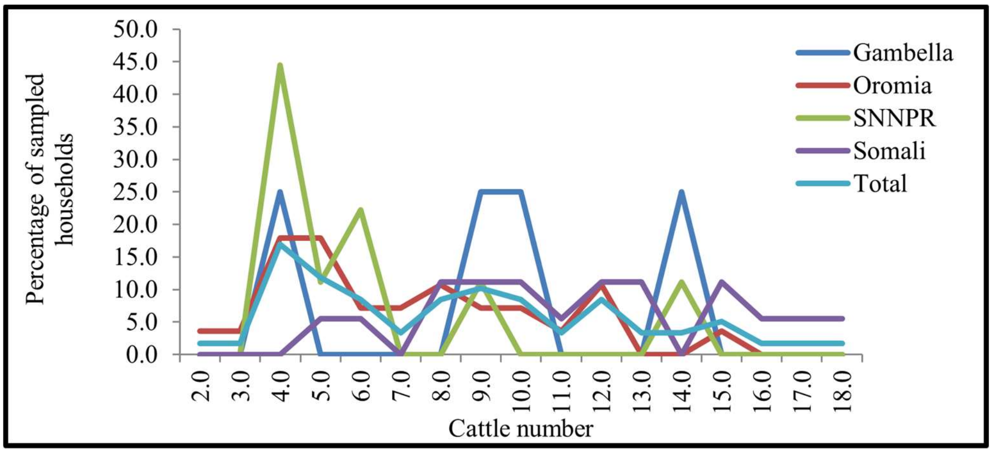

Figure 3. The number of cattle and corresponding number of households.

Table 6. Correlation (r) of volume of bio-digester, and household characteristics.

Household characteristics	Cattle number per household	Bio-digester volume	Amount of household income per year	Distance of water source point (minutes)	Cost of bio-digester construction
Number of persons per household	0.496**	0.339**	0.006	0.246	0.215
Cattle number per household	-	0.417**	0.077	0.157	0.138
Bio-digester volume	-	-	–0.194	0.535**	0.171
Amount of household income per year	-	-	-	–0.201	0.028
Distance of water source point	-	-	-	-	0.420**

**. Correlation is highly significant at $P = 0.01$ level (2-tailed).

3.6. Perception of health impacts of biogas

In Gambella, all the households responded that they perceived the health benefits of biogas by reducing eye infections, respiratory diseases, coughs, and fire-related injuries caused by wood fuel smoke. Similarly, households that use biogas for cooking in Oromia perceived that their health condition was improved because of reduced smoke-induced disease. Accordingly, all the households' perceived reduction in health impacts caused by wood fuel smoke and improved sanitation from dung wastes in the residential areas. All households in SNNP also appreciated the sanitation and waste disposal role of bio-digesters. On the other hand, 88.9% of the households in the Somalia region stated that biogas had improved their health conditions, including reducing eye infections, respiratory diseases, coughs, and fire-related injuries, while 11.1% stated no perceived health benefits of biogas (**Figure 4**).

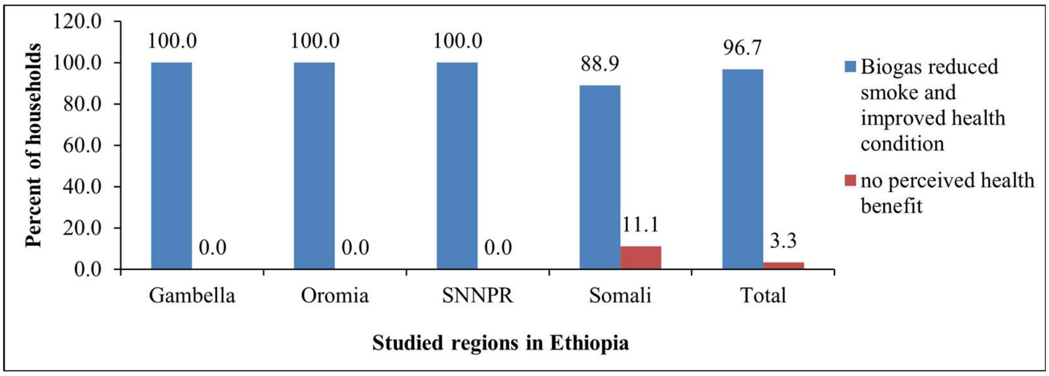

Figure 4. Perception of households on health impacts of bio-digester technology in regions.

3.7. Challenges in biogas production

The major challenges in individual bio-digester-constructed households were the lack of continuous availability of feedstock (dung and water). It was observed that households at the periphery of urban areas that can get pipe water and extra organic wastes were more successful in producing sustainable biogas. Mixing feedstocks such as food waste, vegetables, and other decomposable wastes improved the sustainability of biogas when compared with the feeding of mere dung. Due to seasonal water and dung shortages to feed bio-digesters, households with bio-digesters were forced to use additional firewood or switch totally to wood fuel for their cooking energy sources. Some 10% of the households were not committed to feeding the already-available feedstock to their bio-digester. Therefore, there was a lack of proper training on the technical issues of the bio-digester, awareness creation on the methods of feeding the bio-digester and utilizing the biogas stoves, and a lack of control over the leakage of methane. The frequent breakage of the biogas light bulb and the lack of bio-digester accessories, which are mostly imported as they are not available in local markets, were another challenge when compared to the solar home lighting system. A mix of technologies, including improved biomass cookstoves, solar home lighting systems, and biogas, are needed to sustainably supply energy for rural households. Lack of finance for the purchase of feedstock, water, and labor to manage the bio-digester was another challenge that required public or government support. Support is needed because biogas is required for waste removal and emission reduction purposes for environmental benefit in addition to energy and organic fertilizer.

3.7.1. Challenges in dung supply for gas production of bio-digesters

The cattle in Ethiopia are open or free-grazing (**Figure 5**), and the amount of dung to be used for biogas production was wasted in the grazing field. Moreover, the available feed and water for the cattle is very low because of the culture of poor feeding of free grazing and the occurrence of the dry season, which is more than three months long in most parts of Ethiopia. As shown in **Figure 5**, the grazing field and rangelands lacked sufficient pasture; in some cases, the range lands seemed bare. Therefore, human intervention in rangeland management, including planting palatable plant species and providing water, is highly essential. The livestock disease was the other problem in Gambella, as responded by the bio-digester owners, and proper medication is highly important.

Figure 5. Open free grazing traditional lands in some Somalia lowland areas of Ethiopia.

As can be seen in **Table 7**, the mixture of dung and water was in 1:1 ratio. In Gambella from 4 to 14 cattle about 20 to 70 kg dung was collected, while in Somalia from 5 to 25 cattle about 25 to 125 kg dung was collected (**Table 7**).

Table 7. Amount of dung water mixture in bio-digesters.

Region	-	Cattle number	Daily amount of dung (kg)	Amount of daily water (L)	Daily flow rate of dung and water mixture (L)	Dung with water mix volume (m^3)	Gas holder size (m^3)	Total volume of bio-digester required (m^3)	Total volume of installed bio-digester (m^3)	Proportional size bio-digester (%)	Amount of biogas (m^3)	Number of cooking hours
Gambella	Mean ± Std. Er. of mean	9.25 ± 2.06	46.25 ± 10.28	46.25 ± 10.28	92.5 ± 20.56	2.78 ± 0.62	0.93 ± 0.21	3.7 ± 0.82	6.00 ± 0.00	61.68 ± 13.70	0.28 ± 0.11	0.69 ± 0.26
	Min.	4	20	20	40	1.2	0.4	1.6	6	26.7	0.045	0.11
	Max.	14	70	70	140	4.2	1.4	5.6	6	93.3	0.55	1.37
Oromia	Mean ± Std. Er. of mean	7.14 ± 0.62	35.71 ± 3.10	35.71 ± 3.10	71.43 ± 6.21	2.14 ± 0.19	0.71 ± 0.06	2.86 ± 0.25	6.14 ± 0.18	46.49 ± 3.90	0.17 ± 0.03	0.43 ± 0.07
	Min.	2	10	10	20	0.6	0.2	0.8	4	13.3	0.01	0.03
	Max.	15	75	75	150	4.5	1.5	6	8	100	0.63	1.58
SNNPR	Mean ± Std. Er. of mean	6.22 ± 1.12	31.11 ± 5.58	31.11 ± 5.58	62.22 ± 11.15	1.87 ± 0.33	0.62 ± 0.11	2.49 ± 0.45	6.00 ± 0.00	41.49 ± 7.43	0.13 ± 0.06	0.34 ± 0.14
	Min.	4	20	20	40	1.2	0.4	1.6	6	26.7	0.04	0.11
	Max.	14	70	70	140	4.2	1.4	5.6	6	93.3	0.55	1.37
Somalia	Mean ± Std. Er. of mean	12.39 ± 1.27	61.94 ± 6.35	61.94 ± 6.35	123.89 ± 12.71	3.72 ± 0.38	1.24 ± 0.13	4.96 ± 0.51	7.33 ± 0.23	68.52 ± 6.69	0.51 ± 0.11	1.27 ± 0.27
	Min.	5	25	25	50	1.5	0.5	2	6	25	0.07	0.18
	Max.	25	125	125	250	7.5	2.5	10	8	125	1.75	4.38
Total	Mean ± Std. Er. of mean	8.75 ± 0.62	43.73 ± 3.08	43.73 ± 3.08	87.46 ± 6.15	2.62 ± 0.18	0.87 ± 0.06	3.50 ± 0.25	6.47 ± 0.13	53.48 ± 3.35	0.28 ± 0.04	0.69 ± 0.10
	Min.	2	10	10	20	0.6	0.2	0.8	4	13.3	0.01	0.03
	Max.	25	125	125	250	7.5	2.5	10	8	125	1.75	4.38

As shown in **Table 7**, the bio-digesters constructed in some cases were constructed without proper consideration of the available dung and water. For example, in Gambella, the maximum available feedstock is sufficient for a 5.6 m^3 digester; however, the constructed one was 6.0 m^3. In Gambella, the available feed stock was sufficient to feed only a 3.7 m^3 bio-digester, while the mean size of the installed bio-digester was 6 m^3 and as a result, some 61.7% of the size of the bio-digesters was fulfilled by the available feedstock. The size of bio-digester installed was bigger than the available feedstock. Therefore, more feedstock, which includes more cow dung and water, was required in each household. For a greater collection of dung, zero grazing and home feeding are highly needed, which would double the amount of dung. In Gambella, there was a seasonal drought that removed the available feedstock, and the cattle temporarily migrated to areas where there was pasture and water, which were away from the agricultural land and the constructed bio-digester. After some three months, biogas production was totally abandoned. In Somalia, the larger number of cattle indicates the presence of more biogas production, which requires a bio-digester volume of 10 m^3, higher than the installed 8 m^3 (**Table 7**). In Somalia, the larger number of cows enabled them to produce more dung over the maximum size of the installed bio-digester (**Table 7**). However, water was in deficit, and the production of biogas was not continuous. Therefore, biogas production in such a dry area as Gambella and Somalia was difficult because it required a continuous supply of feed to cattle instead of temporary migration and a continuous supply of water. Otherwise, biogas production on dry land is not recommendable.

In Oromia, the installed bio-digester volume of 8 m^3 is also greater than the available feedstock capacity of only 6 m^3 (**Table 7**); in some parts of the region, the water deficit stays between 3 and 4 months. In Oromia, the maximum proportion of the size of the bio-digester that fulfilled the available feedstock was 100%, that is, the installed bio-digesters were sufficient to the available feedstock and no additional cow dung or water were required.

In the studied households, the amount of gas production ranged from 0.01 to 1.75 m^3, which was sufficient for cooking for 0.03 to 4.38 h. The lowest cooking hour was obtained in Oromia and the highest cooking hour in the Somalia region (**Table 7**) because of the available number of cattle (**Table 1** above). The highest mean amount of biogas and corresponding longest cooking hours were also obtained in Somalia, about 0.51 ± 0.11 m^3 and 1.27 ± 0.27 h, respectively (**Table 7**). The greatest amount of biogas production was obtained in the Somalia region because of the greatest number of cattle, but the lack of water observed in the field visit was expected to reduce the sustainability of biogas production.

In SNNPR, the bio-digester constructed about 6 m^3 and the potentially available feedstocks were closely related. Therefore, the construction of bio-digester in SNNPR was exemplary in considering the available feedstock capacity.

The quality of cattle dung was similar, about 80 kgVS/m^3 in all regions; however, the dung's total solids, and volatile solids in Oromia range from 2 to 15 and in Somalia from 5 to 25. The Organic Loading Rate (OLR) was 0.053 to 0.667 kgVS/m^3/day, the lowest minimum was obtained in Oromia and the highest maximum in Somalia (**Table 8**).

Table 8. Quality, total solids and volatile solids of dung feedstock.

Region	Statistical value	Quality of the feedstock (kgVS/m^3)	Total solids (TS) (kg)	Volatile solids (VS) (kg)	Organic loading rate (OLR) (kgVS/m^3/day)
Gambella	Mean ± Std. Er. of mean	80 ± 0.0	9.25 ± 2.06	7.4 ± 1.65	0.25 ± 0.05
	Minimum	80.0	4.00	3.20	0.11
	Maximum	80.0	14.00	11.20	0.37
Oromia	Mean ± Std. Er. of mean	80 ± 0.0	7.14 ± 0.62	5.71 ± 0.5	0.19 ± 0.02
	Minimum	80.0	2.00	1.60	0.05
	Maximum	80.0	15.00	12.00	0.40
SNNPR	Mean ± Std. Er. of mean	80 ± 0.0	6.22 ± 1.12	4.98 ± 0.89	0.17 ± 0.03
	Minimum	80.0	4.00	3.20	0.11
	Maximum	80.0	14.00	11.20	0.37
Somalia	Mean ± Std. Er. of mean	80 ± 0.0	12.39 ± 1.27	9.91 ± 1.02	0.33 ± 0.03
	Minimum	80.0	5.00	4.00	0.13
	Maximum	80.0	25.00	20.00	0.67
Total	Mean ± Std. Er. of mean	80 ± 0.0	8.75 ± 0.62	7 ± 0.49	0.23 ± 0.02
	Minimum	80.0	2.00	1.60	0.05
	Maximum	80.0	25.00	20.00	0.67

4. Discussion

Biogas technology is essential to supply energy, reduce emissions, and enhance soil fertility. The use of biogas reduced the amount of annual wood fuel consumption by 40% in Gambella, 56% in Oromia and SNNP, and 58% in Somalia (**Table 2),** which is nearly similar to a study conducted in Uganda[19] that reduced 66.32% wood consumption per individual family. Biogas also reduced the amount of emission by 2.78 tCO_2^e in Gambella, 7.28 tCO_2^e in Oromia, 6.39 tCO_2^e in SNNP, and 4.87 tCO_2^e in Somalia (**Table 3),** which were higher than the CRGE gross abatement potential of 2.3 Mt CO_2^e in the year 2030[9]. In the present study, the emission reduction was lower than in other studies, such as the biogas used in individual biogas user households in Uganda, which reduced 432 tons of CO_2 per year[19] which could be because of a lack of sufficient feedstock and a lack of firewood. The amount of emissions reduced in Ethiopia was low because of the low amount of wood reduced and because of the use of wood and biogas at the same time. The amount of biogas energy was said to be insufficient for the whole day of cooking, and then additional wood fuel was used. Moreover, the amount of carbon emissions reduced is determined by the amount of wood fuel replaced by biogas, the net calorific value of wood fuel, and the carbon emission factor of the wood fuel. In the central rift valley of Ethiopia, the biogas reduced the annual carbon dioxide (CO_2) emission capacity to 2.75 tons per bio-digester[20] which is lower than the current study. Therefore, additional efforts are needed to use biogas technologies for the whole day's cooking and to exclude woodfuel. In the exclusion of woodfuel by biogas, the role of biogas in reducing deforestation and energy supply problems facing rural Ethiopia could be realized[21–23].

Most of the households shown in **Table 4** that had constructed the digester from their own sources of income, which showed self-sufficient households, were the ones that constructed the bio-digester and used biogas. Although most of the studied bio-digester owners used their own sources of finance, the cost of construction was greater than the annual income of households. For example, the annual income of households in Gambella was $335 USD, but the cost of bio-digester construction was $483 USD (**Table 4**). However, Miklol[24] identified that 74.5% of biogas users in the SNNP region of Ethiopia took loans from Omo Microfinance Institution to cover part of biogas construction costs. Therefore, some form of direct public support via government grants or through the sale of greenhouse gas credits is highly important for the utilization and additional construction of biogas technologies, as stated in Ghafoori et al.[25]. Although bio-digesters are known to reduce GHG emissions, odours from manure, and the potential for surface-water contamination, they have not been widely adopted in Ethiopia and in other countries, mainly because of the unaffordable costs of construction and maintenance[26].

In this study, most of the bio-digesters, about 69.49%, constructed at household level had a volume of 6 m^3 (**Table 5**) because of the wide experience developed in this size. However, other studies showed that the volume of bio-digesters varied based on the geographical location, availability of substrate, and climatic conditions, as stated in Rajendran et al.[27]. According to Workneh and Eshete[10], the fixed-dome type of bio-digester was used by the National Bioenergy Programme of Ethiopia (NBPE) for promotion at the household scale, which is a modified version of a Nepalese model with an Ethiopian name, SINIDU 2008 and 2010, with a size of 4 m^3 to 10 m^3. SINIDU was the preferred design because of its robustness, ease of operation, accommodating capacity for local materials, and flexible sizing[10]. The size of the digester was positively correlated with the available number of cattle and the family size (**Table 6),** as evidenced in other studies such as Boers et al.[10]. However, the available feed stock was not sufficient to feed the installed bio-digester in most cases, as only 53.48% of the bio-digester was filled on average (**Table 7**).

The amount of biogas obtained was 0.01 to 1.75 m^3 sufficient for cooking for 0.03 to 4.38 h, which varied among regions (**Table 7**). The amount of biogas was not sufficient to cook the rural household's food because rural households usually cook for over two hours[28]. On the other hand, the highest family bio-digesters are required to provide at least 0.8 to 1 m^3 biogas daily, for 2 to 3 "stove hours" of cooking. The dung can be obtained from two mature cattle with zero grazing or from three or four night-stabled heads of free-grazing cattle[28]. Since the 0.01 m^3 gas obtained in the current study was insufficient, it was unavoidable to use additional firewood for rural food cooking.

In the four regions, 96.7% of the households perceived the reduction of smoke and improvement in the health condition of households that use biogas energy as compared to using solid biomass. Actually, all the households in Gambella, Oromia, and SNNPR appreciated the health risk reduction of biogas. Different studies conducted in different parts of the world, such as Marie et al.[29] confirmed that the use of biogas as a clean energy source reduced health risks and associated costs. The continuous supply of biogas was believed to be beneficial for the economy, environment, and health of local people, as stated in Kasap et al.[30].

In the continuous utilization of biogas, the lack of a sustainable supply of feedstock (dung and water) is the main challenge. As stated in Saroj[31], the less commitment of some households to feeding bio-digesters and the lack of continuous supply of feed stocks in Ethiopia were the major changes in biogas technology. The availability of woodfuel at a certain market price reduced the effort to collect feedstock for biogas generation. Therefore, continuous follow-up and training on the management and use of biogas bio-digester are highly crucial for the studied type of rural households.

5. Conclusion

Biogas is a very useful technology for clean energy supply and the amelioration of soil fertility. Methane is a potent greenhouse gas; however, utilizing it in the form of biogas energy converts it to a less potent GHG, called carbon dioxide. Although Ethiopia has long experience, over half a century, in biogas technology, there were limited scopes for sustainable utilization of the technology, and the potential feedstocks were not fully utilized. In the different regions of Ethiopia studied for functioning biogas biodigesters, cattle were the main source of dung to produce biogas, while other types of biomass feedstocks were not utilized because of the lack of experience of the local people and the lack of attention given to biogas research and development. That is, Ethiopian cooking energy sources are dominated by solid biomass and hydroelectric power. Biogas utilization reduced the amount of woodfuel extraction and greenhouse gas emissions by replacing woodfuel energy. The households responded, and measurements showed that the amount of wood fuel saved due to biogas energy was higher in the cold season than the hot season. In the cold season, there is a shortage of wood fuel, so biogas is highly needed in place of wood fuel. About 69.49% of the studied households constructed a bio-digester with 6 m^3; however, the volume of the bio-digester constructed in many cases did not match the amount of feedstock available as the local people had low experience with daily feeding of the bio-digester, a lack of water, and a lack of continuous supply of dung. Subsidizing farmers that install bio-digesters or penalizing those who do not install through the establishment of a market price are essential for reducing GHG emissions. The present study revealed that the non-adopters of biogas technologies were hindered by the ever-increasing cost of the bio-digester since the construction cost was greater than the annual income of households studied. The adoption of biogas technology was hindered by a lack of finance; therefore, awareness creation on credit provision and the initiation of borrowing money for bio-digester construction are highly important. Although biogas is a very promising technology for energy supply and soil fertility maintenance, the cost of bio-digester construction is not easily affordable to rural farmers; therefore, there should be support in the form of grants and long-term credit. The lack of a continuous supply of water and organic waste reduced the functionality of bio-digesters, and therefore, there should be zero grazing, home feeding and watering of cattle, and proper medication for livestock disease to sustainably utilize biogas.

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Conflict of interest

The author declares no conflict of interest.

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