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Original Research Article

Biogas Venting from Household Biogas Technology Use in Sub-Saharan Africa: Evidence from Rwandan Households as a Case

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ABSTRACT

Household biogas technology can potentially contribute to the clean cooking transition. However, when improperly used and not well customised to the user's cooking needs and practices, the technology can lead to counterintuitive and detrimental phenomena, e.g. venting. It not only affects the technology's effective use but also its climate benefits. This work aims to estimate greenhouse gas emissions associated with biogas venting from household biogas technology use and establish its causes. Household biogas utilisation data were collected remotely by using smart biogas meters and validated with conventional analogue pressure gauges. The remotely acquired data were analysed to understand the household biogas utilisation and venting levels from Rwandan households as a case for the study. Results showed that the ratio of biogas utilisation to venting was 16:1. Biogas lost through venting resulted in average monthly emissions of 33–56 $kgCO_{2,e}$ per household. Interactive interviews and field observations indicated that the current household biogas systems are not customised to the local cooking practices and the required heating for cooking specific Rwandan staple meals. This situation results in underutilisation of the produced biogas, leading to venting, hence greenhouse gas emissions. Customising the household biogas systems to local cooking practices and/or adjusting cooking practices to the technology designs can increase biogas utilisation, minimise venting and enhance envisaged technology benefits.

KEYWORDS

Clean cooking, Household biogas, Sub-Saharan Africa, Rwanda, Venting, Greenhouse gas emissions.

INTRODUCTION

Biogas produced from family-sized biodigesters is used as a clean source of energy for household cooking within energy-poor communities [1]. Also, in communities with relatively developed energy systems, the technology has been suggested for manure management [2]. Biogas produced through anaerobic digestion (AD) of biodigestible organic matter is mainly composed of methane (40–75%) and carbon dioxide (15–60%) [3]. Other minor amounts of gases and halogenated hydrocarbons are also produced in the process [4]. Of the produced biogas composition, combustible methane (CH_4) is the targeted component for cooking. In

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response to the global agenda of meeting SDG 7, specifically its indicator SDG 7.2.1, household biogas technology has been deployed in large numbers in South and South-East Asia and in Sub-Saharan Africa (SSA). It is estimated that China alone has more than 40 million biodigesters installed [5]. Through the Africa Biogas Partnership Programme (ABPP), more than 100 thousand household biogas plants were installed from 2009 to 2021 in 11 SSA countries [3]. The increased installation of the technology for the production and use of biogas at household level is motivated by its benefits, e.g., mitigation of health issues associated with the use of solid biomass and fossil cooking fuels [6], household financial savings as a result of reducing energy expenditures [7], environmental benefits and hence global warming mitigations [8], organic manure for soil fertilisation and soil management [9] and other socio-economic benefits [10].

However, in order to achieve the aforementioned benefits of the technology, biogas production and use require proper system operations and management [11]. In some situations, feedstock may be pretreated to increase the quality and quantity of biogas production [12]. Due to the decentralised nature of household biogas technology (HHBT) systems and the fact that daily operational routines are carried out at the household level by household (HH) family members, these systems are often susceptible to inefficiencies in operation and use. This situation has led to a substantial number of nonfunctional and or poorly operated HH biogas plants within user communities [13]. Thus, there is a growing concern over the technology's sustainable use and achieving its intended benefits [13]. It has been evidenced that even in experienced technology user communities, only about 60% of the domestic biogas plants are operated efficiently [14]. Biogas leakage is one operational issue that affects not only fuel resource conversion efficiency but also the technology's climate benefits. Hou *et al.* [15] show that the annual biogas produced from 8 m^3 biodigesters installed in Chinese rural dwellings vary between 47 and 176 m^3 depending on the region. The same study showed that 59%–61% of the produced biogas is used, while the rest is considered as biogas leakages to the atmosphere [15]. Studies continue to report significant environmental benefits of the technology, but also caution that when the technology is not well operated, biogas leakages do affect the intended environmental benefits [16]. Jelínek *et al.* [17] show that there is an unfulfilled potential of HH biogas to mitigate global warming due to the fact that about 40% of biogas is lost through leakages [17]. Nevertheless, leakage sources in small-scale household biogas systems are frequently generalised, thus overlooking the social contexts of use and the technological diversity in biodigester designs.

Contrary to the small-scale HH biogas use, methane emissions from larger-scale production units have been well studied, documented, classified and tracked according to their sources [18]. At the large-scale production level, methane is emitted from flaring, venting, fugitive leakages or through a combination of these sources of emissions [18]. Such classification of large-scale uses helps estimate greenhouse gas emissions (GHGEs) and develop their mitigation pathways. As shown in **Figure 1**, venting is an eminent source of methane emissions from large-scale production plants [18]. However, studies on venting from decentralised small-scale use in households within the technology user communities and the possible detrimental effects of venting are lacking in the literature, leading to uncertainty in developing mitigation approaches. Biogas venting levels associated with HHBT use could be potentially worse in communities with new technology adopters, e.g. in SSA communities. This uncertainty leaves a literature gap, calling for studies on GHGEs caused by venting associated with HH biogas production and use.

While studying the HHBT in the SSA technology user communities, Robinson *et al.* [19] used qualitative research methods to study the venting phenomenon in what they termed "opening the Pandora box". Their qualitative findings show that venting is understudied and call for empirical research approaches, quantifying GHGEs associated with the venting phenomenon [19]. The lack of empirical studies on quantitative measurement approaches to studying biogas venting leads to a lack of knowledge of the carbon footprint of the small-scale bioenergy sector. It can potentially hinder the growth of emerging voluntary carbon markets and bonds aimed to promote HH biogas technology use in energy-poor communities. For example, Strubbe *et al.* [20] have generated insights on net-GHGEs as a result of HH biogas technology in Rwandan households in the Huye District. They have shown that a 4 m^3 HH biodigester can satisfy up to 65% of the HH cooking energy demand for a family of six members, leading to annual GHGEs reduction of about 2.4 $tCO_{2,e}$ per HH when compared to HHs using wood only as cooking fuel.

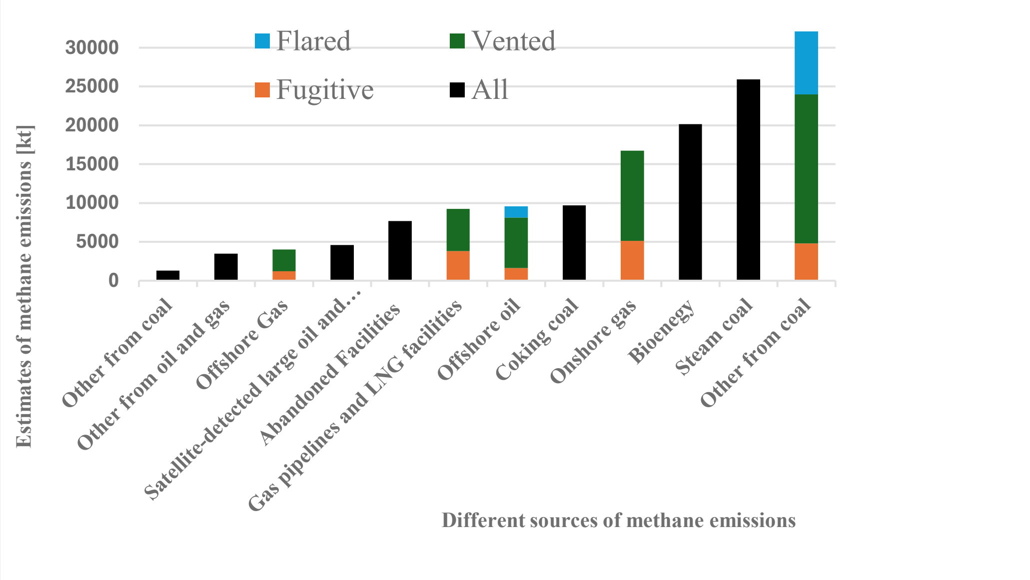

Figure 1. World methane emissions from large-scale energy sources 2024 [18]

Further, Strubbe *et al.* [20] show that when the produced digestate is used as a soil fertiliser, the net-GHGEs reduction is enhanced, leading to an annual decrease in GHGEs of about 2.5 $tCO_{2,e}$ per HH. Such results confirm the benefits of HH biogas technology. Still, their estimations are based on a general assumption that the biogas leakage is about 9% of the total produced biogas from an HH biodigester [20]. Such generalised estimations do not clearly distinguish whether leakages through outlets are intentional (venting to avoid biodigester damage) or unintentional due to damage. When the 9% [20] is compared with 40% [17] of biogas losses due to leakages, the discrepancy indicates that leakages are context-dependent and identifies a gap worthy of filling, hence contributing to the literature on the HHBT use. The discrepancies in the literature on HH biogas leakage and the lack of literature on biogas venting from HH biogas use formed the basis of our study. Thus, this paper aims to study the venting phenomenon associated with HH biogas use, and attempts to answer three research questions (RQs):

- RQ_1: What are the biogas venting levels associated with HH biogas technology use?
- RQ_2: To what extent does venting from HH biogas technology contribute to GHGEs?
- RQ_3: What are the causes of venting from HH biogas plants in rural SSA contexts?

To answer the three RQs, Rwandan HHs are used as a case for the study. The novelty and contribution of this paper can be seen in four aspects: Venting is distinguished from generalised biogas leakage in the context of HHBT use. The use of modern smart biogas meters (SBMs) together with conventional analogue pressure gauges (APGs) provides reliable data for analysing the venting phenomenon, which is not provided by the existing literature. A community-embedded research approach provided a good opportunity to establish and explain the potential causes of biogas venting from within technology-user communities. Based on established causes of venting, we propose potential mitigation approaches which call for further studies.

METHODS AND MATERIALS

In this section, methods and materials are first presented in a general context and then applied to Rwanda as a case used for the study. Methods and materials used are presented in a manner that attempts to answer the three RQs step by step from RQ_1 to RQ_3.

Methods

This subsection describes the overall approach and specific procedures adopted by the authors in their experimental research on biogas venting, as well as the relationships used in the estimation of GHG emissions.

Quantifying biogas venting. The process is guided by the recommended principles of HH biodigester design. There is a maximum (threshold) biogas pressure a biogas holder can handle for a safe HHBT operation, beyond which the produced biogas should be intentionally released (vented) [21]. In Figure 2, the upward arrows illustrate that biogas is continuously collected in the biogas holder while being produced whenever the absolute static biogas pressure (SBP) is still less than the venting threshold. When the produced biogas is underutilised and SBP surpasses the designed threshold value, the pressure can be greater than the compression forces of the biodigester and the gas holder, causing potential cracks, hence biodigester damage and biogas leakage. To avoid this, a maximum allowable SBP for a safe operation is determined based on the biodigester technology to be installed. When the biogas pressure is just above the threshold value, and no auxiliary storage is available, the produced biogas must be intentionally released (vented) to avoid the cracking of the biodigester, allowing the biogas to flow through a designed outlet.

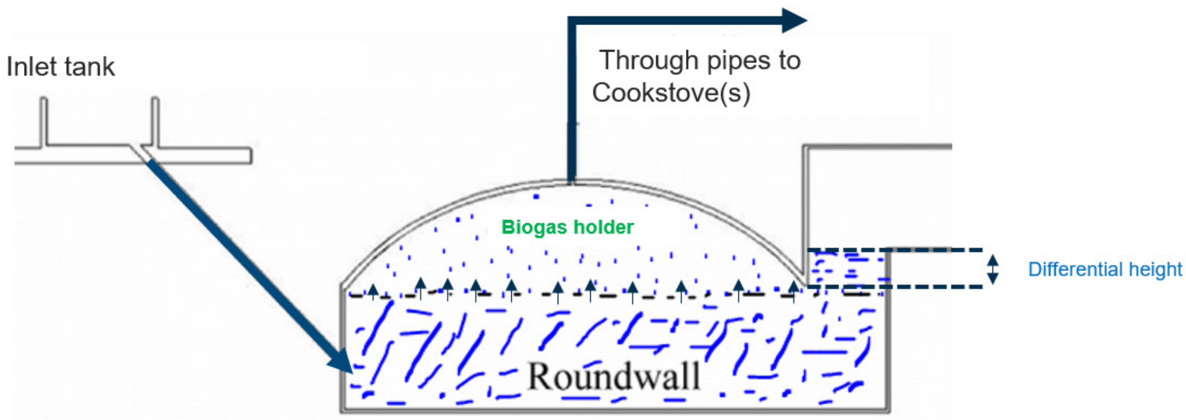

Figure 2. Biogas pressure in the gas holder below the venting threshold; arrows indicate that the produced biogas under this condition (if no cooking event) is collected in the biogas holder

The venting phenomenon is illustrated in Figure 3. The bidirectional arrows indicate that during venting events, any produced biogas that causes the SBP to exceed the venting SBP must be released through designated outlet(s). The intentional release can be done by triggering (through designated biogas valves) or by biodigester design, e.g. differential height, a design mechanism used for fixed dome HH biodigesters. Based on this safety design principle, the vented biogas volume (in m^3) can be recorded, and the associated GHGEs can be estimated. In this study, the vented biogas volume is logged onto the server by using the SBMs, which are described later in the material section.

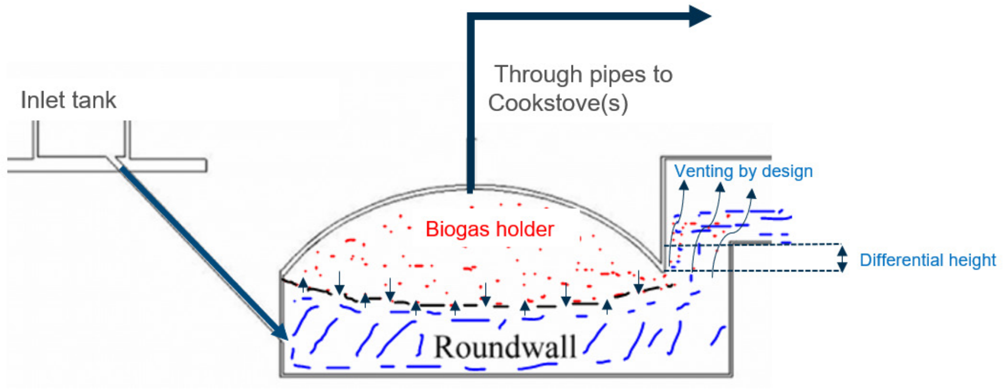

Figure 3. Biogas pressure in the gasholder above the venting threshold; the upward arrows indicate biogas being produced, while the downward arrows indicate biogas being vented

Validating logged data. APGs are used as conventional measurement tools for the SBP of biogas available in the biogas holder. However, as APGs cannot record volumetric biogas utilisation unless calculated from the recorded SBP, they are not convenient for recording instant changes in SBP. As such, SBMs are used as alternative and flexible biogas measurement tools for remote data logging, visualisation, and analysis of HH biogas utilisation for a specific HH, and within a particular time frame. Data validation is first done by the use of APGs to verify the reliability of results from data collected with SBMs. The SBP samples are recorded using APGs during field visits. The SBP is sampled before and after short cooking sessions at the respective technology users' HHs. The sampled SBPs are used to calculate the biogas consumption by using Boyle's law, presented in eq. (1) [20], and the barometric formula in eq. (2). The calculated volume of consumed biogas using APGs is compared with biogas consumption recorded with SBMs for validation. To minimise the potential effect of the produced biogas during these cooking sessions, p_1 and p_2 are recorded from very short cooking sessions. These sampled cooking sessions are made very short so that biogas being continuously produced from AD during the sampled cooking sessions is assumed to be negligible.

$$V_{cons} = \frac{(p_1 - p_2) \times V_{hol}}{p_{alt}} \tag{1}$$

$$p_{alt} = p_o \times e^{\left(\frac{-Mgh}{RT}\right)} \tag{2}$$

Where V_{cons} [m^3] is the volume of biogas consumed during the sampled cooking sessions, p_1 [kPa] and p_2 [kPa] are SBPs recorded at the start and end of a specific short cooking session, V_{hol} is the volume of the biogas holder (2 m^3, in this case), p_{alt} [kPa] is the local atmospheric pressure at the altitude of a specific HH, p_0 is the standard atmospheric pressure of 101.325 kPa, M is the molar mass of air of 0.029 kg/mol, g is the acceleration due to gravity 9.81 m/s^2, h [m] is the altitude at which the biodigester is installed, R is the universal gas constant of 8.314 J/(mol·K)], T [K] is average absolute temperature (T [°C] +273.15).

Estimating greenhouse gas emissions. After validating that the volume of biogas consumed recorded from SBMs is almost equal (with negligible differences) to the calculated values from recorded data using APGs, the biogas consumption and venting are monitored and recorded with SBMs. Using the recorded data of biogas vented over a specific period, GHGEs are estimated. Considering the average local temperature over the data collection period and the local altitude, the ideal gas law is used to determine respective gas densities of CH_4 (ρ_{CH_4}) and CO_2 (ρ_{CO_2}) by using eq. (2) and eq. (3).

$$\rho_{CH_4} = \frac{p_{alt}}{R_{CH_4}T} \quad \rho_{CO_2} = \frac{p_{alt}}{R_{CO_2}T} \tag{3}$$

Where R_{CH_4} of 518.3 J/(kg·K) and R_{CO_2} of 188.9 J/(kg·K) are ideal gas constants for CH_4 and CO_2, respectively. Using eq. (4) and eq. (8) and the recorded data on biogas venting [m^3], the GHGEs associated with the venting phenomenon over the study period are estimated. The values m, k, v, ρ, and E_{tot}, represent the masses and percentages of CH_4 and CO_2 in the produced biogas, volume, density, and total emissions, respectively.

$$E_{tot}\ [\mathrm{kgCO_{2,e}}] = E_{CH_4}[\mathrm{kgCO_{2,e}}] + E_{CO_2}[\mathrm{kg}] \tag{4}$$

Where E_{tot} [$\mathrm{kgCO_{2,e}}$] is the total emission in kilograms of CO_2 equivalent, E_{CH_4} [$\mathrm{kgCO_{2,e}}$] is the methane-related emission in kilograms of CO_2 equivalent, and E_{CO_2} [kg] is the carbon dioxide-related emission. The methane-related emissions are obtained as in equation (5).

$$E_{CH_4}\ [\mathrm{kgCO_{2,e}}] = m_{CH_4}[\mathrm{kg}] \times GWP_{CH_4} \tag{5}$$

Where m_{CH_4} [kg] is the mass of methane and GWP_{CH_4} (equal to 28) is the global warming potential of methane. The methane mass is calculated as in equation (6).

$$m_{CH_4}\ [\mathrm{kg}] = v_{biogas}\ [\mathrm{m^3}] \times\ k_{CH_4} \times\ \rho_{CH_4}\ [\mathrm{kg/m^3}] \tag{6}$$

Where v_{biogas} is biogas volume [m^3], k_{CH_4} is the methane fraction in the produced biogas, and ρ_{CH_4} *is* the methane density. Similarly, carbon dioxide-related emissions are obtained in equation (7).

$$E_{CO_2}[\mathrm{kg}] = m_{CO_2}[\mathrm{kg}] \tag{7}$$

Where the mass of CO_2 [kg] is calculated as in equation (8).

$$m_{CO_2}[\mathrm{kg}] = v_{biogas}\ [\mathrm{m^3}] \times\ k_{CO_2} \times\ \rho_{CO_2}[\mathrm{kg/m^3}] \tag{8}$$

In equations (6) and (8), the values of CH_4 and CO_2 fractions (k_{CH_4} and k_{CO_2}) reported in empirical literature are used.

Establishing causes for venting. Venting is the result of the underutilisation of the produced biogas. Thus, the causes for underutilisation, and hence venting, are analysed through a close observation of HH's cooking practices, usage patterns, interactions, and unstructured interviews during field visits.

Materials

Research materials and tools used in this study are: SBMs for remote monitoring of biogas consumption and venting, a web application (WA) enhanced by machine learning algorithms (MLAs) used to visualise remotely and record biogas consumption and venting patterns, analogue pressure gauges (APGs) for validating the remotely logged data, notebook and log sheets for research notes during research field visits.

Smart biogas meters. SBMs were configured for remote data acquisition, logging, generating patterns using a WA, visualisation and recording of the volumes of biogas utilised and vented (in m^3) in a specific period. The deployed SBMs rely on three sensors of two types; one measures SBP in the gas holder, while the other two measure the differential biogas pressure (DBP) to determine the biogas flow (in m^3/h) over a specific time recorded in hours. The SBMs used in this study are certified under IEC 61326-1:2020 [22]. The use of these SBMs for a different objective and purpose is reported by Robinson *et al.* [23] and Chaney *et al.* [24]. Sensors of the selected SBMs for this study had a maximum flow rate of 2.5 m^3/h and the SBP of 10 kPa. The supplier of the SBMs had different packages; based on the determined maximum threshold pressure for venting (8 kPa), as explained in subsequent sections, a safety margin of +25% (~ 2 kPa) was allowed. Thus, SBMs with a 10 kPa sensor rating were used. Based on the local experience, it was improbable that more than 2.5 m^3 could be consumed in an hour for a HH usage, considering that the total volume of the biogas holder was 2 m^3 for 8 m^3 biodigesters installed at respective HHs. Hence, SBMs with sensors of 2.5 m^3/h flow rate were used. The used SBMs can sample data every 5 milliseconds and have the capacity to cache data for up to 24 hours, in case of data connection disruptions [23].

Web application. The sampled data are averaged every minute, stored in the cache memory, and sent to the WA every hour [23]. The WA provides a summary of biogas consumption, flow rate, and static pressure over a selected time interval by using machine learning algorithms (MLA) and logged data [23]. The MLA also considers specifications of the HH biogas plant, which are defined during system configuration, e.g. the biodigester type, total volume of biodigester and volume of the gas holder. The MLA detect the instantaneous gradients of the SBP in the biogas holder [24], and the WA is used to remotely monitor and analyse data on biogas utilisation and venting over a selected period.

Analogue pressure gauge. Analogue Pressure gauges (APGs) were installed adjacent to the SBMs to validate data recorded by these. The deployed APGs can display the SBP [kPa]. Based on the designed SBP venting threshold of 8 kPa, APGs with a maximum SBP of 16 kPa were used.

Notebook and log sheets. The notebook was handy research material for recording observations and responses from participating HH members based on observed phenomena. The objective was to record a series of observations and establish the underlying causes for the observed phenomena. In addition to the notebook, two log sheets were used. One was used during field visits for data validation, and another was kept at respective HHs to record specific SBP whenever the user was called to do so based on a remotely observed pattern.

Applying Methods and Materials to the Case

Research methods presented earlier were customised to Rwandan HHs as a case for the study because Rwanda is one of the SSA countries with a national domestic biogas programme (NDBP) [25], and its small geographical area allowed for reaching research sites flexibly. A prior literature review and interactions with biogas project officers showed that HH biogas plants deployed in Rwanda used three types of technologies: fixed dome, flex bags, and floating drum, although the latter is not common [26].

Because existing HH biogas plants in Rwanda, installed in the framework of NDBP, were not customised to accommodate sensor-based data collection systems, new installations had to be done at selected sites. Installation of new HH plants was necessary if: (a) existing HH biodigesters installed under NDBP had technical and operation issues and had affected Rwanda's NDBP, (b) distinguishing venting from leakage required high standards of supervised installations, maintenance, and contracts obligating frequent leakage tests and reporting, (c) pipe diameters had to follow the recommended specifications from the SBMs manufacturer. Based on the knowledge above gathered in the local context, this study followed a four-phase research method depicted in **Figure 4**.

In addition to researchers' experience and literature on Rwanda's NDBP, the local authorities recommended research sites (HHs) based on the set criteria: owning at least three cows, reliable access to a piped water supply and willingness to cooperate during data collection. A review of Rwanda's biogas programme indicates that biodigesters of 4 m^3, 6 m^3, 8 m^3 and 10 m^3 satisfy 42%, 62%, 82% and 104% of HH cooking energy demand in Rwandan HHs, respectively [26]. Installing 10 m^3 would not be economical as it would lead to the underutilisation of biogas, while installing biodigesters below 8 m^3 would lead to insufficient gas production. Thus, 8 m^3 biodigesters were chosen for installation on the selected sites. Four HHs were selected for the study to ensure a daily close follow-up on the technology use, and based on the available budget. After selecting HHs (research sites), 8 m^3 HH fixed dome biodigesters were installed for research purposes.

Fixed dome technology was selected because: (a) fixed dome dominated existing deployments, and this would be close to simulating existing Rwanda's NDBP, (b) all construction materials could be sourced locally, and (c) fixed dome technology has a longer lifespan compared to flex bag (balloon-shaped polyethene biodigesters) technology also installed in Rwanda. After installation, the HH plants were fitted with SBMs to measure SBP and DBP. Conventional APGs were installed adjacent to each other to allow for data comparison and validation during fieldwork. The research process was reviewed and approved under research permit Nº:NCST/482/438/2023 issued by Rwanda's National Council for Science and Technology. The SBMs were configured by researchers, while biodigesters were installed by the experienced local contractor who installed HH biodigesters through NDBP.

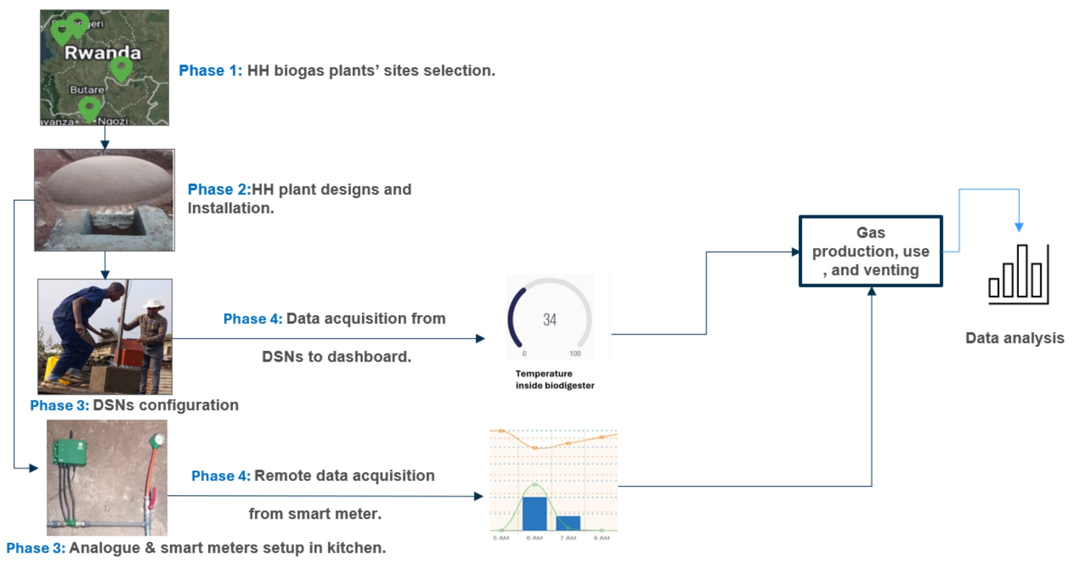

Figure 4. The four phases of the research design

A differential height of 80 cm between the throat and outlet level of 8 m^3 fixed dome technology was designed based on the contractor's experience. The designed venting threshold pressure in this case was ~8 kPa, a value which is dependent on the bioslurry density, differential height and acceleration due to gravity. After initial feeding, a hydraulic retention time (HRT) of 45 days was allowed based on the local contractor's experience [26]. The initial feeding was monitored correctly, and plants were later donated as an HH cooking lab to study the HHs' cooking practices, biogas utilisation and the venting phenomenon. After handing over the HH plants to the selected users, data were collected for seven months, between 1st June–31st December 2024. A monthly inspection was carried out by the contractor to ensure that biodigesters are leak-tight. Portable electronic biogas detectors were used to detect possible biogas leakage, and monthly inspection reports were submitted to researchers. In addition to the monthly inspection report submitted by the contractor, researchers conducted soapy water tests to detect possible biogas leakage through pipes during field visits. Such leakage preventive mechanisms were put in place to differentiate venting from other potential biogas leakages. Further, a number of demarcations were set, and SBP patterns were used to differentiate venting from other possible leakages.

Setting demarcations. Venting was classified as any release of the biogas through designed outlets whenever the SBP just exceeded a set threshold value (8 kPa in this case). As such, venting events could be predicted. On the contrary, any other SBP drop event that would occur due to any unpredictable, unintentional, and uncontrolled phenomena not caused by a cooking session was classified as biogas leakage.

Assumed SBP behaviour. It was presumed that whenever a venting event occurred, the SBP (absolute) remained relatively constant. The implication is that during venting events, the biogas holder has reached its maximum storage capacity, defined by the system's threshold pressure, including the designated safety margin, beyond which additional biogas cannot be retained. Under this assumption, the threshold SBP (8 kPa) is treated as a constant threshold pressure at which venting occurs, recognising that biogas production varies with factors (e.g. temperature, feedstock conditions, and pH). Thus, during a venting event, it is assumed that any biogas continuously produced is vented so that the gas-holder pressure does not rise above the SBP threshold. In other words, the volume of gas being produced is balanced by the volume being vented, maintaining the pressure at the set limit. Thus, the constancy of SBP in this assumption reflects the digester's venting mechanism under leak-tight conditions, rather than an assumption of constant gas production.

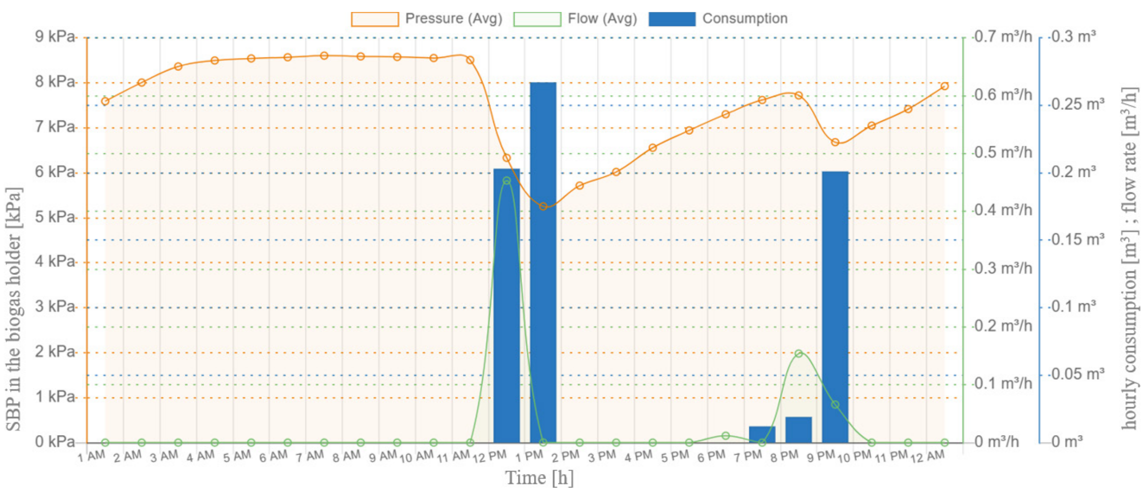

Figure 5. Biogas underutilisation pattern sampled at one of the HHs on
13th June 2024, between 1 am and 12 am

Using a WA, described in the material section, three variables were remotely monitored: the average absolute SBP [kPa] in the biogas holder, the average biogas flow rate [m^3/h] from the biogas holder to the biogas stove during cooking sessions, and the biogas consumption [m^3] in a specific cooking duration [h]. For example, **Figure 5** depicts a sampled event of biogas underutilisation, leading to biogas venting. It can be observed that the SBP remains relatively constant at an average SBP of about 8.5 kPa, just above 8 kPa (venting threshold), between 3 am and 11 am. On the contrary, **Figure 6** indicates a recommended usage pattern, keeping SBP within a proper operation range. Selecting subsequent time slots for biogas utilisation analysis, WA enhanced by MLA helps to display biogas consumption (usage), venting, and leakage as indicated in **Figure 7**. To this end, using equations (1)–(3), data in **Table 1** were generated. Further, using these data as input to equations (4)–(8), together with recorded biogas vented [m^3] from biodigesters installed at the respective participating HHs, the GHGEs were estimated.

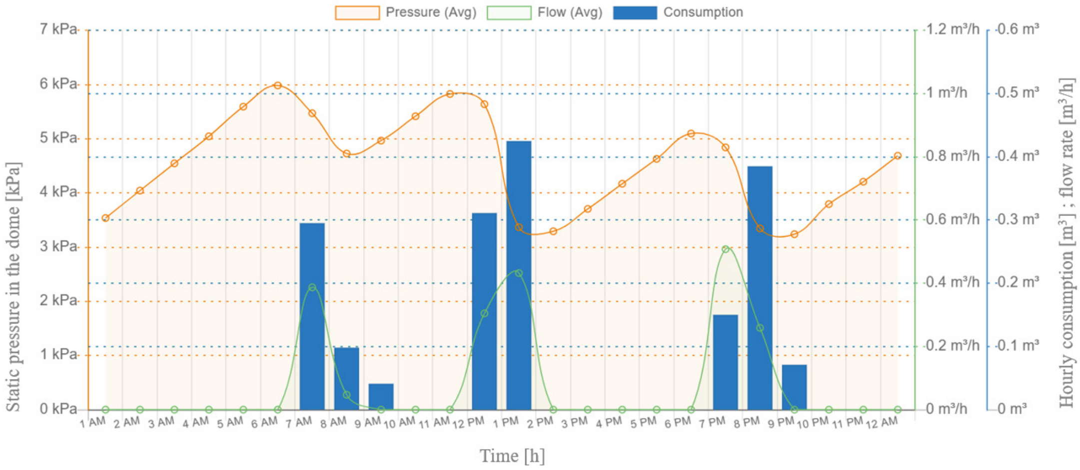

Figure 6. Recommended biogas utilisation pattern sampled at one of the HHs on 1st December 2024, between 1 am and 12 am

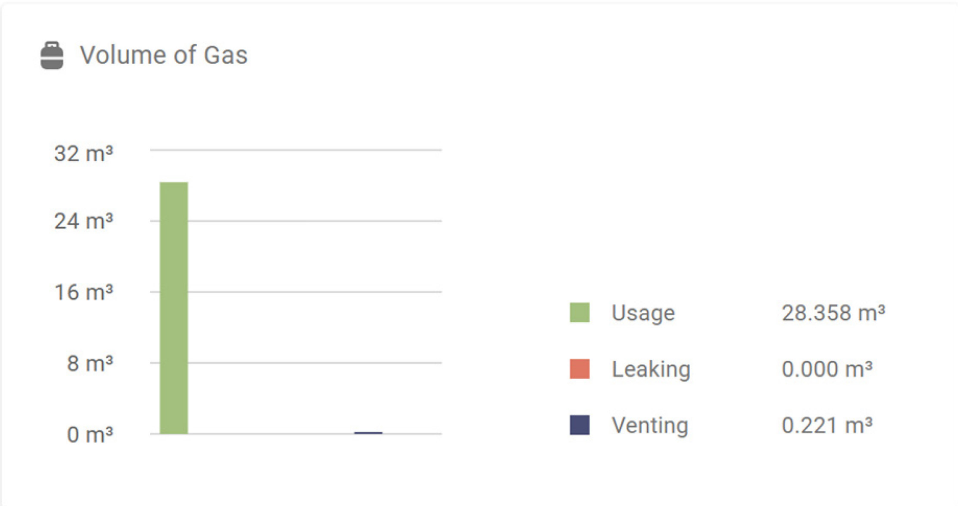

Figure 7. A sample of WA display, enhanced by MLA indicating biogas consumption (usage), venting, and leakage from the four HHs from 15th to 17th July 2024

Table 1. Local altitudes, temperatures, atmospheric pressures, CH4 and CO2 densities

Sites	Altitude, h [m]	T [°C]	p_{alt} [kPa]	ρ_{CO_2} [kg/m³]	ρ_{CH_4} [kg/m³]
Bugesera site	1440	21	85.69	1.54	0.56
Huye site	1800	19	82.15	1.49	0.54
Musanze site	2280	18	77.56	1.41	0.51
Rubavu site	2090	18.5	79.41	1.44	0.52

RESULTS AND ANALYSIS

In this section, results are presented step-by-step to answer the RQs from RQ_1 to RQ_3. It is worth noting that no biogas leakage was detected during the data collection period. If biogas leaked, it was too negligible to be detected by the biogas leakage detectors or by the SBMs.

Figure 8 shows monthly biogas consumption and venting from the four participating HHs. Biogas vented in a seven-month period (during data collection) was 44.5 m^3, 36.4 m^3, 28.3 m^3, and 25.6 m^3 for the Bugesera (Eastern), Huye (Southern), Musanze (Northern) and Rubavu (Western) sites, respectively. Thus, the total biogas consumed by the participating HHs in seven months was 2,172 m^3, while 135 m^3 was lost through venting. As such, results showed that the ratio of total biogas consumption to venting was 16:1. Using recorded volume of biogas vented, equations (1)–(8), ratios of CH_4 and CO_2 in biogas produced from anaerobic digestion [3], and assumptions stated in methods section, the average GHGEs associated with biogas venting ranged between 33–56 $kgCO_{2,e}$ per month per HH as shown in **Figure 9**.

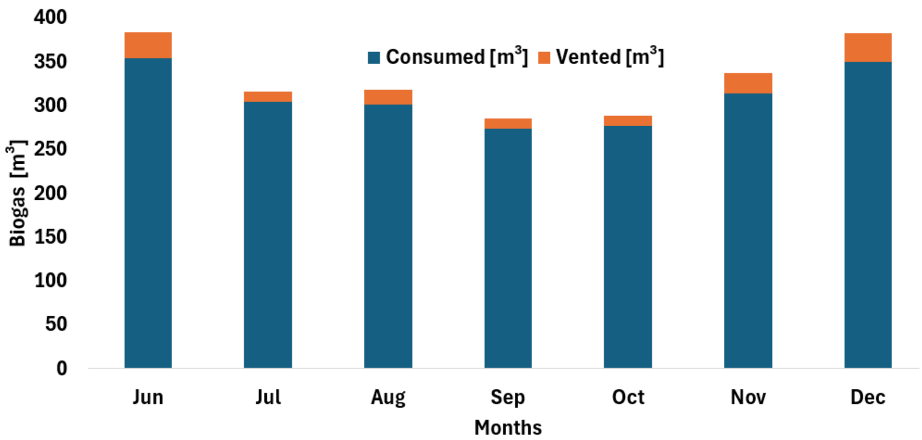

Figure 8. HH biogas monthly consumption and venting from the four HH biogas plants over a period of seven months

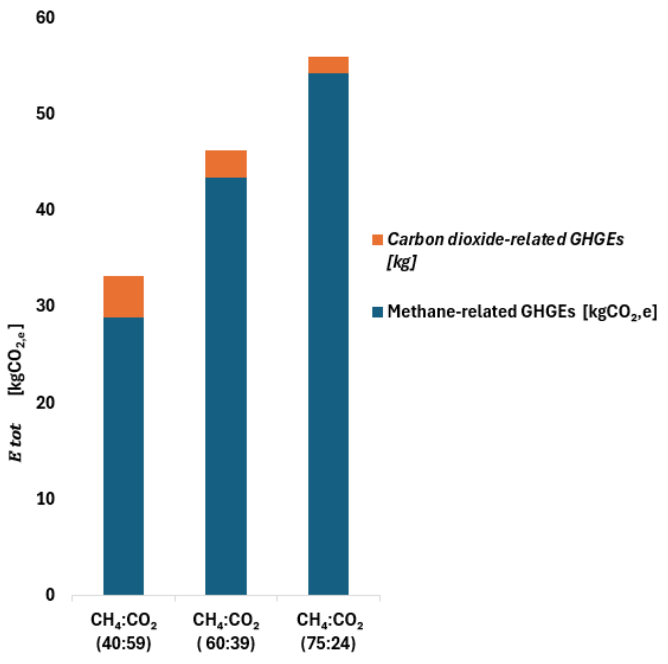

Figure 9. Average monthly GHGEs per HH

Although different HHs showed different utilisation patterns, results showed that venting levels were generally higher in June, November and December compared to other months. An overall decrease in biogas utilisation was recorded in the dry season (July to early October) because of observed intermittent biodigester underfeeding at the Musanze and Rubavu sites, leading to less biogas production. Whenever biogas was used and the SBP dropped below ~1.5 kPa, the biogas flow to the stove became weak, and HHs were advised to wait until the biogas pressure builds up. This approach resulted in a noticeable decrease in biogas utilisation during dry seasons. Although biogas production typically decreased during the dry season, making venting unlikely, venting events were still recorded.

Interactions with participating household members revealed that the types of meals typically prepared during the dry season were largely incompatible with the design and functionality of locally fabricated biogas stoves. The locally cooked bread prepared from corn and cassava flour requires continuous mingling and intensive physical manipulation, which is not supported by the locally fabricated biogas stove structure. Dry beans harvested in June dominated the HH's meals in the dry seasons and required prolonged cooking, which requires high heat not produced by unpurified biogas used directly from anaerobic digestion. Further, the supply of fuel wood was found to be more reliable in the dry season than in the rainy season, and HHs confirmed that they preferred to cook such staple meals with fuel wood. This contributed to a low biogas utilisation in July, August, September, and October.

DISCUSSION

This work answers three research questions rooted in the identified research gap, enhancing the literature on venting associated with small-scale HHBT use, specifically in SSA. The venting levels are quantified with an approach that distinguishes venting from general biogas leakage. Results showed that vented biogas led to an average monthly GHGEs of 33 to 56 kg$CO_{2,e}$ per household. Quantifying and distinguishing venting from generalised leakage can help to mitigate GHGEs associated with such a phenomenon. In this section, this study's contributions, limitations and potential future work are discussed, thereby offering a nuanced understanding of small-scale biogas utilisation and the associated GHGEs.

Contribution to the Existing Literature

This study highlights that venting is a phenomenon worthy of investigation while studying net-GHGEs from HH biogas use. E.g., Strubbe *et al.* [20] quantified net GHGEs from Rwandan households based on the assumption that 9% of biogas was lost through leakage, but such assumptions may lead to misestimations and affect voluntary carbon markets aimed at promoting HHBT use in energy-poor communities. Further, Robinson *et al.* [19] indicate that venting is an understudied phenomenon affecting HHBT use in SSA, but results from their work are qualitative, lacking quantitative justifications. This paper adds to their work by providing quantitative findings.

The field measurements in this study confirm that the observed operating pressures are consistent with published thresholds and fall within the safe design limits for household-scale fixed-dome digesters presented in **Table 2**. The HH biogas systems assessed in this study were 8 m^3 fixed-dome digesters, which operated close to their designed threshold of 8 kPa. Literature indicates that fixed-dome biodigesters in the 4–12 m^3 range generally maintain operating pressures of 7–9 kPa, with venting or failure occurring around 8 kPa [19]. Technical manuals further specify a design maximum of approximately 9.8 kPa [100 cm H_2O] across this household size range, regardless of exact volume [27]

The digesters in this study released an average of 33–56 kg CO_2e per HH per month through venting. Although venting has long been acknowledged as a risk in small-scale digesters, quantitative household-level data expressed in $CO_{2,e}$ are lacking.

Table 2. Safe design limits for household-scale fixed-dome digesters

Fixed-dome digester size	Typical operating pressure	Design / relief threshold	Discussion notes
4 m^3	~ 7–8 kPa	Venting/failure at ~ 8 kPa	Robinson *et al.* [19] report ~ 8 kPa as a venting/failure point in household-scale fixed-dome units.
6 m^3	~ 7–8 kPa	Design maximum ~ 9.8 kPa	Vietnam Biogas Programme [27] specifies 100 cm H_2O (~ 9.8 kPa) as the safe maximum pressure for small household fixed-dome digesters.
8 m^3	~ 8 kPa	Venting/failure at ~ 8 kPa	Robinson *et al.* [19] confirm ~ 8 kPa as the venting/failure threshold; aligns with design specifications in this study.
10 m^3	~ 8–9 kPa	Design maximum ~ 9.8 kPa	Vietnam Biogas Programme [27] indicates slurry-head driven pressure with maximum ~ 100 cm H_2O (approx. 9.8 kPa).
12 m^3	~ 9 kPa	Design maximum ~ 9.8 kPa	Vietnam Biogas Programme [27] guidance remains consistent across household sizes, capped at ~ 9.8 kPa.

Vu *et al.* [28] studied the life cycle assessment (LCA) of small-scale digesters in Vietnam. They mention biogas losses from cracks and intentional release, test sensitivity analysis and highlight venting as a factor affecting GHGEs balance, but do not report household-level $CO_{2,e}$ values. Hou *et al.* [15] report biogas leakage in general terms. They report adverse effects of venting/leakage, but do not provide $CO_{2,e}$ per HH from the venting phenomenon. Regarding the total emissions from HHBT, Roubík *et al.* [29] show that 79.41% are produced during construction, 15.40% during operation, and 5.19% during demolition; no quantification of GHGEs from venting is provided. Bond and Templeton [1] highlight that construction quality, maintenance, and gas leakage are recurring challenges for household biogas programmes, but do not report venting emissions in quantitative terms, reflecting the broader gap in standardised data on this issue. Against this backdrop, our results present field-based quantifications of household-level venting emissions expressed in $CO_{2,e}$ not found in existing studies, thereby filling a clear gap in the literature. These findings not only confirm that venting can contribute substantially to the climate footprint of small-scale digesters but also provide data that can be directly integrated into greenhouse gas inventories and inform targeted mitigation strategies.

On the Materials Used and Practical Limitations

Data collected by using the APG during data validation often resulted in slightly lower values compared to the logged data from the SBMs. The absolute differences are graphically presented in **Figure 10**, ranging between 0.01 and 0.04 m^3. The differences may be due to the analogue readings of SBP [kPa] from the APG, which are not as precise as digital data from SBMs, and/or the assumed gas laws presented in the methods section. The SBMs provided a convenient way for remote and timely acquisition of data on biogas utilisation and venting compared to APGs, which do not offer instant data, require the physical presence of researchers, and require the conversion of recorded biogas pressure from kPa to m^3. Although normalised cubic meters [Nm^3] are generally preferable, the off-the-shelf SBMs used in this study did not have the capacity to capture the continuous (e.g. temperature, atmospheric pressure) data required for accurate normalisation. Applying assumed corrections risked introducing additional uncertainties, which we avoided by recording biogas volumes in m^3 for consistency. While differences from Nm^3 values may exist depending on temperature and pressure, these are not expected to alter the study's conclusions.

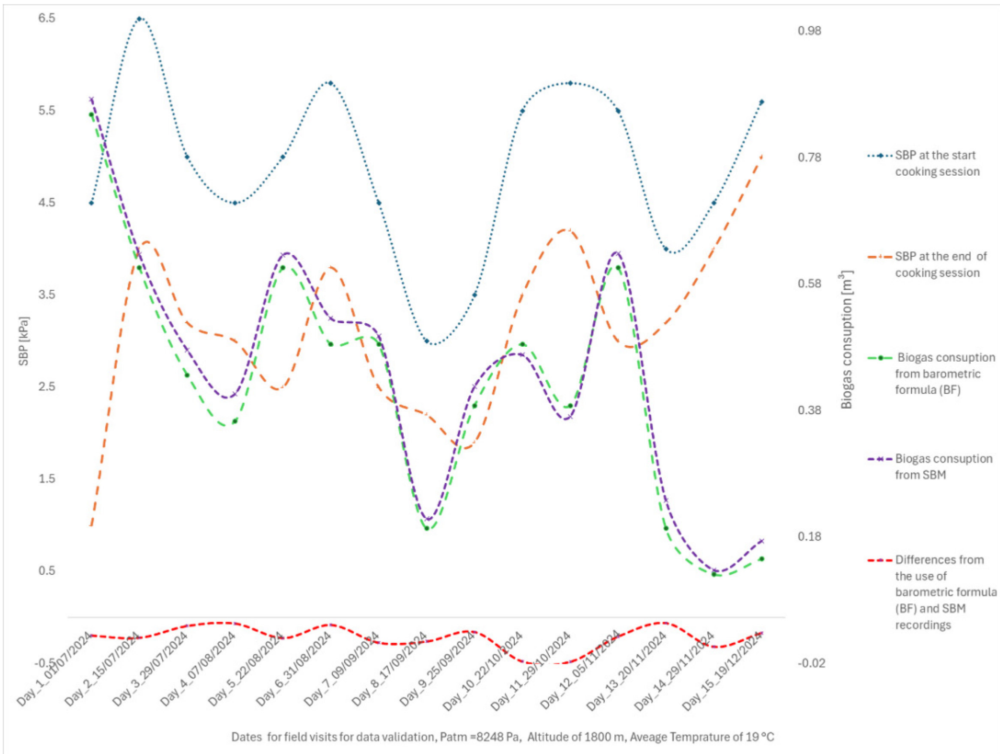

Figure 10. Data validation output from short samples of cooking sessions

Using SBMs with Machine Learning Algorithms (MLAs) embedded in the WA provided direct readings of data required for the study. Due to the growing need for remote data acquisition in the energy sector, developing cost-effective and small-scale embedded electronic modules for HH biogas technology monitoring could enhance technology data acquisition, lead to data-driven HHBT designs and policies, and thus enhance intended benefits. Powering such devices can be an issue due to the remoteness of technology user communities, but the increasing use of pico-solar modules and portable batteries can mitigate such challenges [30].

Through this study, it has been realised that contractors installing HH biogas plants in the framework of Rwanda's NDBP do not account for the effect of altitude on atmospheric pressure. This approach can lead to misestimations in the design of threshold biogas pressure for venting. Rwanda's terrain is hilly and mountainous, especially in the northern and western provinces. Using the same differential height of 80 cm for an 8 m^3 fixed dome biodigester at all sites might have marginal effects on the results.

Limitations and Potential Future Work

This study relied on measured data and equations without modelling the anaerobic digestion (AD) process. Practically, during sampled cooking sessions for data validation, however short they may last, there is a continuous gas production through AD, and this might have marginal effects on estimations. Further studies combining anaerobic digestion modelling and the use of SBMs can add more insights to the findings of this study. Also, this work quantified the HH biogas venting levels and GHGEs associated with the venting phenomenon, and established causes of venting from HHBT by using data from an 8 m^3 fixed dome biodigester. The results obtained using different sizes and biodigesters' designs could broaden the literature on the use of HHBT technology and the associated venting phenomenon. The locally fabricated and distributed biogas stoves, see **Figure 11**, do not follow a well-standardised and regulatory framework and do not support local cooking practices and needs. Hence, technical studies focusing on how to improve and customise biogas stoves to local cooking practices, as well as the use of auxiliary biogas gas storage instead of venting, are required to ascertain how such modifications can impact the technology use. Further still, during field work visits, it was observed that HHBT use depends on daily HH livelihoods. Thus, though this study generated insights on causes of venting, a mixed-method research approach combining in-depth qualitative and quantitative data can broaden the understanding of how HH livelihoods affect the HHBT use, contributing to its sustainable use.

Figure 11. Locally fabricated and distributed biogas stove

CONCLUSIONS

This study recorded venting levels from HH biogas plants installed in energy-poor communities. Underlying causes of HH biogas venting from HHBT use were established, and GHGEs associated with such venting phenomenon were calculated. Results show that vented biogas led to an average monthly GHGEs of 33–56 $kgCO_{2,e}$ per household. When such results are extrapolated over a whole year, this leads to average annual GHGEs of 0.4–0.7 $tCO_{2,e}$ per HH. Thus, HH biogas venting not only causes loss of the biogas energy carrier but also contributes to GHGEs. Even when there is sufficient biogas for cooking, HHs opt for fuel wood to cook specific local meals, which cannot be cooked using the locally fabricated biogas stoves supplied with the HH biogas plants. Research work focusing on technical development to customise the technology, especially the biogas stoves to the cooking practices of local meals, cost-effective purification methods and auxiliary biogas storage can minimise venting and enhance the envisaged technology benefits.

In addition to technical measures, demand-side practices can also help reduce venting by better matching gas availability with cooking demand. Where culturally feasible, HHs could adjust cooking times so that meal preparation overlaps more closely with peak gas production, thereby reducing pressure buildup and subsequent venting. Cooking durations may also be shortened to make biogas more suitable for foods that are typically avoided due to long simmering requirements, such as dry beans (e.g., through pre-soaking). Although some HHs may be reluctant to adopt pre-soaking dry beans because of taste preferences, such measures can be introduced as optional household-level adaptations that improve biogas utilisation and further minimise venting.

AUTHORSHIP CONTRIBUTION

James Ntaganda: Literature review, conceptualisation, research methodology development, data collection, cleaning, validation, and analysis, manuscript draft, and subsequent revisions. Basílio Zeloso Salvador Tamele: Manuscript review, discussion and editing. Erik O. Ahlgren: Supervision, conceptualisation, manuscript reviews, feedback, and editing.

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NOMENCLATURE

E	emissions	[$kgCO_{2,e}$]
h	height	[m]
m	mass	[kg]
M	molar mass	[kg/mol]
p	pressure	[kPa]
T	temperature	[°C], [K]
v	volume	[m^3]

Greek letters

ρ	density	[kg/m^3]

Symbols and units

$CO_{2,e}$	carbon dioxide equivalent
$kgCO_{2,e}$	carbon dioxide equivalent in kilograms
$tCO_{2,e}$	carbon dioxide equivalent in tons

Subscripts and superscripts

alt	altitude
cons	consumption
tot	total

Abbreviations

ABPP	Africa Biogas Partnership Programme
AD	Anaerobic Digestion
APGs	Analogue Pressure Gauges
Avg	Average
DBP	Differential Biogas Pressure
GHGEs	Greenhouse Gas Emissions

GWP	Global Warming Potential
HH	Household
HHBT	Household Biogas Technology
IEC	International Electrotechnical Commission
MLA	Machine Learning Algorithm
NCST	National Council for Science and Technology
NDBP	National Domestic Biogas Programme
RQs	Research Questions
SBMs	Smart Biogas Meters
SBP	Static Biogas Pressure
SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
STP	Standard Temperature and Pressure
WA	Web Application

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