From animal waste to energy: Exploring the effects of household livelihoods on biogas technology use in Rwanda

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Original research article

From animal waste to energy: Exploring the effects of household livelihoods on biogas technology use in Rwanda

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ABSTRACT

Using household biogas technology effectively can advance clean cooking transitioning in energy-poor communities. While the existing literature largely examines potentials, adoption barriers, and impacts of the technology, little is known about how household livelihoods affect its use. This study addresses this gap through a mixed-methods approach. Smart biogas metres were deployed to collect biogas utilisation data from 4 Rwandan households for 7 months. Field observations, semi-structured interviews, and phenomenological questioning were used to collect mixed data for triangulation. Pattern analysis and interpretive phenomenological analysis were used for the data analysis. Findings indicate that households with consolidated land-based livelihoods, spending more time at home, operated and used their biogas systems more consistently than those whose livelihoods are spread across fragmented landholdings. Households with stable year-round family composition operated and used the technology more effectively than those experiencing seasonal changes in family membership. Further, findings show that households continued to use solid fuels even when biogas was available. Locally fabricated biogas stoves lacked the firepower and mechanical strength needed for cooking staple meals requiring continuous stirring and mixing. This resulted into intermittent underutilisation of the produced biogas, hence biogas venting. 4–9 % of the daily biogas production was vented, depending on each household's operational practices and patterns of technology use. Biogas venting leads to energy loss, greenhouse gas emissions, and undermines the technology's intended benefits and expected impacts. This study shows that understanding the household livelihood dynamics in technology-user communities is crucial for its use and for formulating customised clean cooking policies.

1. Introduction

The global sustainable development agenda targets universal access to clean cooking fuels and technologies by 2030 [1]. Technologies anchoring the clean cooking transitioning include, e.g. stoves powered by: electricity, liquefied petroleum gas, natural gas, biogas, solar, and alcohols [1]. While global access to clean cooking solutions grew by 16 % from 2010 to 2022, about 2.4 billion people continued to use polluting fuels for cooking their daily meals [1]. Business-as-usual projections show that six out of ten people relying on polluting cooking fuels will be living in sub-Saharan Africa (SSA) by 2030, with little or no improvement anticipated by 2050 [1]. To advance clean cooking, household biogas technology (HBT) has been supported as a potential technology to contribute to this transitioning [2]. Household (HH) biogas systems are designed in such a way that feedstock (e.g. livestock excreta, crop residues, kitchen waste) are fed to family-sized biodigesters, where they undergo anaerobic digestion to produce biogas (mainly methane) used for cooking [3]. The HBT is commonly deployed in energy-poor communities mostly in some Asian countries and in sub-Saharan Africa.

Although HBT can potentially advance the clean cooking transitioning in these communities, its uptake and sustained use are constrained by a number of barriers, common across these regions. These barriers largely stem from high investment costs, technical and socio-technical challenges, and administrative or institutional constraints [4,5]. In Asian communities, however, the use of HBT is relatively more established and successful than in SSA. Successful cases in e.g. China, India, Nepal, Vietnam, Sri Lanka, and Indonesia have been driven by

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strong private-sector engagement, innovative financing mechanisms, and advances in technology design [6,7]. For example, Bhat et al. [7] show that 85 % of HH biogas plants in Sirsi, India, satisfied the HHs cooking energy needs because of these innovative approaches. Although HBT barriers are prevalent across these regions, variations in enabling conditions and implementation approaches are reported to shape HBT use. While the existing literature has largely focused on potentials, adoption barriers, enabling conditions and impacts of HBT, little is known about how HH livelihoods shape its use, particularly in SSA, where its successful use remains limited. This underscores the need for in-depth investigations onto HBT utilisation in a SSA context [8].

1.1. Household biogas technology use in the SSA

Building on reported success stories from Asian countries, the Africa Biogas Partnership Programme (ABPP), initiated in 2007–2008, was adapted and integrated into the national policies of several SSA countries [9]. Such policies and joint funding mechanisms between international organisations and respective SSA governments enhanced the HBT use, and more than 100,000 household biogas plants were installed in 11 SSA countries in 2009–2021 [10]. The increase in HBT deployment and use was attributed to technical potential growth driven by an increasing number of cattle across Africa and access to water, thus increasing HH biogas system feedstock [11]. Although technical potentials increased within SSA technology-user communities, the success of HBT use remains generally limited [8]. This is attributed to barriers related to high investment cost, technical, socio-technical, and administrative and institutional issues [5].

Although these barriers persist, several socio-economic and environmental benefits of the technology have been reported in SSA. Strubbe et al. [12] show that Rwandan HHs using HBT for cooking and bioslurry as a soil fertiliser displaced 2.5 $tCO_{2,eq}$ annually per HH. However recent studies reveal HBT utilisation patterns undermining the technology's environmental benefits within SSA communities. Robinson et al. [13] report substantial biogas venting from small-scale systems in SSA, triggering further inquiry onto the technology use. Their findings are qualitative, and thus call for quantitative evidence [13]. While Chaney et al. [14] show insightful quantitative findings on HBT utilisation patterns in Kenyan and Ugandan HHs, their findings lack in-depth explanations of the reported biogas utilisation patterns. The HBT is operated, maintained, and utilised by HH members as part of their daily routines. Thus, the biogas production and use are inherently shaped by HH livelihoods. HH labour commitment is integral to the sustained functioning of the technology. Diouf and Miezan [15] report that the daily labour required for operating a HH biogas plant (e.g. collecting organic feedstock, manual stirring, feeding, and cleaning inlets and outlets) accounts for approximately 25 % of the total operational cost.

In a broader perspective, Kelechukwu and Kollur [16] show that HH livelihoods, daily routines, and labour dynamics are critical to the understanding of clean cooking transitioning. Further, in a more technology-specific study, Kalina et al. [8] emphasise that there is a need for social science research approaches interrogating embedded practices and sparking critical reflection on HBT use in SSA where its successful use continues to be limited. Although they focused on test statistics, Nalunga et al. [17], in their study on HBT use in central Uganda suggest to carefully assess particular HH dynamics before introducing the use of HBT to HHs.

The limited success of HBT use in the SSA, coupled with the absence of in-depth studies on how HH livelihoods affect its use highlights a research gap deserving attention, and worth investigating, thus, forming the basis for this study. The aim of this study is to examine how HH livelihoods affect the production and use of biogas in domestic settings, and to derive context-specific insights that could enhance its effective and sustained use. Thus, this study is guided by two research questions:

RQ1. How do household livelihoods affect biogas production and use?

RQ2. What lessons can be drawn from the ways household livelihoods affect the use of household biogas technology?

This paper's novelty spins on its HH livelihoods-centred inquiry. It links HH livelihoods to operational realities analysed from data logged from smart metres, field observational data, semi-structured interviews, and phenomenological questioning–a triangulation of data not used by existing studies on HBT use. This study adopts a HH livelihoods framework as an analytical tool.

2. Conceptual framework

The analytical framework used in this study conceptualises HBT use as a function of distinct, but interconnected household resources. A "*household*" is defined as *"a group of people who eat from a common pot and share a common stake in perpetuating and improving their socio-economic status from one generation to the next*", while a "*livelihood*" is defined as "*the command an individual, family, or other social group has over an income and/or bundles of resources that can be used or exchanged to satisfy its needs*" [18]. As such, this work focus on five HH resources defined by Carloni and Crowlet [18]: (a) Physical resources (PRs)–the physical assets e.g. buildings and home appliances, (b) Human resources (HRs)–the family members, their education levels, available labour force and their skills, (c) Social resources (SRs)–an indicator of how a specific HH is connected to local social networks and hierarchies, (d) Financial resources (FRs)–the HH's ways and means to generate income and support its daily living, e.g. salaries and/or wages, access to financial schemes and loans, and (e) Natural resources (NRs)–the naturally existing resources used or exchanged to satisfy the HH needs, e.g., access to water bodies for fishing.

These resources interlink to each other, but each of them influences HBT use differently, as illustrated in Fig. 1. The conceptual framework used in this study is framed in such a way that the five household resources influence biogas utilisation without presuming feedback effects, a relationship represented by unidirectional arrows from each resource toward biogas utilisation. In other words, the study explores the effects of HH livelihood on the technology use but does not study the impact of the technology use on the HH livelihoods. The framework also builds on the livelihoods resources outlined by Scoones [19,20], but omits the '*sustainability*' component to focus solely on how the HH livelihoods affect the HBT use, thereby establishing a basis for future studies on the technology's sustained use.

3. Methodology

The methodology is developed based on epistemological and ontological alignments to the identified research gaps, research questions, data collection and methods of analyses responding to the research

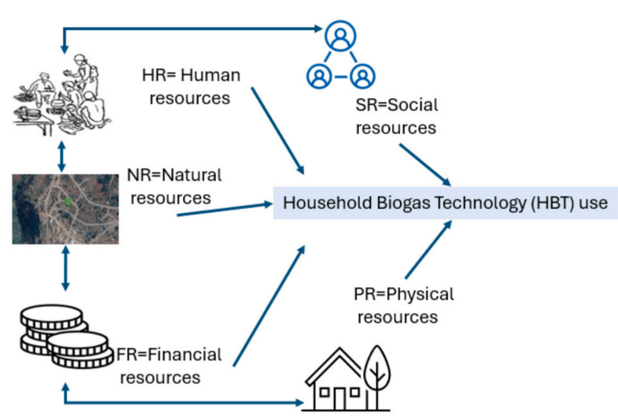

Fig. 1. The five resources used to define households' livelihoods and develop a conceptual framework for data analysis [18].

questions, practical limitations and ethical considerations.

3.1. Epistemological and ontological alignment

This study is guided by a realist methodological approach which recognises the real existence of social objects as well as physical objects. The empirical realism and critical realism guided the research design process. From a realism perspective, the ontology is concerned with the reality while the epistemology is concerned with how to gather the knowledge [21]. As such, the methodology has been developed to align with the epistemological priorities of the study (depth and explanations), rigor (triangulation), and longitudinal engagement (collecting data for a sufficient time to deepen insights). The empirical realism and critical realism lead to three stratified levels [22]: *empirical level* at which events are experienced, observed, and understood through human interpretation, *actual level* at which events occur whether observed or not, and *real level* at which mechanisms cause events to occur at the empirical level [22].

A research design developed from this epistemological and ontological reasoning is depicted in Fig. 2. Smart biogas metres, analogue pressure gauges and data sensor networks are employed for collecting data on biogas production and utilisation. Biogas utilisation data are analysed through pattern analysis (PA). Empirical data on biogas production and utilisation provide continuous and quantifiable measurements of technology performance. HH livelihoods data are obtained through semi-structured interviews, while phenomenological accounts are gathered through phenomenological '*questioning*' and analysed thematically using Interpretative phenomenological analysis (IPA) [23]. Observational data are also incorporated to triangulate evidence.

With such a design, the empirical component situates biogas use in observable HH practices and technology's measured performance. The phenomenological orientation captures the lived experiences and the meanings HHs assign to the technology [24]. These two paradigms are integrated carefully to ensure methodological coherence: empirical data provides objective evidence of HBT utilisation patterns, whereas phenomenology reveals how HHs perceived, interpreted, and lived with the technology use. Linking measurable performance with subjective experience offers a comprehensive account of how HH livelihoods affect HBT use. It is worth noting that the phenomenological orientation was purposively applied at the later stage of the study to probe for details on the technology users' lived experiences, thus linking empirical accounts to broader causal explanations.

3.2. Participating HHs and practical context

In alignment with the chosen methodology priorities, the number of participating HHs was determined based on different scholars' opinions regarding the number of participants for studies which prioritise depth over breadth. Sandelowski [25] suggests to keep a small number for case-oriented studies, Morse [26] recommends a minimum of six participants for interpretive phenomenology, while Smith et al. [23] and Creswell [27] indicate that a small number, as small as two to ten participants can be appropriate when the research focus is on detailed, and in-depth understanding. Sharma et al. [28] developed a rule of thumb regarding the number of participants for research designs relying entirely or partially on qualitative data, suggesting 4–5 for case-oriented studies and 3–25 for interpretive phenomenological research designs. Smith et al. [23] urge that the number of participants depends on degree of commitment to the case, the level of analysis and reporting, as well as constraints the researcher is operating under.

Aligning with Creswell's lower range of participants to prioritise depth for explanation over breadth for generalisation [27], the practical

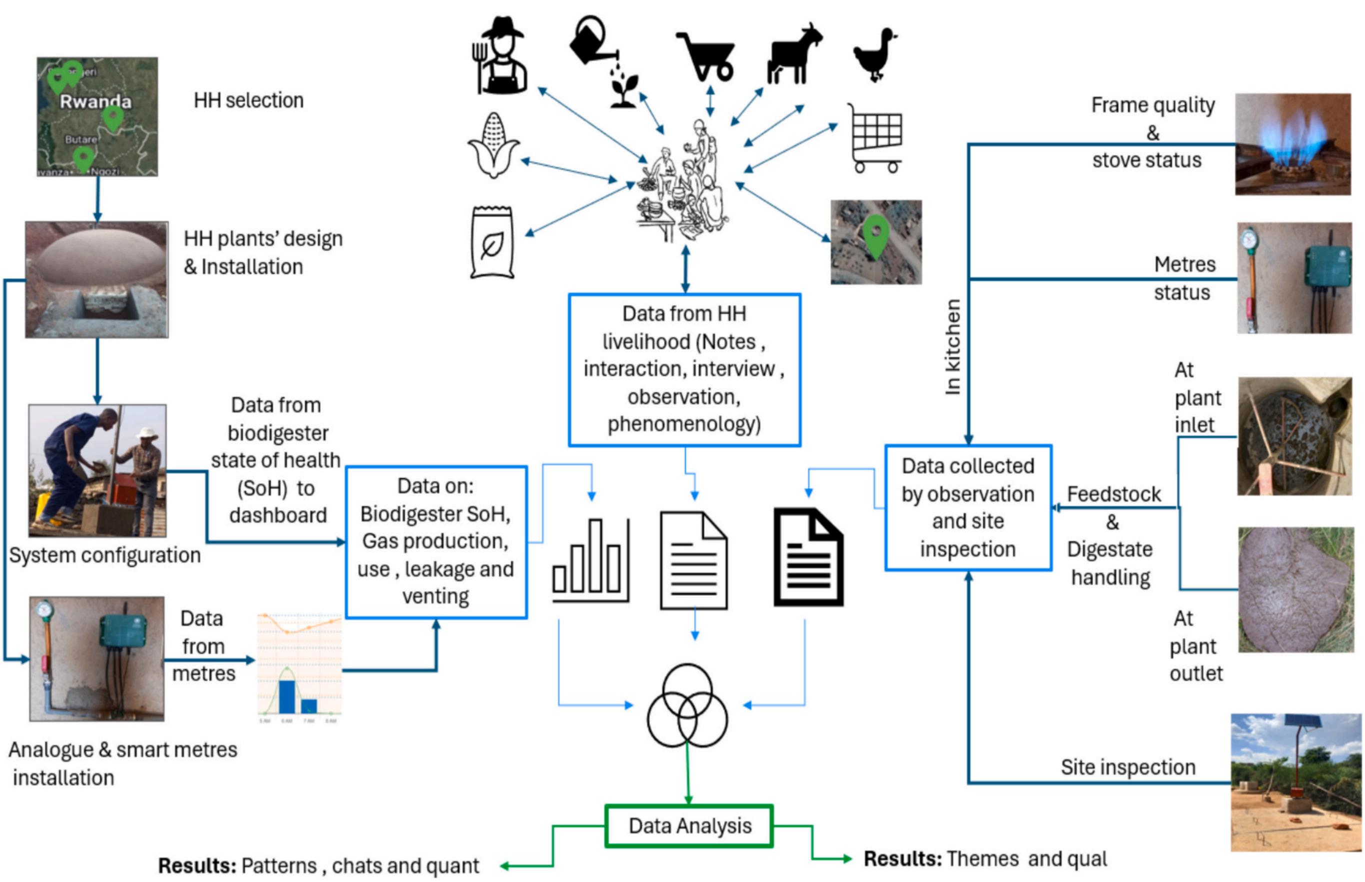

Fig. 2. Research design used for this study indicating three main sources of triangulated data.

context and researchers' constraints acknowledged by Smith et al. [23], four HHs were selected for the study. Investigating HHs cooking practices requires trust-building with participating HHs. Such practical context required a small number of HHs to ensure that data collection remains manageable while maintaining high analytical quality. This constrained the number of HHs during research design for this study but ensured culturally sensitive, and high-quality data collection.

3.3. Application of the methodology to the case of the study

Rwandan HHs were used as case for the study because of: (a) limited success of Rwanda's National Domestic Biogas Programme [29], (b) its national strategies for green growth and institutional engagement in carbon markets for clean cooking [30], (c) steadily growing information communication technology policies and infrastructure that support smart biogas monitoring [31], (d) Rwanda's rural areas with a strong livestock-rearing culture, and, (e) Rwanda's small geographical size (26,338 km^2) enabling researchers to reach remote study sites with ease.

From a national perspective, household biogas use in Rwanda was launched through the National Domestic Biogas Programme (NDBP) in 2008, just after the establishment of the Africa Biogas Partnership Programme. It was initiated to reduce reliance on fuelwood and improve rural energy access. In 2012, about 1800 household digesters had been installed, and by 2022 the number had grown to about 10,200 [32]. However, since 2022, new installations reduced dramatically, and many installed HH biogas plants have been abandoned. Thus, the role of HBT in Rwanda's rural energy mix presents dual narratives: the technology's potential to enhance the clean cooking transitioning versus persistent challenges constraining its widespread and sustained use. The technology's potential narrative continues to report the technology's potential to reduce the greenhouse gas emission [12], and reducing HH annual energy expenditure [33]. On the other hand, a critical review on the Rwanda's NDBP has raised doubts about the technology's success due persistent challenges [32]. The critical review further highlights the need for clarity on the technology operations and explicit definition of whether the HH biogas programme aim to fully or partially substitute other cooking fuels and ensuring technical and financial viability [32]. This calls for community-embedded research approaches.

3.3.1. Recruiting participants

Through the grassroot administrative authorities, the four HHs were selected based on: (a) having a reliable piped water supply, (b) owning at least three cows, (c) keeping at least 3 cows at their HH residence, (d) committed to participating and providing relevant data during data collection, (e) using the same type and size of biodigesters. The recruitment ensured that the four participating HHs came from four of the five provinces of Rwanda (North, South, East and West), excluding central Kigali which hosts the capital city. Two HHs were from the Northern and Western provinces, both in mountainous areas with high population density and settlement policies developed to manage the land scarcity. The other two households were from the Eastern and Southern provinces, located in lowlands and plateaus, respectively, where settlements are relatively less dense.

3.3.2. Ethical and practical considerations

In compliance with Rwanda's research guidelines, this study did not involve human health data, but a research permit had to be granted by the National Council for Science and Technology (NCST). The study was conducted under research permit N^{o}:NCST/482/438/2023. While families were generally hospitable during the pre-selection process, Rwandan HH cooking areas are taken as highly private spaces, making access for research purposes culturally sensitive. Each HH provided informed consent to allow observing, interviewing, and recording required data, provided that the participants' requested anonymity is observed: coding participating HHs ('*NGT*', '*WMT*', '*EKF*' and '*SJB*'), and not taking pictures of participants' faces and their meals.

3.4. Data collection

A mixed-data collection approach was used. Data collection lasted for seven months starting from 1st June to 31st December 2024. This time frame allowed for capturing seasonal (dry and rainy) influence on the HH livelihoods. This allowed for studying how the latter affects the technology use. Biogas utilisation data, HH livelihood data, observational data, and phenomenological data were collected from the participating HHs by using different but complementary research tools and approaches.

3.4.1. Biogas utilisation data

Smart biogas metres were used for logging data on the biogas utilisation at each HH. The smart biogas metres used are enhanced by machine learning algorithms and web application which allow to remotely plot, visualise, and monitor biogas utilisation at each HH. The role and use of smart biogas metres for the remote monitoring of the small scale biogas technology use is reported by Robinson et al. [34]. To ensure data accuracy, analogue pressure gauges were installed adjacently to the smart biogas metres, purposely for the verification and validation of data logged with smart biogas metres. Data validation by using analogue pressure gauges was done during fieldwork days, at least 15 days at each HH during the seven months period. Methods of use and specifications for the two metres are explained in the supplementary materials (SM.1, SM.1.1, and SM.1.2).

3.4.2. HH livelihood data

Livelihood data were collected through scheduled semi-structured interviews. Interviews focused on five key categories of HH livelihood resources, presented earlier in Section. 2. The questionnaire used for collecting HH livelihood data is presented in supplementary material (SM.2) while the collected livelihoods data are presented in supplementary material (SM.2.1–SM.2.4) and summarised in the Results section.

3.4.3. Observational data

Observational data were collected through randomised site visits to assess plant conditions, as well as event-triggered observations such as remotely visualised biogas underutilisation (leading to venting) or overutilisation (leading to weak biogas flames). Direct observations helped to collect data on observable realities such as the status of the biogas flame indicating among other things, the absence/presence of vapour and potential impurities in the produced biogas. Observations helped to capture evidence of certain phenomena through their outcomes when direct observation was not possible. An example is the observation of the state of bioslurry at the outlet (compost pit) as indicator of biodigester feeding. While feeding patterns were observed during field visits, the condition of the bioslurry at the biodigester outlet served as another observable indicator of the biodigester feeding consistency or inconsistency, even in the absence of witnessing the act of feeding itself. Samples of observational data collected during fieldwork are presented in Fig. 3 and detailed in the supplementary material (SM.3).

3.4.4. Phenomenological data

Phenomenological data are used to understand the lived experience [23]. The phenomenological orientation focuses on the '*what…?*', and the '*how…?*', seeking the individual meaning and making sense of a particular experience. The data collection process is guided by avoiding manipulative, leading, or closed-ended questions, and is characterised by allowing participants to express their experiences freely and authentically [23]. Phenomenological data were collected during the final phase of data collection to enable the gathering of longitudinally rich insights. Questions (*not questionnaire*) used for collecting phenomenological data are presented in the supplementary material (SM.4).

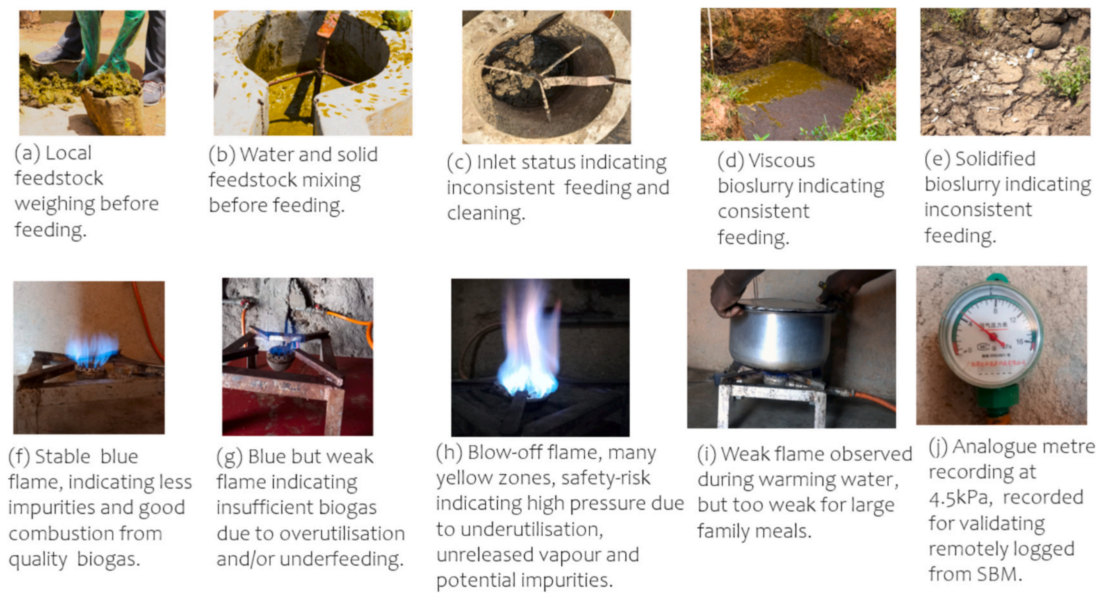

Fig. 3. Samples of observational data collected during the research field visits.

3.5. Data analysis

The research methodology (Realism) underpinning this work recognises objective realities of empirical data and interpretations of qualitative and phenomenological data. Thus, data analysis involved two main complimentary methods: The pattern analysis and interpretive phenomenological analysis.

3.5.1. Pattern analysis (PA)

The pattern analysis approach has been used by different scholars to study energy usage at HH levels for different research purposes. Klein et al. [35] used PA to investigate how employment routines influence recreational activities and energy consumption at HHs. Their findings indicated that pattern analysis uncovers latent patterns and goes beyond monetary dimensions [35]. Further, Chen et al. [36] indicate that the pattern analysis of energy usage at HHs enhance understanding of household energy consumption and user behaviour.

Owing to the detailed nature of this study, pattern analysis was employed to examine variations in biogas utilisation patterns across the four participating HHs. Analysis of patterns focused more on data logged from smart metres not to quantify the performance in a predictive or statistical sense, but to uncover biogas system utilisation behaviours and how they are affected by daily HH livelihoods. Fig. 4 and Fig. 5 are used to exemplify and explain the variables of interest for pattern analysis in this study. The average instantaneous static biogas pressure measured in kilopascal (kPa) is used to indicate and allow for analysis of the patterns of biogas pressure in the biogas holder. The average biogas flow rate measured in cubic metres per hour (m^3/h) is used to indicate and allow for analysis of patterns of the biogas flow from the biogas holder to the cooking stove (burner) during a specific cooking event. The average biogas consumption measured in cubic metres (m^3) is used to indicate and allows for analysis of biogas utilisation levels in a specific time frame, at a specific HH.

By analysing the patterns of these variables, Fig. 4 is used to explain

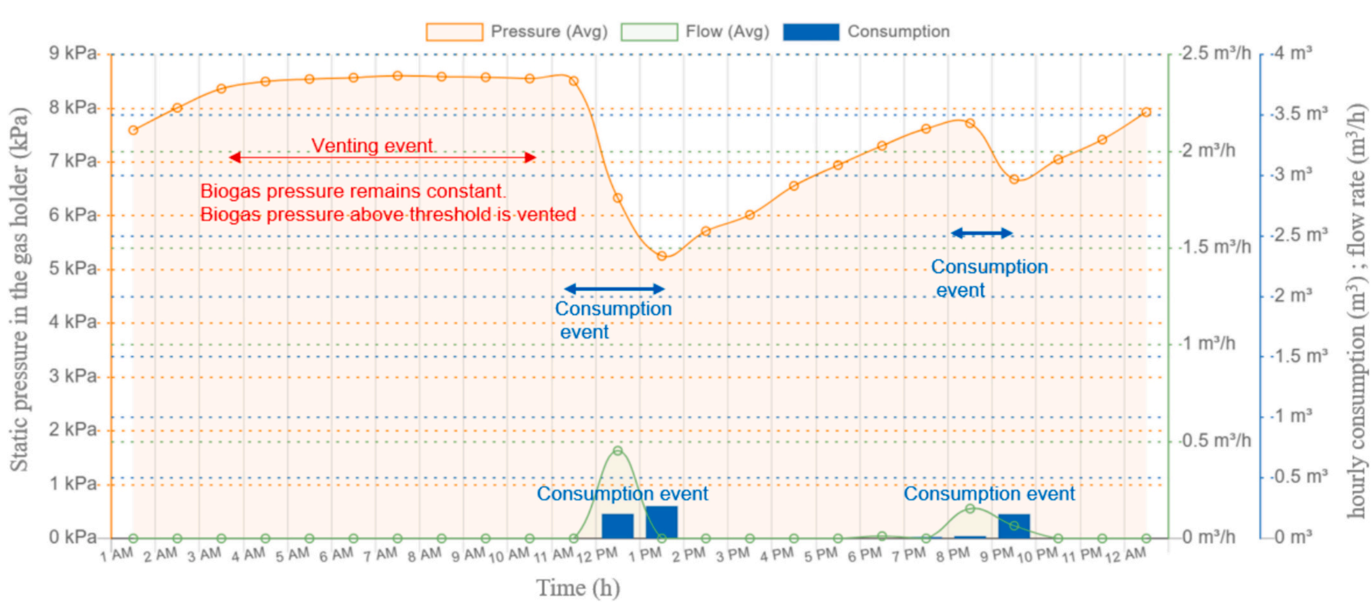

Fig. 4. Biogas underutilisation patterns leading to venting.

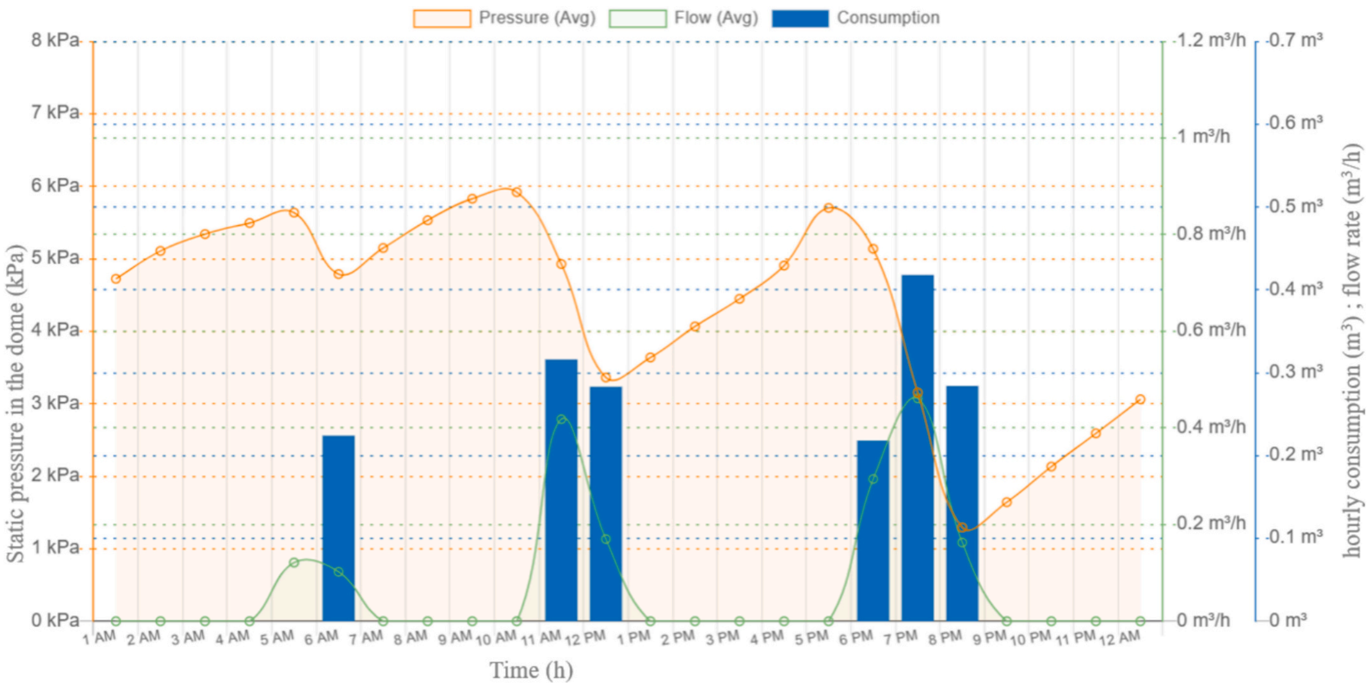

Fig. 5. Recommended biogas utilisation patterns keeping the SBP in a recommended utilisation range.

venting events from a sampled underutilisation pattern in a time frame of 24 h. At this particular day, the HH coded as '*EKF*' did not use biogas for cooking breakfast, and a small amount of biogas was used for tea while other meals were cooked by fuelwood. On the contrary, a recommended daily biogas usage pattern was observed at the HH coded '*SJB*' where three cooking events in a 24-h time frame kept the SBP in the recommended range, as presented in Fig. 5. Monitoring these events over a seven-month period allowed for a comprehensive pattern analysis. Further, using the smart biogas metres with machine learning algorithms, described in supplementary material, each HH's daily biogas consumption and venting were recorded, and the average values were calculated using Eq. (1) and Eq. (2).

$$\overline{v} = \frac{\sum_{d=1}^{D} v_d}{D} \tag{1}$$

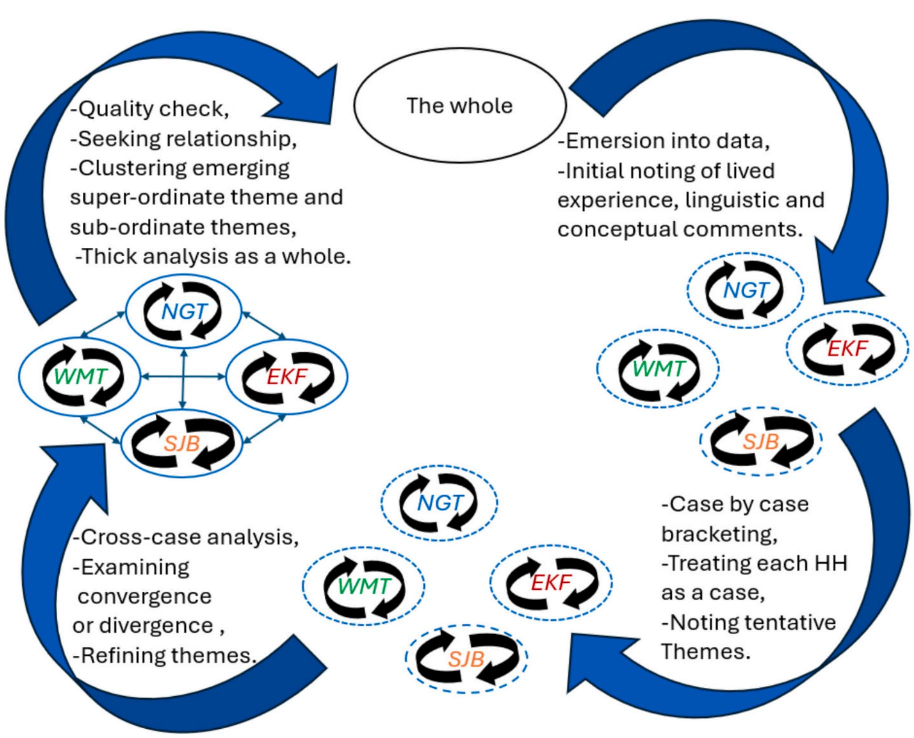

Fig. 6. Hermeneutic circles used in the interpretive phenomenological analysis [38].

$$\overline{c} = \frac{\sum_{d=1}^{D} c_d}{D} \tag{2}$$

Where $\overline{v}$ is the average vented biogas per day (m^3), $\overline{c}$ is the average consumed biogas per day (m^3), v_d is total daily biogas vented (m^3), c_d is the total daily biogas consumed (m^3), D is the total number of days in a specific month.

3.5.2. Interpretive phenomenological analysis (IPA)

IPA is commonly used in healthcare and education studies and is increasingly being applied to explore lived experiences in other disciplines. Mbekezeli et al. [37] applied IPA to study blended librarianship, while Van den Berg et al. [38] applied IPA to study circular design experiences in construction. Phenomenological methodologies (descriptive or interpretive) differ depending on their commitments but they all agree on the significance of studying experiences and their meanings [39]. This study used interpretive phenomenological approach, describing objects beyond words in conversation and puts them into context–the interpretive hermeneutics whereby the researcher '*mediates*' interpretations from diverse meanings [38]. Thus, '*hermeneutic circles*' in Fig. 6 were used to explore holistic meanings of the technology user lived experience – the holism. The cyclic arrows signify iterative reading of notes and interpretations. This allows for the emersion into the notes and transcripts. Dashed outline signifies openness to include new information and data until thematic saturation is reached, thus allowing for updating new information, hence avoiding premature themes. The solid lines around HHs signifies reaching thematic saturation, a final stage where any information falls within the established themes. The network of arrows signifies the seeking of relationships between themes and treating parts as a whole, allowing for interpretation of the findings in a broader context.

While coding software or mind-mapping can be valuable in large-sample studies, their application to depth-oriented analysis carries the risk of disaggregating narrative coherence and reducing contextual sensitivity. Thus, given the small number of households and the depth-oriented nature of this study, the IPA followed a manual analysis process. The manual, diary-informed process allowed for immersion into the data, facilitating a holistic interpretation of each HH's context through *hermeneutic circles* encompassing four different but linked stages: (a) stage one involved reading of transcripts, observation notes and diarised reflex memos; (b) stage two involved the bracketing of emerging information case by case, treating each HH as case and condensing notes into tentative emerging super/sub-ordinate themes; (c) stage three involved cross-case analysis, examining convergence or divergence, and refining super/sub-ordinate themes; (d) stage four involved quality checking, seeking related themes, clustering sub-ordinate themes to form super-ordinate theme.

3.5.3. Integrated data analysis

The integrated data analysis proceeded in three stages: in the first stage, a descriptive profile of each HH, obtained from the semi-structure interviews, were compiled to capture each HH livelihood characteristics together with daily biogas utilisation patterns. These profiles served as the foundation for subsequent analyses. In the second stage, pattern analysis was conducted in parallel with interpretative phenomenological analysis, as well as reflecting on each HH's descriptive profile. In the final stage, an integrated data analysis was conducted by aligning each HH's descriptive profile with the episodes identified through pattern analysis and the experiential themes from the interpretative phenomenological analysis, hence allowing for explanation of the HBT use within the lived realities of the HH livelihoods. This manual process was done by using the table presented in supplementary material SM.6.

4. Results and analysis

This section presents the findings of the study in three sub-sections. First, descriptive results are presented in 4.1 to summarise HH livelihoods and recorded system outputs. Second, thematic results are presented in 4.2 to explain how the system outputs (HBT use) are situated within HHs' experiences and livelihood contexts, thereby answering Research Question 1 (RQ_1). Third, in the context of answering Research Question two (RQ_2), lessons learned are presented in 4.3.

4.1. Descriptive results

All HHs recruited for this study shared several baseline characteristics that qualified them for biodigester installation. They were all engaged in farming, owned at least three cows required for feedstock supply, had reliable access to water, and were formally linked to community groups or leadership of local associations. These commonalities ensured that each HH met the technical and social prerequisites for HBT installation and use.

Despite these similarities, differences were observed across the recruited HHs. Household size ranged from three members in '*EKF*' to eleven members in '*SJB*', with varying proportions of children and working-age adults. The ages of household heads also differed, with '*WMT*' and '*EKF*' led by individuals over 60 years, '*NGT*' in the mid-50s, and 'SJB' the youngest at 48 years. Educational backgrounds varied, with '*WMT*' and '*EKF*' reporting primary-level education, while 'SJB' had attained high school. At the time of this study, three HH heads were retired, while the head of '*SJB'* remained active as an artisan alongside farming.

Farming practices further distinguished the HHs. Two of four HHs reared cows and cultivated crops on their consolidated landholdings while other two cultivated fragmented plots and reared cows at their homesteads. Differences were observed in the number of cows and their rearing practices. In terms of system performance, the descriptive data indicated that all HHs utilised biogas daily, although to different extents. Recorded utilisation ranged between 0.92 m^3 and 3.80 m^3 per day, while venting volumes varied between 0.04 m^3 and 0.39 m^3 per day. This variation across HHs indicated that although all systems were functional, their day-to-day operation differed depending on individual HH livelihoods. The descriptive findings, presented in Table. 1, outline both the shared baseline features and the diversity of HH profiles, establishing the foundation for the subsequent results analysis.

4.2. Thematic results

Through the integrated data analysis described in *sub-section 3.5.3*, twelve sub-ordinate themes were identified and clustered into four super-ordinate themes: *HH land ownership, Season-dependence, Family structures and Off-farm activities*. These thematic results are presented in Table. 2 and analysed in the subsequent sub-sections (*4.2.1–4.2.1)*.

4.2.1. HH land ownership

HHs owning consolidated land, used for both crop production and animal husbandry resided at their farms. This provided sufficient time to operate and use the technology consistently, leading to better HH biogas system use.

"…my farm (3.5 hectares) is consolidated here (where the family stays) … all my farming activities are done here…, you can see (as we toured the farm) the grass here (as we moved around and showing Napier grass planted all over) are enough for even more than the four cows we own…" EKF.

On the contrary, HHs using fragmented land distributed across multiple locations faced challenges in regularly managing and operating their biogas systems. Crop production was carried out on leased parcels of land distant from the homestead while livestock, particularly cows, were kept at the HH compound. This separation led to inconsistencies in digester feeding, system maintenance, and the overall production and

Table 1
Descriptive profiles of the participating households.

HH code	*EKF*	*WMT*	*SJB*	*NGT*
Location (province)	Eastern	Western	Southern	Northern
HH size (age range)	3 (adults), sometimes 4 (when the son comes for university holidays)	8 (3 less than 14 years old)	11 (4 less than 14 years old)	7 (4 less than 14 years old)
Family head (gender, age, and education).	Male (64, primary 6).	Female (68, secondary education).	Male (48, primary 8, equivalent to current Rwandan middle school).	Male (61, basic primary education).
Professional training	Masonry	Non	Woodwork artisan	Security service
Number of cows	4 kept through the study period (7 months)	4 at the beginning of the study but relocated 2 and remained with 2 at the HH residence.	4 kept through the study period (7 months)	4 kept through the study period (7 months) but at times moved them out in search of extra pastures.
Farming practice and land size.	Mixed farming, practiced on consolidated land (3.5 ha), cows kept indoors.	Mixed farming, fragmented, cows kept indoor at residence plot (40 by 25 m), and crop farming done at distant and leased plots.	Mixed farming, practiced on consolidated land (3 ha), cows kept indoors.	Mixed, fragmented, cows kept indoor at residence plot (25 by 45), and crop farming done at distant and leased plots.
Average monthly income (Rwandan Francs)	150,000–200,000	100,000–150,000	200,000–300, 000	100,000 –180,000
Status of employment	Retired mason	Retired (self-employed in informal sector)	Active woodwork artisan	Retired security personnel
Source of income	Farming and financial schemes	Farming and financial schemes	Farming and financial schemes	Farming, financial scheme and woodwork
Social status and networks	A village leader (voluntary leadership role for basic unit of local government)	Opinion leader in local women financial and social schemes	Opinion leader in at village level	Participates in livestock farming associations
Reason for selection to win a HH biogas plant	Approached by the local veterinary officer, having minimum required number of cows (3), keeping them at home, reliable source of water and having water tank, being active in local social structures, committed to maintaining the technology.	Having the minimum required number of cows (3), keeping them at home, reliable source of water, active in local social structures, committed to maintaining the technology.	Having the minimum required number of cows (3), keeping them at home, reliable source of water, being active in local social structures, committed to maintaining the technology.	Having the minimum required number of cows (3), keeping them at home, reliable source of water, being active in local social structures, committed to maintaining the technology.
Other household assets	Own house, communication sets (TV and Radio).	Own house, communication sets (TV and Radio).	Own house, communication sets (TV and Radio).	Own house, communication sets (TV and Radio).
Type (size of biodigester)	Fixed dome (8m^3)	Fixed dome (8m^3)	Fixed dome (8m^3)	Fixed dome (8m^3)
Source of feedstock	Cow dung	Cow dung	Cow dung	Cow dung
Access to water	Reliable piped water, and rain harvest water tank.	Reliable piped water, and rain harvest water tank.	Reliable piped water, and rain harvest water tank.	Reliable piped water, and rain harvest water tank.
Other sources of energy (end-use)	Fuel wood and biogas (cooking), electricity (lighting, powering electronic devices)	Fuel wood and biogas (cooking), electricity (lighting, powering electronic devices)	Fuel wood and biogas (cooking), electricity (lighting, powering electronic devices)	Fuel wood and biogas (cooking), electricity (lighting, powering electronic devices)
Daily biogas venting range, calculated from monthly venting data using Eq. (3)	0.15–*0.39 m^3*	0.04–*0.22 m^3*	0.1–0.3 m^3	0.04–*0.20 m^3*
Daily biogas consumption range, calculated from monthly data using Eq. (4)	*3.0–3.50 m^3*	*0.92–2.30 m^3*	*3.6–3.80 m^3*	*1.2–2.40 m^3*

use of biogas.

"...we were given instruction how to use it (biogas plant), feed it, and periodically empty the compost pit ... but I must be honest ... I have left this to this guy (a farm worker who takes care of cows) ... he keeps moving between here and there ... I honestly do pity him… he is sometimes overstretched …" WMT.

The IPA indicated that HHs with consolidated land to accommodate their family residence, livestock, and crop production on a single plot lived an agrarian livelihood with an integrated mixed farming practices allowing the necessary stability and proximity to manage and utilise the household biogas technology. This was further confirmed from logged data, presented in Fig. 7, showing that the average daily biogas consumption at '*SJB*' and '*EKF*' from 1st June and 31st December 2024 ranged between *3.6 and 3.8 m^3* and between *3.0 and 3.5 m^3*, respectively. On the contrary, '*WMT*' and '*NGT*' managed their livestock on relatively small plots of land hosting their residence, while cultivating crops on separate and distant leased parcels. Fodders were sourced by manually collecting grass from these fragmented plots, necessitating frequent travel between locations. This spatial fragmentation results into a considerable time expenditure and contributed to inconsistencies in the feeding and maintenance of the biodigesters. Results show that the average daily biogas consumption at '*WMT*' and '*NGT*' from 1st June and 31st December 2024 ranged from *0.92 to 2.3 m^3*, and from *1.2 to 2.4 m^3*, respectively.

4.2.2. Season-dependence

During the dry season (late June to early October), HHs with fragmented land parcels faced additional constraints in accessing livestock

Table 2
Super-ordinate themes and their sub-ordinate components derived from data analysis.

Super-ordinate themes	Sub-ordinate themes
HH land ownership:	Size of the land owned
	Proximity of the farming land to the HHs
	Methods of farming
Season-dependence:	Fluctuations in the number of livestock
	Changes in meals preferences and the cooking practices
	Changes in social activities
Family structures:	Number of HH family members
	Age composition of the HH family members
	Role distribution in the HH family members
Off-farm activities:	Community roles
	Social capital
	Indirect /direct benefits

feed. This increased time required for searching and collecting livestock fodder leading to inconsistency in operating biodigesters. During site selection phase, '*WMT*' had four cows but during the dry season, the HH remained with only two cows at their residence while the other cows were relocated. This led to insufficient feedstock and affected biogas production, leading to a decrease in biogas production and usage as shown in Fig. 7. The same constraint was witnessed at HH '*NGT*' where the number of cows did not reduce but were frequently moved out during the dry season for outdoor grazing in the neighbourhoods, leading to difficulties in collecting the cow dung.

"... do you remember the first time you came here? (the time during site selection) ... we had four cows ... but it becomes difficult in dry seasons to keep all of them here (at the family residence), ... the number cows we keep here changes depending on the season ..." WMT.

Although '*EKF*' maintained consistent operation of their biodigester, biogas consumption declined between August and October 2024. During this period, the neighbouring HHs who previously came to cook on this particular HH's biogas visited less frequently. The decline in the shared use of biogas was due to an increased availability of fuelwood during the dry season, compared to its scarcity during the rainy months.

"... when we at home, we call neighbours to cook on our biogas when it becomes much (high static pressure) ... because we monitor its level here (as he points at analogue pressure gauge installed) ... sometimes they help in feeding ... now (late august 2024) they have plenty of firewood collected over this dry season ..." EKF.

Another factor that contributed to the drop in the consumption during the dry season (July–October) was the seasonal meals preferences. Dominant meals during this season came from flour of sun-dried corn and tubers. Such meals included mingled corn flour, locally known as '*kawunga*', cassava flour, locally known as '*ubugali*', which requires continuous physical mingling and stirring not supported by the installed biogas stove structures while dry beans required higher firepower than the HH biogas system could provide.

Further, after the harvesting period (June–July), as HHs waited for the next ploughing period (mid-October - November), there was a noticeable change of social lifestyles, whereby the frequency of attending wedding parties, visiting extended families (a noticeable culture in Rwanda), and other social events increased. Field visits had to be prebooked during the dry season, in contrast to the rainy seasons when HH heads were available for discussions even at randomised field visits. The shift in lifestyles increased absence at home, leading to intermittent inconsistency in feeding and operation, hence a noticeable reduction in biogas production and consumption for '*EKF*', '*NGT*' and '*WMT*'.

"... you are lucky to find me here today (with a smile). During this period, we do not have much work except feeding cows, normally done by the farm worker ... I have weddings to attend almost every week ..." EKF.

4.2.3. Family structures

HHs dominated by school-aged children boarding at schools showed lower levels of daily participation in biogas system operation and maintenance. Worse still, the June–September school holidays coincided with the dry season characterised by a reduced supply of biodigester feedstock but increase in supply of fuel wood. This increased the use fuel wood, and biogas was selectively used only to cook tea, porridge and other light meals. This pattern of utilisation was evident, particularly at *'WMT'*, where biogas consumption dropped sharply despite increased cooking needs during the school holidays. Fig. 7 shows the fluctuations in gas consumption reflecting this phenomenon, emphasising the critical interplay between HH demographics and system performance.

"... we mostly use fuelwood for cooking in this period because of biogas

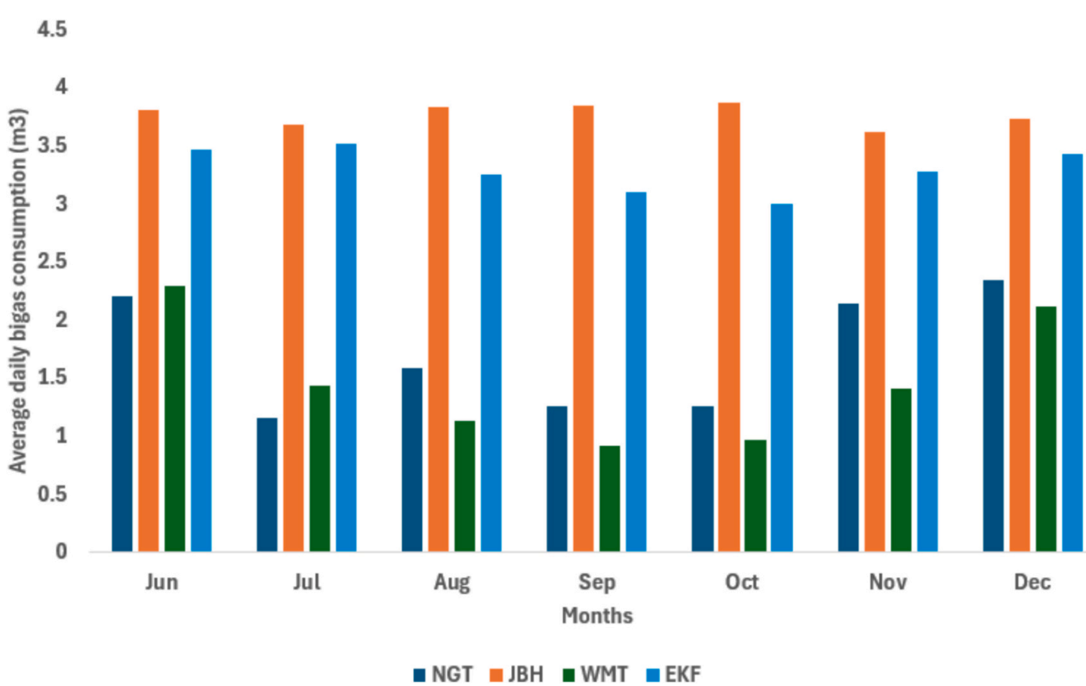

Fig. 7. Average daily biogas use per household and month during the data collection period.

cannot cook for all of us in holidays, but because these other guys (extended family young ones) are not at school, they frequently cook tea and porridge using biogas ..." *WMT.*

Family composition with mixed multi-age structures and shared labour roles demonstrated consistency in system operation and maintenance. The presence of non-schooling members enabled regular feeding of the digester and timely maintenance activities. This reduced the risk of operational lapses, improved biogas availability, and uninterrupted biogas utilisation. This was evidenced at '*SJB*' where biogas utilisation showed less fluctuations in the seven months. Kids at this particular HH studied at nearby day-schools, and the HH employed two farm workers. The two farm workers operated the biodigester consistently and day-schooling of kids kept biogas consumption relatively constant compared to the rest of the HHs as depicted in Fig. 7.

"*... I am an artisan ... I spend much of my time at home working on this woodcraft (as he showed his woodwork) ..., so, I supervise the feeding ... when I am not around, these two guys (two farm workers) feed the biogas (biodigester) and empty the compost pit to put the manure (bioslurry) in the crop farm (where they grow crops) ... my wife is good at remembering to clean the stove and removes the vapour through this thing (pointing at the valve designed purposely for vapour release) ...*" *SJB.*

4.2.4. Off-farm activities

Beyond household structure and labour availability, competing social obligations of HH heads influenced the use of HBT. Although the heads of the HHs were not employed in the formal sector, they were actively involved in various community roles and local social networks, including village committees and agriculture cooperatives. These engagements often brought social capital and indirect economic benefits. However, in situations where the family structure could not compensate for the absence of the HH head, particularly in HBT operation management tasks, the operation of the system was affected. Time constraints and shifting priorities led to irregular and untimely feeding schedules, resulting in inconsistent production and use. Moreover, HH heads tended to maintain stronger ties with alternative fuel sources, such as fuelwood and charcoal which were readily available from nearby trading centres. This created a behavioural fallback. When biogas production declined, rather than working on improving the biogas system, they increased the use of fuelwood.

"*... I do partake and sometimes lead different roles in our local village women financial schemes [...], and other eldership commitments in the village ..., the person who looks after cows can sometimes be overstretched. In the evening, because I do not trust the available biogas, I ask some guys to bring me a bundle of fuelwood on my way to home ...*" *WMT.*

On the contrary, '*EKF*' leveraged his involvement in local agricultural cooperatives, and community associations to strengthen HBT performance and continuity. Social networks were used to accesses casual labour from the neighbourhood ensuring a more stable feeding biogas usage, and these strong social networks allowed for engagement with local agriculture and environment officers. '*EKF*' served as informal advocate for the HBT within the community and maintained high satisfaction with the HBT due to the HH's role in local knowledge exchange by allowing neighbouring HHs to come and cook using the HH biogas when it was produced in surplus. This suggests that when social resources are well aligned with household human resources and the technology operation requirements, it can be a reinforcing factor for decentralised HH biogas systems.

"*... when bigas approaches 8 (8 kPa as he pointed at the analogue gauge metre) ... we call our neighbours to cook on our biogas whenever we do not intend to cook with biogas the same day ... I have demonstrated how to use the technology. They sometimes help in feeding even when I am not around, and they have shown interest in the technology ...*" *EKF.*

4.3. Lessons learned

Using triangulated data analysis, this study revealed key lessons, thereby addressing RQ_2. In contrast to other clean cooking technologies which can be used immediately after purchase, HBT requires sustained HH labour beyond the initial capital investment. Consistent feeding, vapour release through dedicated valves, breaking of the scum layer, cleaning of the bioslurry passage and a proper feed stock mixing ratio affected the biogas production. Having enough HH labour and sufficient biogas production, however, did not translate into complete displacement of solid biofuels. Preferences in preparing local staple foods contributed to uneven or sub-optimal biogas utilisation, as households often preferred solid biofuels for cooking traditional meals. Locally fabricated biogas stoves lacked the physical capacity to support the preparation of staple foods such as *kawunga* (maize-based cornbread) and *ubugali* (cassava flour bread) requiring continuous stirring and physical manipulation not supported by the locally fabricated and installed biogas stove structures. This resulted in underutilisation of produced biogas and, hence, biogas venting. The venting patterns presented in Fig. 8 were recorded across the participating HHs where the average daily biogas venting ranged between 0.04 *and* $0.39\ m^3$, representing 4–9 % of the total daily biogas produced.

5. Discussion

This study examines how household livelihoods affect the use of household biogas technology. The following sub-sections discuss findings of the study in relation to the existing literature, highlighting the study's contributions and practical policy implications. Limitations of are also acknowledged, suggesting directions for potential future research.

5.1. Contribution to the literature and policy implications

The application of the household livelihoods framework as an analytical lens reveals that households within similar financial categories do not necessarily use household biogas technology (HBT) with the same level of effectiveness. Differences in technology utilisation are shaped by the specific household livelihoods affecting daily technology operations. While the existing literature often identifies financial constraints as a major barrier to the success of HBT [5], this study highlight that financial capacity does not necessarily translates into effective use of the technology. The findings, indicating that specific household livelihood shape the technology use, are in line with Nalunga et al. [17], reporting that a critical assessment of HH labour dynamics is essential prior to diffusion of HBT into communities. Thus, policies on HBT diffusion ought to consider a deeper analysis of HH dynamics to enhance effective HBT use.

The role of land ownership and the proximity of the land to the HH residence played an important role for the technology use. HHs depending on consolidated farmlands around their residence spent more time at home, allowing for regular biodigester feeding and other HBT operations. In contrast, HHs with fragmented plots, located away from their residence, spent much of the day away attending to dispersed crop cultivation activities. The daily absence limited the consistence in HBT operation and maintenance, hence contributing to inconsistent biogas production and use. This is in line with findings in the literature indicating that integrating HBT into agriculture and national manure management policies leads to considerable HBT success [40].

While none of the HH heads were formally employed, all HH heads were actively involved in community groups and informal leadership roles. In cases where HH labour could not compensate for their absence, these external commitments led to a neglect of the HBT operation. However, other social engagement had enabling effects, e.g., '*EKF*' used local engagements to share biogas with neighbours when there was a biogas surplus, providing short-time casual labour for technology operations and promoting HBT knowledge. The two cases highlight how HHs' social capital can both constrain or support HBT sustained use depending on context. The social obligations linked to HHs social

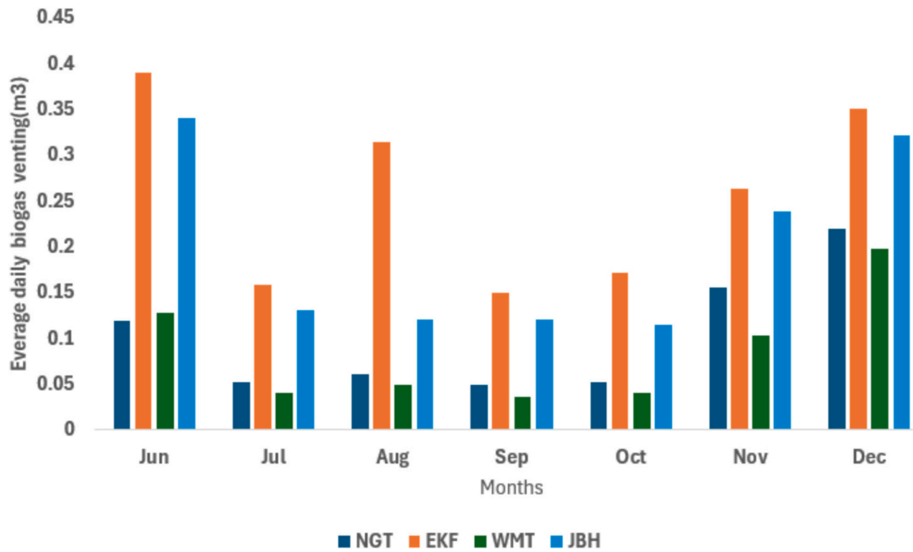

Fig. 8. Average daily biogas vented per household and month during the data collection period.

resources shaped HBT use behaviours. This aligns with and responds to the necessity of conducting inquiry with community-embedded approaches, which reflect deeply on HBT use in Africa [8]. Policies on technology adoption and its sustained use should be designed with a bottom-up approach, reflecting household and livelihood contexts, rather than imposing top-down strategies.

Sufficiency of biogas at some HHs did not stop the use of fuelwood for cooking, and none of the participating households achieved full substitution of traditional fuels. Biogas was selectively used, often limited to meals that fit within the design constraints of locally fabricated stoves. This counterargues the viewpoint that the use of bigger biodigesters can improve the overall HBT efficiency. For example, a critical review on the Rwanda's National Domestic Biogas Programme show that a 10 m^3 can meet 104 % of required Rwanda's HH cooking energy (equivalent to 31 MJ or 4.5m^3 per day per HH) [29]. However, our study show that availability of biogas does not necessarily translate into solid biomass fuel replacement when the technology is not well aligned with the local cooking practices. The findings of our study are consistent with findings from a study conducted in Uganda indicating that biogas stoves were limited to specific sizes of pots not suitable for cooking Ugandan's staple food and thus only suitable for cooking light food [41]. Developing customised biogas stoves can potentially enhance the effective use of HBT.

The selective use of biogas for cooking specific meals resulted into underutilisation of the produced biogas use, leading to biogas venting. The quantitative findings in this study add to the qualitative findings by Robinson et al. [13] reporting significant biogas venting in what they called "*opening a pandora box*", signifying a research gap in studies on this phenomenon in the SSA context, a gap that this study attempted to fill by using HH livelihoods as analytical framework. The findings of this study also align with existing literature suggesting that integrating sensor-based approaches with qualitative methods enhances understanding of household biogas technology (HBT) use, going beyond earlier approaches that relied mainly on periodic surveys or focused exclusively on technical parameters [14].

5.2. Reflection on gender and HH biogas systems

While this study did not explicitly aim to analyse gender dynamics, field observations revealed consistent gendered divisions of labour in the operation and maintenance of household biogas systems. In most cases, women were responsible for routine tasks such as cleaning the stoves and releasing vapour from the gas pipes, while male household heads tended to lead major decisions related to the systems such as feeding cows.

"*... my wife is good at remembering to clean the stove and removes the vapour through this thing (pointing at the valve designed purposely for vapour release) ...*" *SJB.*

This aligns with broader evidence from rural sub-Saharan Africa indicating that women often bear the day-to-day operational responsibilities of household energy technologies for cooking, whereas men retain greater influence over strategic decisions and resource allocation [42]. These roles did not emerge as a primary theme in our analysis but acknowledging them is crucial for the understanding of the practical and social contexts in which HH biogas technology is utilised.

5.3. Limitations and potential further studies

Although this study employed triangulation of data combining interviews, observations, logged system data, and phenomenological inquiry to generate an in-depth and contextually transferable analysis, it was subject to practical limitations. The small number of participating households and the uniformity in biodigester size constrained variability, limiting comparison across the range of family-sized systems used in Rwanda. Consequently, while the study offers a deeper understanding of household biogas use, the findings may not capture the performance of households operating biodigesters of different sizes. Further studies using the same approach but using biodigesters of different sizes can enhance further the understanding of how HH livelihoods influence biogas technology use across different technology settings. This can potentially validate and refine the findings of this study.

This research did not include technical investigations into aspects such as biogas stove thermal analysis and performance or gas purification methods due to budget and infrastructure limitations. Investigating these two aspects with a contextualised approach is critical to the understanding of how effective and sustainable the HBT can be in the framework of clean cooking. Such an investigation can provide empirical evidence in line with local cooking needs, preferences, and practices, as well as how cost-effective biogas purification technologies might enhance usability, and user satisfaction. Exploring these technical dimensions alongside livelihood and social factors can offer a more comprehensive understanding of how to support long-term HH biogas use and its impact. Conducting such technical investigation from a pre- and post-installation perspective would allow for generating comprehensive results on the cost-benefit analysis of the technology.

The smart metres used had no technical capability to record parameters influential to biodigester health (e.g. internal temperatures and pH levels), thus not allowing them to be synchronised with the biogas utilisation readings. This somehow limits the certainty in attributing biogas utilisation patterns solely to household livelihood factors. Developing deployable smart metres with technical capability of integrating these parameters would refine and enhance results of this study.

6. Conclusions

All participating HHs owned land under emphyteutic lease but the proximity of the land to the HH residence and size of the land owned at their residence influenced the methods and type of farming, the latter distinguishing the HBT use across the HHs. The seasonal variability affected fluctuations in livestock numbers, shifts in cooking practices, and changes in social activities, all of which varied across HHs and affected the use of household biogas technologies (HBT) differently. Family structures, particularly age composition and roles allocation within HHs members had a notable effect on the use of the HBT. The off-farm activities, notably community roles were found to be linked to social capital and indirect economic benefits, all of which influenced how each HH used the technology depending on how these activities were aligned with the households human resources and the technology operation requirements.

It can be concluded that assessing individual HH livelihood dynamics prior to deploying the HH biogas plant is essential to its effective use. National target-driven diffusion into communities without such a bottom-up assessment is likely to lead to unsustainable use of the technology. Technology users complained of weak firepower provided by biogas. Developing cost-effective biogas purification to enhance methane levels would improve the thermal output of the HH biogas systems. Unless biogas stove design and the entire biogas system are aligned with local cooking needs and practices, biogas will continue to serve as a supplementary rather than primary energy source for cooking, regardless of the technology's available potentials, leading to venting, and hence jeopardising the environmental benefits of the technology.

CRediT authorship contribution statement

James Ntaganda: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Erik O. Ahlgren:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

Authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.104443.

Data availability

Data has been provided in the supplementary material except data revealing participants' assured privacy and confidentiality such as photos of meals, faces of participants, HH's livestock and other culturally sensitive data.

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