Thesis for the Degree of Licentiate of Engineering

From Dung to Joules: Household Biogas Production and Use as a Socio-Technical System in Rwanda

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Gothenburg, Sweden 2026

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Abstract

Household-scale biogas technology is widely designed and promoted as a decentralised clean-cooking intervention in energy-poor communities. It is promoted in the framework of advancing Sustainable Development Goal 7 (SDG 7), particularly its indicator SDG 7.1.2 which tracks the proportion of the population with primary reliance on clean fuels and technologies for cooking. Beyond potential cooking fuel substitution, biogas systems can generate context-specific co-benefits: improved bio nutrient recycling through bio-slurry use for improved crop production (SDG 2), reduced exposure to household air pollution in cooking areas (SDG 3), time saving that may support women's economic and educational opportunities where cooking and fuel collection are gendered responsibilities (SDG 5), capturing methane emissions from enteric fermentation of unmanaged cow dung (SDG 13), and reducing pressure on forests associated with tree cutting for cooking fuelwood (SDG 15). Despite these promises, evidence from the sub-Saharan Africa indicate that the sustained use and functionality of the technology are limited, thereby constraining its expected benefits in a region with substantial clean-cooking access deficits. Existing literature provides limited explanation for why widespread deployment of small-scale biogas systems has not delivered anticipated benefits, especially regarding the influence of household livelihoods on technology use.

Using Rwanda as a case for the study, this thesis addresses this gap by analysing household biogas technology as a socio-technical system. The main body of the thesis is developed through two complementary analytical components: *(i)* a stratified survey that integrates thematic interpretation of user narratives with descriptive analysis of their closed-ended responses, and *(ii)* examination of behavioural, operational, and technology utilisation patterns interpreted through a household livelihoods framework. These core analyses are supported by two auxiliary mechanisms. First, a metering system was conceptualised and deployed to generate time-stamped traces of technology utilisation. Second, these utilisation traces were quantified to analyse household biogas consumption and venting, and the vented biogas was converted into household-level CO_2e estimates. Together, these approaches reveal behavioural and operational patterns that can undermine or promote the intended benefits of household biogas systems.

A countrywide survey revealed that about 9% of sampled household biogas plants remained fully functional, 70 % had been abandoned, while other plants remained in transitional conditions. Interpretive analysis from user narratives indicate that two themes dominated abandonment: *(i)* feasibility-assessment deficits arose where eligibility for household biogas support was reduced to oversimplified "*two heads cattle + access to water*" criterion, overlooking underlying household conditions and cross-sector policies that influence technology operation and use, *(ii)* unmet user expectations arising from insufficient raw biogas firepower, un expected labour requirements for the technologies daily operation, and limited mechanical robustness of locally fabricated biogas stoves which are often unsuitable for cooking Rwandan staple dishes. Triangulated analysis, interpreted through a household livelihood lens, revealed divergent patterns of technology utilisation. Regular operation and sustained use of the system were more feasible in households where cattle were kept indoors on consolidated land, with reliable water access and stable year-round household composition, whereas fragmented landholdings and fluctuating household size reduced available labour, constrained operation and biogas output, hence leading to intermittent system use. Where household biogas systems were sustained, the continued use appeared to be influenced by: the perceived agronomic benefits of bioslurry within mixed crop–livestock systems, improved kitchen cleanliness, and the relatively faster ignition process of biogas compared to firewood or charcoal for preparing light breakfasts under morning time constraints. Longitudinally metered data revealed heterogeneous patterns of biogas utilisation across households, including periods of underutilisation resulting in venting and associated greenhouse gas emissions. The monthly average emissions from HHs using $8m^3$ biodigester were estimated at ≈ 33–56 kg CO_2e per household per month (≈ 0.4–0.7 tCO_2e per household per year). Nevertheless, underutilisation did not necessarily imply the availability of surplus biogas following the satisfaction of household cooking energy demand or the complete substitution of conventional fuels. Instead, biogas was used selectively for certain dishes, while fuelwood or charcoal remained in use for others, resulting in only partial displacement of solid biomass fuels. This underscores the centrality of household livelihood dynamics within technology-user communities in shaping the design of more context-responsive clean cooking interventions, programmes, and policies.

List of papers

This thesis takes an integrative perspective on the following appended papers, cited in the text by Roman numerals (I–IV), and examines their collectively implication.

I. Ntaganda J., Ahlgren E. O, “Adoption and abandonment of household biogas technology as a process: examining expectations, post-adoption trajectories and lived experiences in Rwandan households,”. Resubmitted to the Journal (Under Peer review).

II. Ntaganda. J., Ahlgren E. O, “From animal waste to energy: exploring the effects of household livelihoods on biogas technology use in Rwanda,” *Energy Research & Social Science*, vol. 130, Art. no. 104443, 2025, doi: 10.1016/j.erss.2025.104443

III. Ntaganda J., Tamele B. Z. S., and Ahlgren E. O., “Biogas Venting from Household Biogas Technology Use in the Sub-Saharan Africa: Evidence from Rwandan Households as a Case,” *J. Sustain. Dev. Energy Water Environ. Syst.*, vol. 14, no. 1, article 1130631, 2025, doi: 10.13044/j.sdewes.d13.0631

IV. Ntaganda. J., Twahirwa. E., Gasore. G., Mukamugema. J., Mukashyaka. A., Niyonsaba. O., Tamele. B. Z. S., and Kabera. T., “Enhancing biogas production and use by remote data acquisition and analysis–Household biogas use in Rwanda as case for the study,” in *Proc. 2024 IEEE PES/IAS PowerAfrica (PAC)*, Johannesburg, South Africa, Oct. 2024, doi: 10.1109/PowerAfrica61624.2024.10759380

Authors contribution

Ntaganda J. is the principal author of ***papers (I-IV)***, and performed: literature review, research gap identification, research conceptualisation, data collection and analysis, manuscripts drafting, manuscript revisions, final editing and subsequent submissions. Ahlgren E. O. did the supervision, guidance and polishing research concepts, manuscript reviews, feedback, and editing for ***papers I, II and III***. Tamele. B. Z. S., contributed to discussion and editing for ***paper III***. Twahirwa E., Gasore G., Mukamugema J., Mukashyaka A., Niyonsaba O., Tamele B. Z. S., contributed to discussion during system designs and proofreading for ***paper IV***. Kabera T. did the supervision and contributed to discussion during system designs and proofreading for ***paper IV***.

Contribution to literature

This thesis contributes to the ongoing scholarly debates on the role and use of household biogas technology in advancing clean cooking transitions. It examines user perspectives, biogas production and use patterns, household-level dynamics and existing energy policies focusing on energy-poor communities–a triangulation not in available literature. While this thesis addresses the identified research gap, it also stimulates further inquiry. I invite you to engage with the chapters that constitute this thesis.

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List of abbreviations

Abbrev.	**Full term**	**Meaning in this thesis**
ABPP	Africa Biogas Partnership Programme	A public–private partnership initiative that installed household biogas digesters in collaboration with local enterprises, NGOs, and African governments
AEC	Alternative Energy Carrier	Non-biogas clean fuel used for cooking (e.g., LPG) when users switch or stack.
BCR	Benefit–Cost Ratio	Present value of benefits divided by present value of costs.
CAPEX	Capital Expenditure	Up-front investment costs (e.g., digester, stove, purification).
CA	Content Analysis	Qualitative method to structure raw text prior to theme building
CBA	Cost–Benefit Analysis	Economic appraisal framework to be used in the PhD extension from licentiate work.
CH_4	Methane	Principal energy component of biogas needed for combustion, but also key driver of CO_2e in venting.
CO_2e	Carbon-dioxide equivalent	Standardised emissions metric (venting to CO_2e using GWP).
CMO	Context–Mechanism–Outcome	Realist synthesis pattern used to explain sustained/abandoned use of biogas systems.
DHT22	Digital Humidity/Temperature 22	Ambient temp/humidity sensor in the telemetry stack.
EDCL	Energy Development Corporation Limited	Rwandan energy agency involved in national energy programmes coordination.
ESP32	Espressif ESP32	Low-power microcontroller used for IoT data logging.
FA	Feasibility Assessment	Household-level eligibility appraisal
GHG	Greenhouse Gas	Atmospheric gases contributing to warming (e.g., CO_2, CH_4).
GWP	Global Warming Potential	Factor used to convert GHGs (e.g. CH_4) to CO_2e over a time horizon.

Abbrev.	**Full term**	**Meaning in this thesis**
HBT/HHBT	Household Biogas Technology	Household-scale anaerobic digestion system and appliances.
HH	Household	Unit of analysis for adoption, use and telemetry.
H_2S	Hydrogen Sulphide	Corrosive biogas contaminant; targeted by purification options.
IAQ/IAP	Indoor Air Quality / Pollution	Health dimension impacted by clean cooking transitions.
IPA	Interpretative Phenomenological Analysis	Method to interpret lived experiences.
IoT	Internet of Things	Low-power telemetry for pressure/flow and digester-use traces.
IRR	Internal Rate of Return	Discount rate that sets NPV to zero (CBA metric).
KPI	Key Performance Indicator	Programme metrics: use continuity, cooking demand coverage, venting ratio.
LMIC	Low- and Middle-Income Country	Country context for many biogas deployments, incl. Rwanda.
LPG	Liquefied Petroleum Gas	Alternative clean cooking fuel; sometimes replaces biogas.
M&E	Monitoring and Evaluation	Programme follow-up; weaknesses linked to "assumed users."
MIPA	Mixed Interpretive Phenomenological Analysis	Heuristic combining CA, TA, IPA with theme frequency.
MRV	Measurement, Reporting and Verification	Evidence system for service/emissions; telemetry supports MRV.
NDBP / RNDBP	(Rwanda) National Domestic Biogas Programme	National roll-out programme for household digesters.
NPV	Net Present Value	Present value of (benefits − costs) over time (CBA metric).
NRB	Non-Renewable Biomass	Share of biomass considered non-renewable in emissions accounting.

Abbrev.	**Full term**	**Meaning in this thesis**
O&M	Operation and Maintenance	Routine service activities affecting sustained use.
OPEX	Operating Expenditure	Recurrent costs (e.g., repair parts, technician time).
PRV	Pressure Relief Valve	Safety/pressure management device in gas systems.
QA/QC	Quality Assurance / Quality Control	Procedures for reliable data.
SDG	Sustainable Development Goal	UN goals; core focus on SDG 7 with co-benefits to SDG 2, 3, 5,13 and 15.
SDG 7	Affordable and Clean Energy	Central SDG addressed by household biogas for clean cooking.
SHT30	Sensirion Humidity/Temperature 30	Internal temp/humidity sensor in the IoT stack.
SIM800L	GSM/GPRS Modem	Cellular backhaul module used for telemetry.
SSA	Sub-Saharan Africa	Regional context highlighting uneven programme outcomes.
SBP	Static Biogas Pressure	Line pressure at rest; used in event detection for biogas utilisation (usage) and venting signatures.
TA	Thematic Analysis	Method to group coded content into sub-themes/themes.
UR	University of Rwanda	Rwanda's only public university.
UUE	Unmet Users' Expectations	Theme describing mismatch between biogas service, prior user expectations and post-adoption experience.
VCM	Voluntary Carbon Market	Potential results-based finance route valued in the CBA.

1. Introduction

Household biogas technology converts wet organic residues, e.g. livestock manure, kitchen waste into methane-rich raw biogas (≈50–70% CH_4 , ≈30–50% CO_2 , traces of H_2S and water vapour) through anaerobic digestion [1]. Small-scale biodigesters are installed in different technological designs to produce biogas for domestic use, mainly for cooking [2,3]. These household-scale biodigesters are disseminated in energy-poor communities as a decentralised clean-cooking technology to advance SDG 7, particularly its indicator 7.1.2 [4,5]. The technology comes with other co-benefits [6]. Where bioslurry is effectively managed and applied, it contributes to SDG 2 through improving soil fertility, and hence crop yields [6,7]. Where it reliably displaces solid biomass for cooking, it can contribute to SDG 3 by reducing $PM_{2.5}$ in cooking areas. The extent to which it can advance SDG 5 depends on local fuel-use practices, intra-household labour divisions, including whether it reduces time spent collecting cooking fuels and cooking activities are gendered [8]. It can also support SDG 13 by lowering net greenhouse gas emissions from enteric fermentation (from unmanaged cow dung) [7], and SDG 15 where it reduces fuelwood demand in contexts of local forest pressure [6–8].

Evidence from regional and country-level deployments indicate that the sustained and functional household biogas use supported by innovative programmes can contribute to clean cooking transitions and these associated co-benefits [9–11]. Bhat et al. [9] show that involving private entrepreneurs has led to customised designs of biodigesters and programme-supporting mechanisms, leading sustained use in southern India where about 85 % of HH biogas plants in Sirsi satisfied the HHs cooking energy needs. A study in Vietnam indicate that using biogas could reduce GHG emissions by 50.4–148.4 Mt $CO_{2,e}$ between 2020 and 2050 [10]. Ghimire et al. [11] estimate that an average household biogas plant installed in Nepal displaces ~4.5 tons of biomass per year. The study further estimate that a 1 m^3 HH biogas plant results in direct annual savings of: NRs 9,000 (~ 60 USD, 2025 rates) in the Terai, NRs 2,250 in the hills and NRs 4,500 in the mountains [11]. The installed household biogas plants were estimated to displace ~1.8 million tonnes of fuelwood annually and avoid ~2.8 million tCO_2e. When monetised, indirect/social benefits (e.g., bioslurry-related productivity gains, time savings, health and environmental benefits) added ~35–43% beyond direct savings, and subsidies improved overall feasibility [11].

Despite the documented technical potentials and benefits of the technology, its sustained use remains uneven across South and Southeast Asia [11]. In the sub-Saharan Africa (SSA), these challenges are even more acute. Household biogas initiatives have been promoted as national programmes in SSA but their success remain limited [12]. E.g., the Africa Biogas Partnership Programme documented high rates of fuel and technology stacking among adopters, with continued biomass use, as well as instances of system non-functionality in earlier adoption cohorts [12]. Country-specific case studies identify multiple barriers to the technology, the majority of which are socio-economic, technical, and financial in nature [13,14]. While these barriers remain well documented, the role of household livelihood dynamics in shaping the use of this household technology remains underexplored [12,15].

Examining the interplay between household biogas systems and household livelihoods can help bridge this gap and inform effective and contextualised policy formulation. Understanding this interplay is foundational to the use of this technology because it is contingent on the day-to-day mobilisation of household resources, especially the family labour. Unlike other clean cooking fuels and off-the-shelf technologies which are purchased in their ready-to-use form, household biogas systems require consistent family labour (e.g., regular biodigester feeding, cleaning inlets and outlets, breaking the scum layer, releasing the water vapour in biogas pipes and keeping biogas pressures in recommended levels) in addition to other maintenance and operational expenditures (OPEX) [12,16]. This underscores the need for studies focusing on user-centred service models and monitored performance as pre-conditions for biogas to deliver its expected contribution rather than add to stranded assets. Addressing this gap, however, requires reframing household biogas technology and its use in a manner that captures underlying dynamics of HHs from communities in which the technology is embedded. As such, this thesis frames HH biogas technology use as a socio-technical system to examine how the everyday HH livelihoods shape its use.

1.1 Aim of the thesis

The broader aim is to examine the interplay between household livelihoods and biogas production and use, thus deriving lessons that can support its sustained use. The household biogas technology use is studied as a socio-technical system focusing on technology user lived experiences after technology adoption, technology functionality against its intended end-use service (cooking), potential environmental effects of technology due to its ineffective use, and how household livelihoods affect the technology use. This broader aim is addressed through four research questions (RQs), with RQs 1–3 serving as transitional to inform the core research question (RQ4):

- RQ1: What post-adoption trajectories characterise household biogas plants deployed under Rwanda’s National Domestic Biogas Programme?
- RQ2: What factors contribute to the abandonment of household biogas technology?
- RQ3: What factors underpin the sustained use of household biogas systems?
- RQ4: How do household livelihoods affect the production of biogas and its use?

RQ1 examines post-adoption trajectories, while RQ2 and RQ3 explain divergence within these trajectories by examining factors linked to the technology abandonment and its sustained use. RQ4 then situates these factors within the context of household livelihoods, providing an integrative lens that connects technology use patterns to everyday livelihood realities. The novelty of this thesis lies in its integrated analysis of user perspectives, biogas production and use patterns, household-level dynamics, and energy policy contexts within energy-poor communities–a triangulation not addressed in the literature. To communicate such findings, this thesis is structured to reflect an integrated interpretation of triangulated forms of evidence, each playing a distinct but a complementary role. The complementarity and the integration of data sources and their methods of analysis allows for answering the four research questions.

1.2 Thesis structure and framing

This thesis is structured such that interpretive analysis occupies a central role, while measurement and quantification complement and enhance the interpretation process. As depicted in Fig.1, the thesis framework illustrates an abstracted structure in which data flow from three primary sources: survey-based user perspectives, livelihood and technology-use data, and measured data. These three data streams are initially analysed independently; Data from the survey generate user insights, data from technology use and HH livelihoods generate a deeper contextual understanding while remotely monitored data generate patterns of technology use to support interpretation. Findings from the three methodological approaches are integrated and interpreted to elucidate their overarching implications.

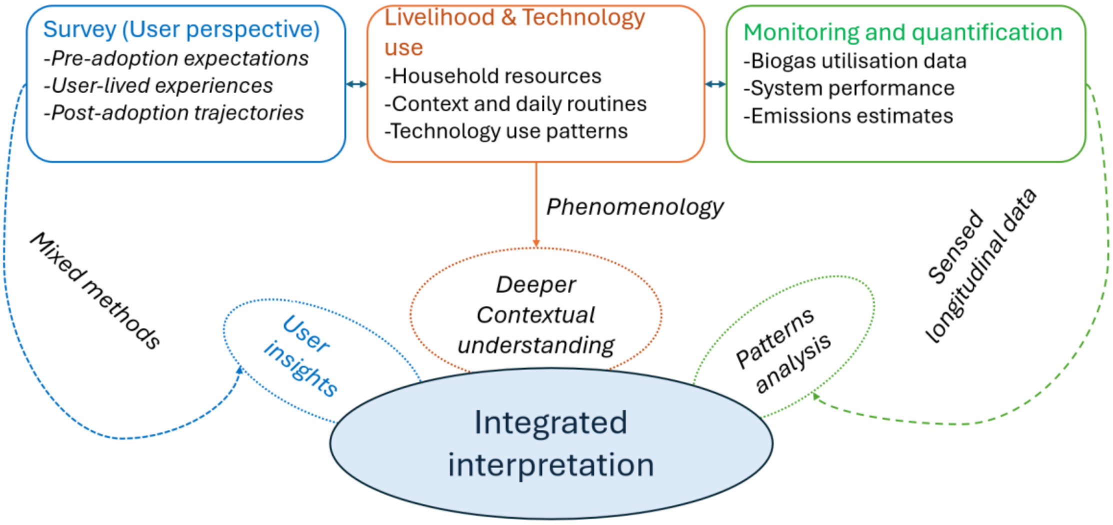

Fig.1.Conceptual structure of the thesis showing how complementary forms of evidence converge into an integrated interpretation (source: author).

Based on such a conceptual framing, this thesis is organised into 8 chapters. Chapter 1 introduced the context, highlighted the broader aim, specific research questions and presented the structure of the thesis. Chapter 2 provides the background of household biogas technology and its use at global, regional (sub-Saharan Africa), national levels, introducing Rwanda as the case for the study. Chapter 3 outlines the research design (methodology), approaches (methods) of data collections, forms of data collected and methods of data analysis. Chapter 4 presents results and analysis. Chapter 5 presents the discussion, Chapter 6 concludes the thesis and highlights policy-oriented recommendations. Chapter 7 highlights key contributions of the thesis, while Chapter 8 presents a forward-looking proposal for future doctoral research work.

2. Background

2.1 A general context.

From a global perspective, the use of HH biogas technology emerged in 1970s–1980s, notably in China and India which promoted and standardised family-sized digesters using animal manure to produce biogas for cooking and lighting, and returning digestate to fields as a soil fertiliser [17]. These small-scale biodigesters produce raw low-pressure biogas from a four-stages (hydrolysis, acidogenesis, acetogenesis, methanogenesis) anaerobic digestion [18]. They are typically grouped into three dominant types: fixed-dome, floating-drum, and tubular digesters (balloon-shaped polyethylene, commonly referred to as flex-bags) [18,19]. While each design presents specific contextual advantages and disadvantages, they share a common feature of supplying low-pressure biogas that is used without further upgrading [19]. Thus, the quality of cooking service derived from biogas (methane-rich energy carrier) depends on regular maintenance and operation of the system, high ratios of methane content (low CO_2, H_2S and other impurities) [19], and biogas burner geometry [20–22].

Following decades of standardisation and sustained policy support, an estimated 44 million household biodigesters have been installed across Asia, around 40 million of which are in China [23]. India implemented household biogas mainly through the National Biogas and Manure Management Programme (NBMMP), which promoted small-scale digesters for cooking and organic fertiliser production [24]. Nepal is often cited as a relative success case due to the Biogas Support Programme (BSP), which combined subsidies, quality control, private-sector delivery, and after-sales services with the installation of about 440,000 household biogas plants [11]. Vietnam and the rest of Southeast Asia implemented small-scale household biogas programmes, often linked to livestock waste management rather than national energy transitions [25].

The global dissemination of household biogas systems is driven by expectations that they can provide modern cooking services, reduce household air pollution in cooking areas, and mitigate climate impacts through the substitution of solid biomass and the capture of methane from enteric fermentation in livestock [26]. Nevertheless, household biogas systems have consistently fallen short of their anticipated benefits because discontinuation, abandonment, and ineffective use persist while access to clean cooking remains limited, particularly in Sub-Saharan Africa. As depicted in Fig. 2, access to clean cooking fuels and technologies continues to be a significant challenge in sub-Saharan Africa, as population growth has exceeded clean cooking access rates, leaving approximately four-fifths of the population without clean cooking solutions in SSA [27]. The persistent patterns of discontinuation, abandonment, and ineffective use of household biogas systems in Sub-Saharan Africa underscore the need for closer empirical investigation of the conditions influencing system functionality and sustained use, given their potential to contribute to clean cooking transitions and their relevance to broader Sustainable Development Goals.

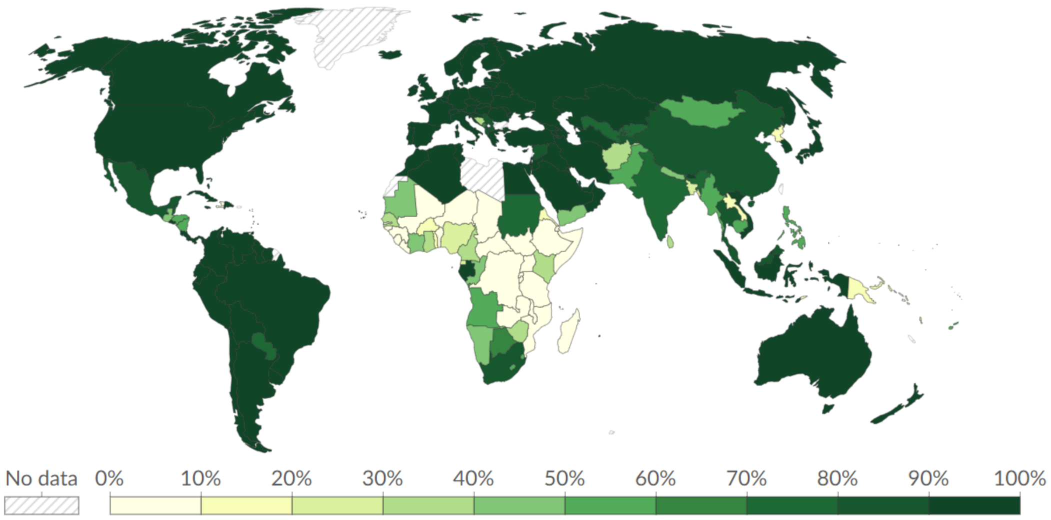

Fig.2.A global picture of the population with access to clean fuels for cooking by 2023 [27]

2.2 Sub-Saharan context

Drawing on reported cases of household biogas success in pioneer countries, e.g., China and Nepal, biogas featured prominently as Sub-Saharan African governments, and their development partners sought clean cooking options for livestock-owning households. Hence, the Africa Biogas Partnership Programme (ABPP) was launched in 2008-2009, aimed to establish national programme teams within designated implementing agencies and building their capacity by strengthening technical skills [28].To improve programme effectiveness and further promote biogas technology, Phase 2 was launched in 2014 [28]. This phase set explicit targets for cost reduction, expanded credit uptake, and delivery to attract private sector [28]. Beyond ABPP, the IEA reports biogas projects operating in at least 17 SSA countries and a technical potential of more 110 billion cubic metres (biogas equivalent) per year [29]. The report notes a shift towards prefabricated digesters to lower costs and ensure quality control [29].

Despite the thousands of household biogas units across SSA countries [30], successful biogas use remains limited in the region. More consequential than low uptake is the rapid failure and abandonment of installed systems. Evidence indicates that after an initial period of donor-driven growth, new installations have stagnated or declined in several SSA countries, indicating weakening demand rather than cumulative scaling. In Uganda, nearly all tubular digesters and up to 80 % of fixed-dome systems were abandoned within the first quarter of their lifespan [31]. This calls for contextualised and explanatory inquiry in the framework of clean cooking transitioning [12].

2.3 Rwanda as case for the study

Rwanda's energy consumption remains highly concentrated in the residential sector. As indicated in Fig.3, the national energy-balance indicate that households account for more than 80% of total final energy use, compared with transport (~7.8%), industry (~7.5%), and commercial and public service (~3%), and (~3%) for other uses [32]. Within households, cooking dominates demand which is still biomass-based [33]. The EICV7 (2023/24) reports more than 75.0% of households primarily cook with firewood, 18.8%

with charcoal**,** 5.4% with gas (mostly LPG), 0.6% with crop waste, and only 0.1% with other fuels (including negligible electricity use). Combining both firewood and charcoal, solid biomass use contributes to more than 90% of cooking fuels.

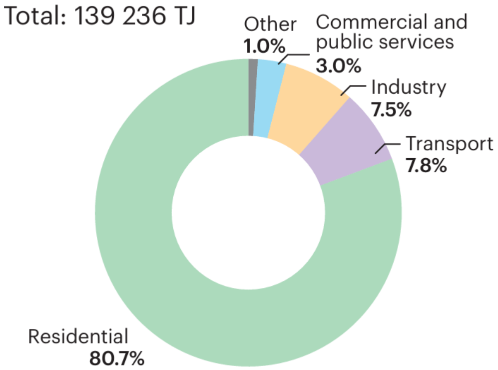

Fig.3.Rwanda's energy use by sector by 2022 [32]

While Rwanda has expanded electricity access rapidly, with about 72 % of Rwanda's households access to electricity (50% on National grid, 22% on solar power, and approximately 1% with dual access to both the National grid and solar power) [34], the persistence of biomass as primary cooking fuel proves that the electricity access did not have a proportional impact on the clean cooking transitioning, as shown in Fig.4. Consequently, policy frameworks emphasise the need for parallel clean-cooking interventions beyond electrification. These parallel solutions include LPG adoption, biogas deployment, dissemination of high-efficiency (improved biomass stove), and e-cooking [35]. Household biogas is still regard as part of the mix regardless of its negligible contribution to Rwanda's clean cooking transitioning. Infact, Rwanda had launched the National Domestic Biogas Programme (NDBP) in 2007 with a headline target of 15,000 family-sized plants by 2011, aiming to reduce fuelwood reliance, improve indoor air and realise agronomic benefits via bioslurry [36].

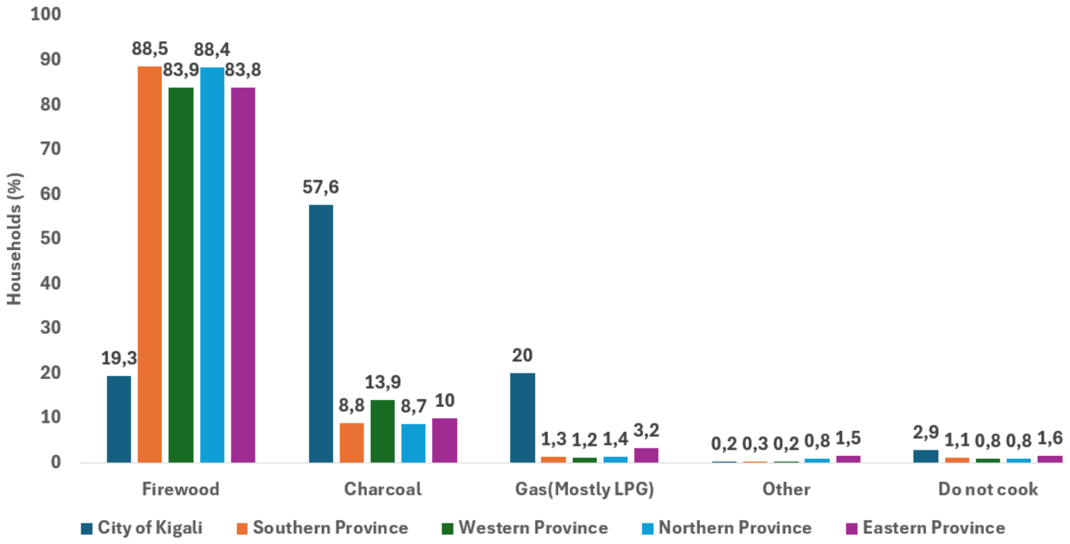

Fig.4.Rwanda's cooking fuel mix. The figure generated by the author from Rwanda's HH census of 2022 [33]

The successful dissemination of household biogas in Rwanda would not only contribute to the clean cooking transitioning, but also would capture part of methane from enteric fermentation, manure management, and managed soils, hence substantially contributing to Rwanda's NDCs, depicted in Fig. 5 [37]. Literature on HH biogas in Rwanda indicate that using bioslurry from a 4 m^3 biodigester as fertiliser can lead to annual GHG emission reductions of about 2.4 $tCO_{2,e}$ per HH when compared to HHs using wood only as cooking fuel [38]. From a socio-economic perspective, it was estimated that owning a digester in Rwanda could lead to a 31–32% decrease in annual energy expenditures, and this could reduce the daily consumption of fuel by 34% [39]. However, despite the potentials of the technology, its deployments trends show that about only 2,446 household digesters were installed by 2012, well below the initial target of 15,000 [36]. The unsuccessful use the technology in Rwandan communities has been attributed to barriers largely stemming from high investment costs, technical and socio-economic challenges, and administrative or institutional constraints [14]. Irrespective of the reported technology's barriers to its diffusion and successful use, Rwanda's clean cooking policies continue to view biogas as a potential technology to anchor clean cooking transitioning.

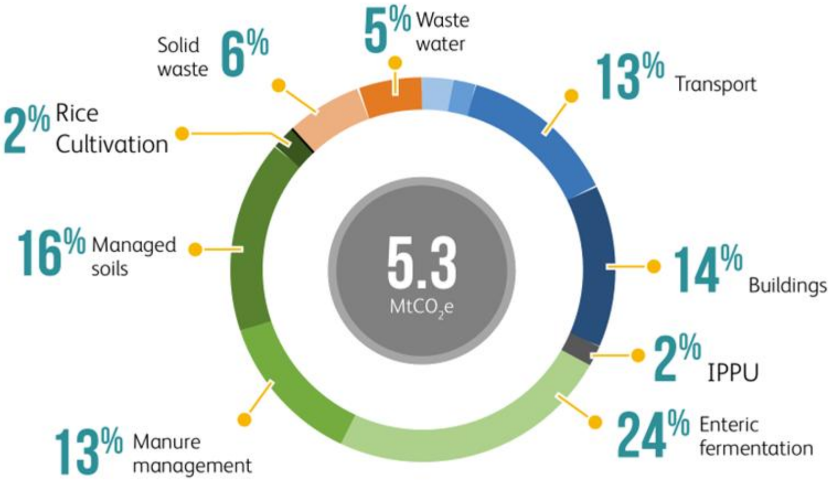

Fig.5.Enteric fermentation contributes a bigger share to Rwanda's NDCs 2.0 [37]

The belief in the HH biogas technology is reflected in the Rwanda's energy policy of February 2025 which explicitly addresses biogas within the Rwanda's energy supply and clean-cooking policy mix, providing a high-level framework for investment in and implementation of HH biogas alongside sector strategic clean coking technologies [35]. This, however, calls for an evidence-based examination of Rwanda's household biogas system that is grounded in local context. This forms the basis for the work presented in this thesis.

3. Methodology

3.1 Research design and logic of enquiry

This thesis is centred on interpretive phenomenology, rooted in technology user's lived experiences & empirical evidence. The core inquiry is exploratory and explanations-driven. Quantitative data are used as supporting evidence for the interpretation and explanation. Thus, the thesis seeks to establish what households say they do and think about the technology (reported practices and perceptions), what happens (observations and metered operational data), and quantifies the measured episodes (biogas consumption and leakages). The supporting evidence explains *why* seemingly similar systems diverge in utilisations, output, and outcomes. Integrating these together, the thesis addresses the four research questions (RQ1–RQ4) presented earlier.

3.2 Units of analysis and scope

The empirical focus of this thesis is the biogas systems installed for cooking as an end-service in rural and peri-urban contexts typical of Sub-Saharan Africa, using Rwanda as case for the study. The unit of analysis is the household biogas system embedded within the household's livelihood configuration. National programmes or policies and literature are incorporated as baselines for discussion.

3.3 Key definitions

In the framework of examining the interplay between the HH livelihood and the technology use, two key definitions were used; 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*" FAO [40]. Fig.6 presents an abstraction of the five HH resources used study this interplay.

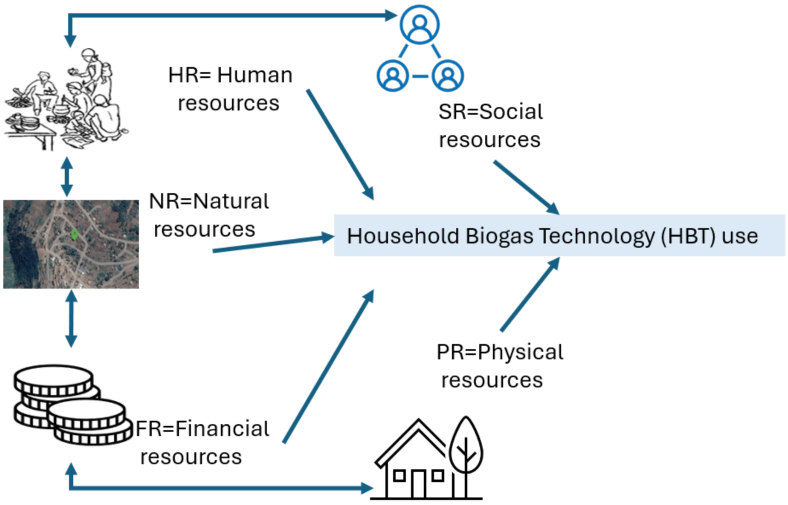

Fig.6.The five household resource domains used to conceptualise household livelihoods and underpin the analytical framework [40,41]

Accordingly, this study adopted a household livelihood perspective centred on five resource domains defined by Carloni and Crowley [40,41]. These include: (a) physical resources (PRs), referring to tangible assets such as housing structures and household appliances; (b) human resources (HRs), encompassing household members, their education levels, skills, and available labour; (c) social resources (SRs), reflecting the extent to which a household is embedded within local social networks and hierarchies; (d) financial resources (FRs), denoting household income sources and financial capacity, including wages, salaries, and access to credit or financial schemes; and (e) natural resources (NRs), comprising naturally available assets that households use or exchange to meet their needs, such as access to land or water bodies for activities like fishing [40,41].

3.4 Recruiting participants

Participant recruitment followed a two-stage process. The first stage used a countrywide survey that was breadth-oriented and aimed to capture the national context. The second stage recruited a small number of households situated in a wider Rwanda's context but prioritising depth over breadth.

In the first phase, a nationwide survey was conducted using administrative registers of household biogas plants installed under the national biogas programme as the sampling frame. A stratified random sampling was used to achieve diversity and representativeness in the sample. The sample size (n) was derived from the finite population ***(N)*** using Eq. (1) [42].

$$n = \frac{(Z^2 * q * p) + ME^2}{ME^2 + (Z^2 * q * p)/N)} \qquad Eq(1)$$

Where, ***N*** denotes the number of domestic household biogas plants installed in Rwanda from 2000 to 2021. A Z-score of 1.96 was adopted as the critical value for a 95% confidence level, striking a balance between reliability (high probability of capturing true population characteristics) and practicality (avoiding an excessively large sample) [42]. The margin of error (ME) was set at ±5% to balance representativeness with logistical constraints: a smaller ME would inflate sample size, whereas a larger ME would erode population coverage [43]. The proportion parameters were specified conservatively as $p = 0.5$ and $q = 1 - p = 0.5$, which maximises variance and guards against underestimating variability [44]. These parameter values were used solely for sample size determination, not for hypothesis testing. They were used to secure adequate population coverage and support thematic saturation during thematic analysis. To accommodate potential non-response (assumed at 1%), a marginal number n_m was added to the computed sample n, yielding a final target of $n + n_m$. After fixing the target sample, strata were computed from the relevant administrative regions and sub-regions using Eq (2).

$$n_h = Nh * \frac{n}{N}; Nh = n_h * \frac{N}{n} \qquad Eq\ (2)$$

where, n_h denotes the number of households to be sampled from stratum h, and $N_h$the total number of households in that stratum [42]. Strata were defined using a multi-level stratified (top-down) approach, proceeding from higher-level administrative regions to their sub-regional units. According to Eq. (2), n_h was proportional to the number of deployed biogas plants in each region and sub-region to ensure representativeness. Within each stratum, n_h households were then selected by simple random sampling to preserve diversity and avoid selection bias. The study population comprised 10,701 households that adopted biogas technology between 2000 and 2021 (N = 10,701). Using Eq. (1), a sample of 372 households was derived, with a small margin (n_m = 4) added to account for non-response, yielding a final sample of 376 households. From the study sample, stratum sizes for all 30 districts of Rwanda were calculated using Eq. (2).

In the second phase, as depicted in Fig.7, the recruitment followed a purposive selection of participants based on the set criteria and in alignment the interpretive phenomenology's priorities. The number of participants was guided by phenomenological approaches, suggesting small number of participants [45]. Accordingly, four households from four of the five provinces, excluding Kigali City, were selected for phenomenological inquiry, longitudinal monitoring, and analysis. The selected and coded households (*EKF, WMT, SJB, and NGT*) were embedded within a broader Rwandan context. Two of the four households were located in the Northern (Musanze District) and Western (Rubavu District) provinces, both mountainous and high–population-density areas where settlement policies have been implemented to manage land scarcity. The remaining two households were situated in the Eastern (Bugesera District) and Southern (Huye District) provinces, in lowland and plateau regions respectively, where settlement patterns are comparatively less dense. The selection based on: (a) access to a dependable piped water supply and rainwater harvest tanks; (b) ownership of three or more heads of cattle; (c) keeping at least three heads of cattle at the household residence; (d) willingness to participate and provide relevant data throughout fieldwork; and (e) ownership of biodigesters of the same type and capacity (8 m^3 fixed dome biodigester).

A smart metering system was installed at each of the purposively selected HHs for remote data collection. As sketched in Fig.8, low-pressure sensors were used for logging stove-level biogas utilisation patterns. Auxiliary analogue static pressure gauges were also installed at each of these HHs and used for data validation. These measurement mechanisms were used to enhance and complement the survey and phenomenologically collected data.

3.5 Forms of data

Survey data: Mixed (mainly qualitative and key quantitative) sets of data collected were related to prior expectations from technology users, year of acquisition, biodigester size and type, current working status of the technology, HH daily routines, type of feedstock, access to technical support, source of initial investment, challenges or benefits of the technology, and current opinions on the technology use. Data collection allowed for opened-ended discussion to allow further probing.

Telemetry data: biogas utilisation data was logged over seven months spanning dry to rainy seasons with an intention of linking specific observed pattern to the system operation routines and system outputs. In Fig.9, the sampled daily utilisation patterns are presented for explanations. They indicate key events of interest (e.g., venting event, biogas consumption event) and their patterns of occurrence. The venting event indicates a time slot of biogas underutilisation, leading to intentional release of produced biogas by the system design [46]. Biogas consumption event indicates the magnitude and frequency of biogas used for cooking. These episodes and the linked determinants were longitudinally documented to enhance the integrated interpretation.

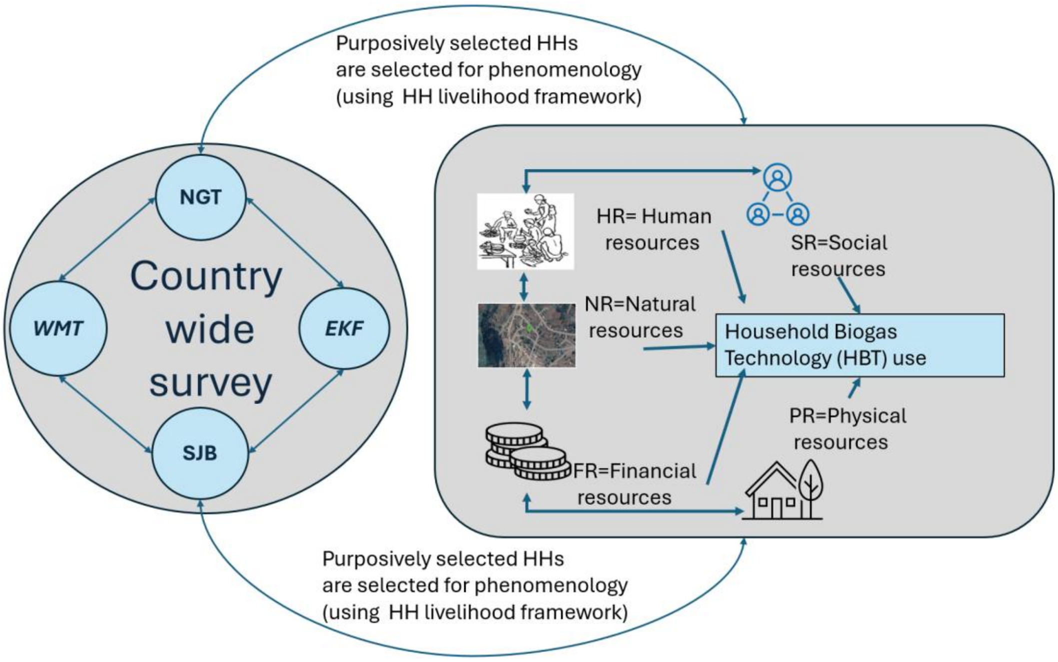

Fig.7.Abstraction representation of research participant recruitment. EKF, WMT, SJB and NGT are codes given to the HHs selected for data collection through a HH livelihood framework (source: author)

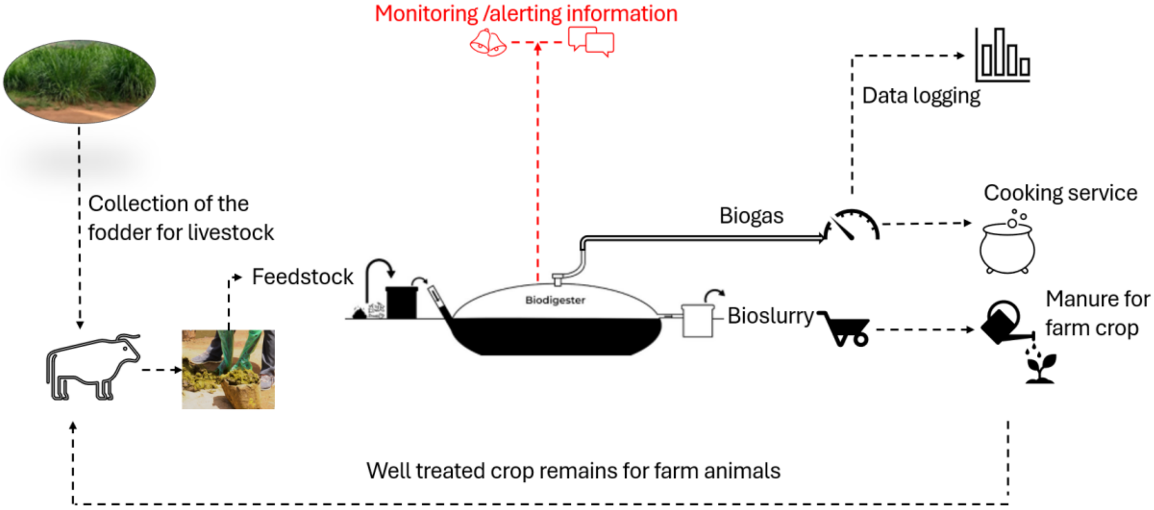

Fig.8.A conceptualised physical HH biogas system with smart metering (source: author) [47]

Observational data: During site visits (planned or triggered by observed system utilisation pattern), direct observation captured visible operational hints, e.g. flame colour and stability as proxies for moisture carry-over and other gas impurities. Where the technology user behaviour and practices could not be witnessed directly, outcome-based indicators were used, e.g. the condition of bioslurry at the outlets and compost pit served as a tracer of feeding regularity and the biodigester state of health (SoH). Samples of observational data are presented in Fig.10.

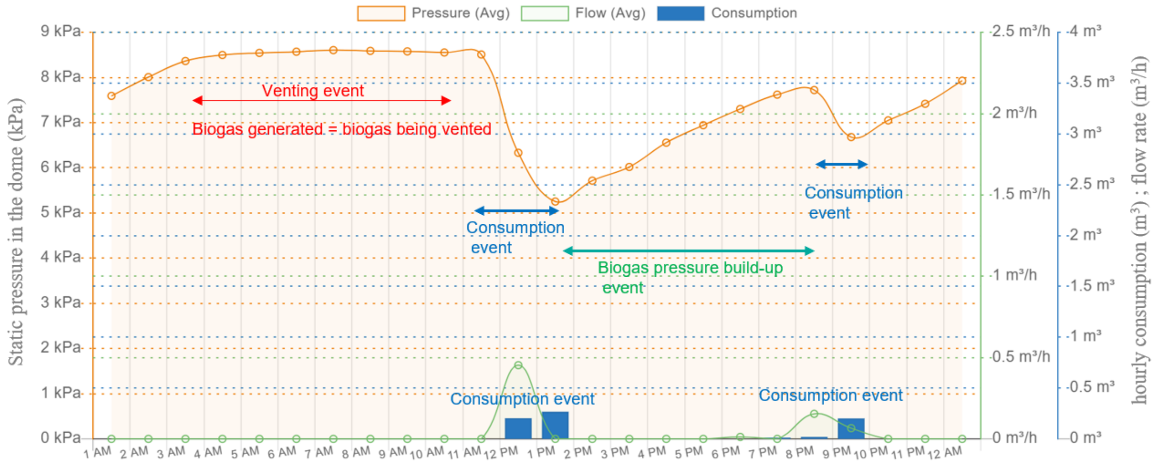

Fig.9.A sample of data logging output from telemetry data showing patterns of interest for analysis: venting, consumption, time of use, duration, and daily quantities (source: author) [41].

Phenomenological data: phenomenological data were collected through phenomenological questioning (not through traditional questionnaire) to answer the '*what*', (e.g. what fuel did you use to cook yesterday–probing for anomalous utilisation pattern), "*why*", (e.g. why did you chose to use fuel wood when biogas levels were sufficient to cook, i.e. if the participant confirms they used fuel wood yet venting was observed), '*how*', (e.g. how do you feel like when cooking dry beans with biogas, i.e. in cases where the participants confirmed they did not use biogas but cooked a specific food with fuelwood instead of biogas).

(a) Water and solid feedstock mixing before feeding.

(c) Stable blue flame, indicating less impurities and good combustion from quality biogas.

(e) Viscous bioslurry indicating Consistent feeding.

(b) Inlet status indicating inconsistent feeding and cleaning.

(d) Blow-off flame, many yellow zones, safety-risk indicating high pressure due to underutilisation, unreleased vapour and potential impurities.

(f) Solidified bioslurry indicating inconsistent feeding.

Fig.10.Samples of observational data collected during field visits (sporadic, planned and event-triggered). Green letters indicates recommendable use practices and output while red indicates red flags (source: author) [41].

3.6 Data analysis

Findings in this thesis emerged from three analytical tracks, shaped by the type of data, their collection approach, and the purpose: Thematic analysis (TA) and interpretative phenomenological analysis (IPA) constituted the core qualitative methods. Pattern analysis (PA) of measurable and quantifiable parameters provided complementary evidence to support interpretation. An integrated analytical approach then synthesised insights across the three strands to develop overarching explanations.

3.6.1 Qualitative data analysis

Qualitative data analysis employed two complementary approaches, distinguished by their emphasis on breadth or depth. Qualitative data collected through a countrywide survey prioritised breadth over depth, and hence, were analysed using conventional thematic analysis (TA) [48]. Thematic analysis (TA) focuses on identifying patterns or themes across a dataset by examining recurring features in participants' responses, as conceptualised in Fig.11. Through a five-steps approach, the TA's typical outputs are defined themes, often represented through thematic maps or analytical frameworks [49–51]. Interview materials were transcribed and segmented into condensed meaning units.

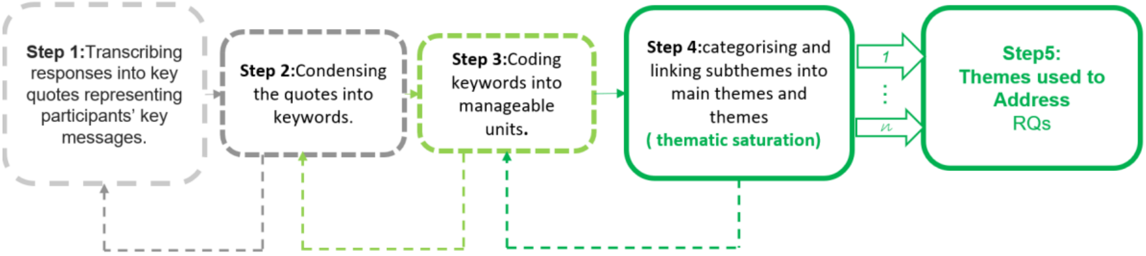

Fig.11. Thematic analysis process. The feedback loop indicates iterative data checking and cross-verification. Grey outline represents early stages of data analysis, during which themes have not yet been formed. Dashed outlines indicate openness to newly emerging data, while solid outlines denote thematic formation and saturation, with qualitative data consolidated under established themes (source: author) [52].

These units were inductively coded, with related codes grouped into sub-themes and then synthesised into higher-order themes, which were subsequently interpreted to elucidate participants lived meanings. A relationship map was further developed to establish a categorical link strength (strong, normal or weak) between themes and the working status of each HH biogas plant in the sample.

Qualitative data collected through phenomenological questioning from the purposively selected HHs prioritised depth over breadth, and hence, were analysed by Interpretive phenomenological analysis (IPA) [53]. The IPA was used to achieve analytical depth by examining technology user experiences and their lived realities. As indicated in Fig.12, the IPA is grounded in phenomenology, hermeneutics, focusing on detailed, case-by-case analysis in which each participant is analysed individually before patterns are considered across cases as a '*whole*' [54–56].

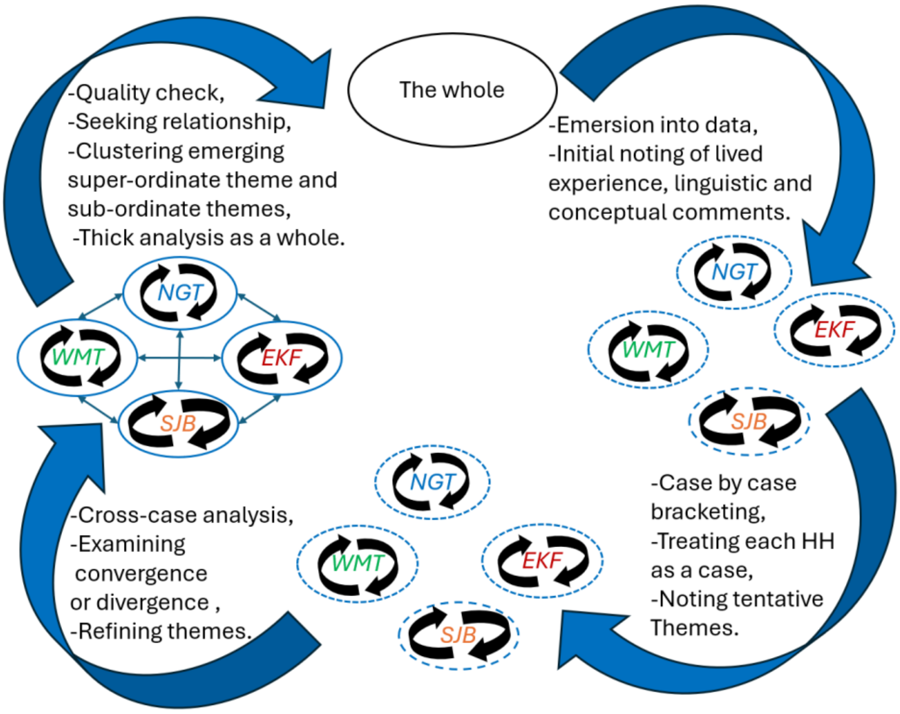

Fig.12.Interpretative Phenomenological Analysis (IPA) illustrating in-depth, case-by-case analysis, followed by cross-case interpretation. "SJB, EKF, WMT, NGT" represent the coded participating households (source: author) [41].

3.6.2 Patterns analysis

In the framework of enhancing interpretation of thematically and phenomenologically analysed data, biogas utilisation traces were analysed through household biogas utilisation patterns analysis (PA) [41]. The PA focused on timestamps and events exemplified in Fig.9. Event detection combined biogas static pressure and biogas flow rate to segment stove-use episodes (onset, cessation, duration and integrated quantities). The PA identified potential venting events that required further qualification.

3.6.3 Measurement and quantification

Building on event-segmentation, traces of biogas utilisation patterns flagged potential venting. The venting was analysed by: *(i)* defining rule-based distinctions between *venting* and *leakage* using a threshold for static biogas pressure (SBP) and associated pressure-plateau logic [46], *(ii)* estimating vented volumes over time from the venting episodes; *(iii)* validating meter-derived consumption and venting against short-session calculations from analogue pressure readings using Boyle's law and an altitude-adjusted barometric relation [46], and *(iv)* converting the vented volumes of biogas to CO_2e by using ideal-gas densities, methane fraction from literature and GWP factors to yield household-level monthly emission estimates [46].

3.6.4 Integrated data analysis

This analytical approach integrated metered indicators (daily consumption, utilisation rates and volumes, peak-flow flags, and venting episodes and volumes) together with observational field notes to triangulate and contextualise the thematic findings, thereby addressing the study's livelihood-centred explanatory enquiry. As shown in Fig.13, household-level profiles were developed, the interview and observational materials were analysed through a household-livelihoods lens using an interpretive phenomenological approach to foreground lived experience.

Telemetry episodes were then aligned with the emergent and phenomenologically derived mechanisms to construct claims that explain observed usage patterns. Cross-case pattern matching helped to assess the recurrence and variation of these mechanisms across households, thus generating explanatory propositions that account for divergence in metered performance in terms of differing livelihood conditions and situated practices [41].

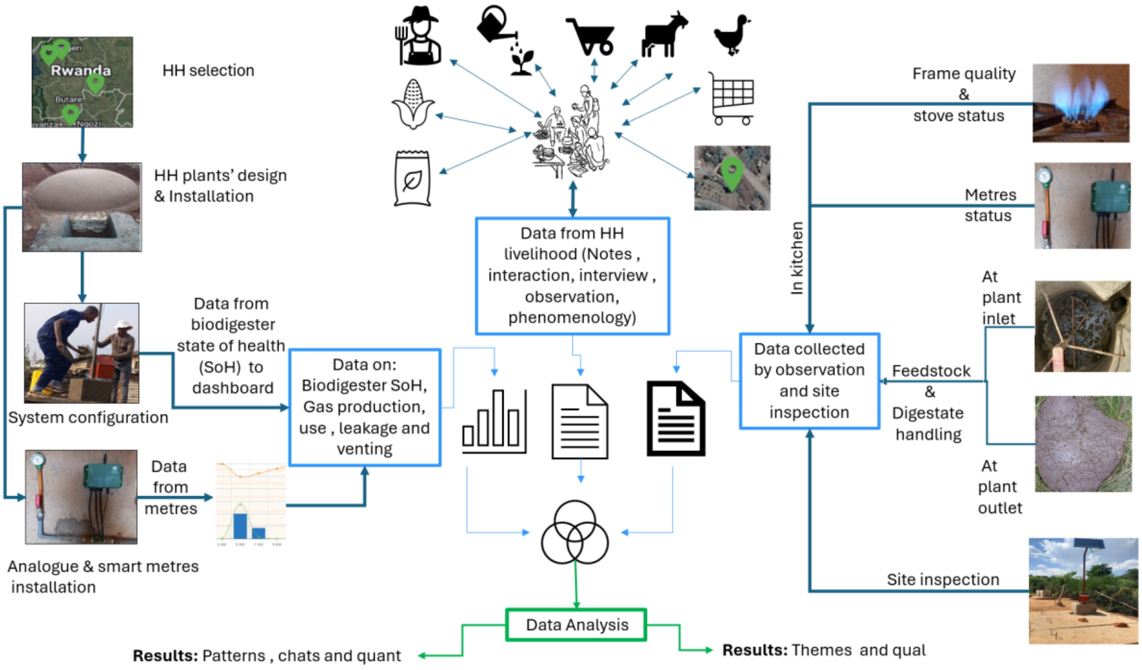

Fig.13.A mixed methods approach for the Integrated data analysis (source: author) [41]

4. Results and analysis

The results are organised and analysed into three subsections. *Section 4.1* reports descriptive results using basic statistics on post-adoption technology trajectories, while *Section 4.2* presents the thematic findings that explain the drivers shaping these trajectories. *Section 4.3* provides supporting evidence for the thematic findings and environmental implications of ineffective technology use.

4.1. Descriptive results

Results from a countrywide survey, in Fig.14, show that the national programme-driven adoption scaled up through the mid-2010s after the launch of Rwanda's national biogas programme (2007–2008). The fixed-dome technology was the backbone of the programme while flex-bags was deployed later for rapid and lower-cost deployment. The short-lived surge in flex-bags reflect the ease and speed of installation, but their rapid decline together with fixed dome hints at durability concerns relative to fixed-domes. Fiber glass never materialised because of its high initial installation cost and supply chain constraint compared to its alternatives; the prefabricated flex bag is foldable, cheapest and easy to install while fixed dome is constructed using local materials and by locally trained masons. The results also show that deployments followed a clear three-phase diffusion trajectory: First, emerging phase (2000–2007) with low annual counts dominated by fixed-dome units. Second, a scale-up phase (2008–2016) where fixed-dome installations rise steadily and brief technology diversification occurs: flex-bag (canvas) plants appear to increase from (2012-2013) and peaked in 2015-2016. Third, a contraction phase (2017–2021) with a sharp decline for both technologies to only a few installations by 2019–2021. Fibreglass plants remained negligible throughout. This three-phase pattern reflects Left-skewed (negative skew) bell-shaped diffusion curve in which a long tail on the left side indicate a slow early adoption followed by a rapid spike-to-peak during technology scale-up, but the absence of innovation and adaptive support led to declines as saturation and persistent constraints limited further expansion. This asymmetric diffusion pattern suggests a long capacity-building phase followed by a policy- or programme-driven surge, and then a rapid contraction triggered by rapid loss of confidence from widely shared negative experiences.

Based on sampled units (n=376) installed (2000–2021), as presented in Table.1, 70.2% (n=264) had been completely abandoned, while 9.0% (n=34) remained fully functional. 5.6% (n=21) were underperforming but still in use, 6.9% (n=26) were suspended but in repairable conditions, and 8.2% (n=31) had never operated since their installation [52]. Installation per province show that the eastern province which had the highest number of deployments and a large cattle base also recorded high numbers of the technology abandonments whereas Kigali city suburbs recorded the lowest deployments and abandonment. The overall abandonment appeared proportional to the scale of deployment within each province as. This suggests that abandonment represents a form of post-adoption discontinuance inherent to the technology diffusion process, particularly in contexts where sustained support mechanisms and adaptive innovation are lacking.

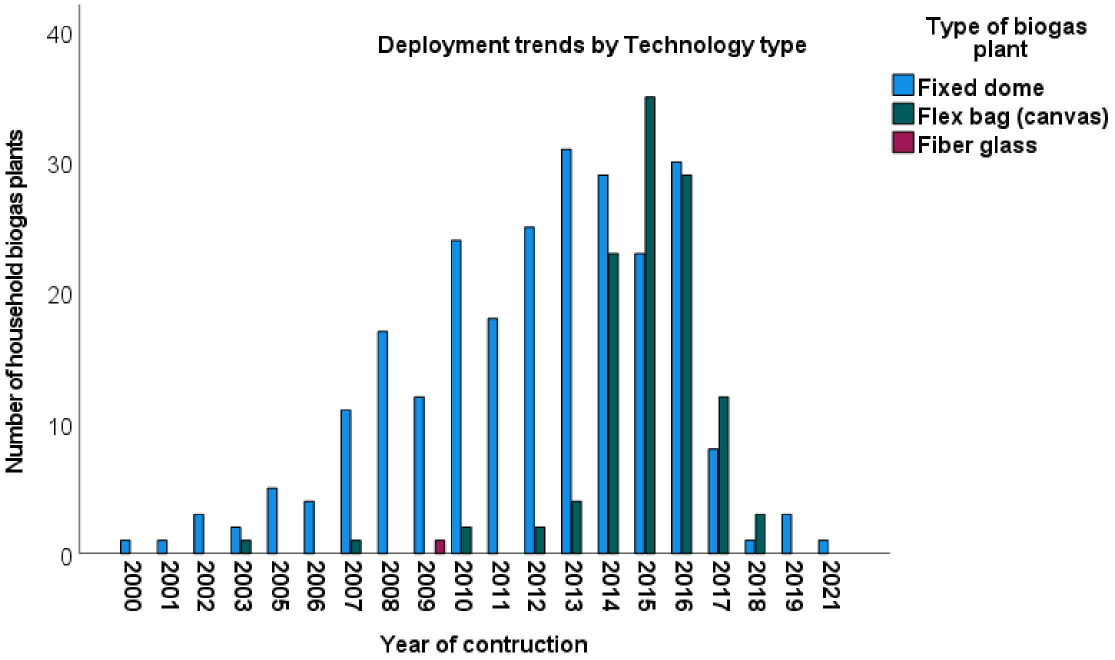

Fig.14.Household biogas plants uptake by technology of the sample units (Source: author, also the published in the conference proceeding) [47]

Further, Table.2 shows that among households with valid responses, i.e. those able to recall when their plants began to malfunction, 51.7% reported that their biogas plants stopped working properly within three years of installation, a duration shorter than the lowest lifespan expectations often associated with flexi-bag systems. 45.2% reported proper operation for more than three years, while 3.1% reported malfunctioning beginning in the third year. The 22.9% missing values correspond to households that could not recall when malfunctioning began. As such, is interpreted with caution. Nevertheless, the pattern indicates limited post-installation longevity for a substantial share of the sampled plants.

Table.1. Working status of surveyed HH biogas plants by Province (source: author) [52]

		Plants working status					
		Properly working	Not working to its full capacity	Temporary not working	Completely shut down (abandoned)	It never worked	Total
Province	East	9	8	9	87	8	121
	Kigali	0	2	0	9	0	11
	North	12	6	6	61	4	89
	South	9	2	9	73	12	105
	West	4	3	2	34	7	50
Total		**34**	**21**	**26**	**264**	**31**	**376**

Table.2. Response to the question asked, "*if it is not working properly, how long did it work properly?*" *(source: author)* [52]

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Stopped in third year	9	2.4	3.1	3.1
	Less than 3 years	150	39.9	51.7	54.8
	More than 3 years	131	34.8	45.2	**100.0**
	Total	**290**	**77.1**	**100.0**	
Missing		86	22.9		
Total		**376**	**100.0**		

4.2. Thematic results

While basic descriptive statistics in *Section 4.1* present a general overview of post-adoption trajectories in numbers, *Thematic results* presented under this section are core to the thesis. Thus, findings are presented under two further *subsections (4.2.1 and 4.2.2)* by data source and their methods of analysis.

4.2.1. Thematic results from survey data

Survey findings showed that two systemic drivers account for most of technology abandonments cases: *(i)* feasibility assessment (FA) deficits that mis-matched eligibility and the everyday resources required for operation (dung, water, labour, repair parts/service, siting within evolving land-use and cross-cutting policies), and *(ii)* unmet user expectations (UUE) arising from stove-task misfit and the labour burden of daily feeding and maintenance compared to energy harvested. Contrary to the assumptions underpinning Rwanda's national biogas programme design, sustained use (SU) is anchored in the perceived value of bioslurry as a co-product for agronomic strategy rather than the sole cooking-focused service goal. The weaker themes: Monitoring and Evaluation (M&E) gaps, theft (The), Weather (We), Alternative Energy Carrier (AEC) switching, and Isolated Cases (IC) shape edges of the technology working status but do not explain the bulk of abandonment. The relationship map between the working status of the sampled plant and linked themes is presented in Fig.15 and further explained under this section [52].

Feasibility Assessment (FA); Systematic gaps were identified in the household-level feasibility assessments (FA) used by the national programme. While eligibility screening of potential adopters largely relied on the minimum criteria (two heads of cattle and water access), the process gave limited attention to other determinants of the technology's viability, including land size, household labour capacity, and cattle characteristics and management (breed, age, husbandry practices). Programme guidelines indicated minimum inputs of 20/40/60 kg day^{-1} of dung and 20/40/60 *l* Day^{-1} of water for 4/6/8 m^3 digesters, respectively. Yet some adopters who met the "*two-heads of cattle*" criterion, particularly HHs who benefited from one cow per poor family programme ("*Girinka")* could not reach the daily dung requirement and subsequently abandoned their plants. Where households lived in more 500 *m* from a water source, 3,000 *l* rainwater harvest tanks were provided, but during 3–4-month dry seasons the stored water was insufficient due competing demands from livestock and domestic uses. Further, land-use changes (e.g., plots rezoned from farming use to housing use) prompted households to move cattle off-site, making dung collection impractical, hence abandoning the technology. Spare-parts and technician access were not secured in advance; flex-bag shades tore and proved hard to replace locally, and technicians were difficult to reach. Together, these issues formed a coherent FA deficit linked to abandonment (106 cases) [52].

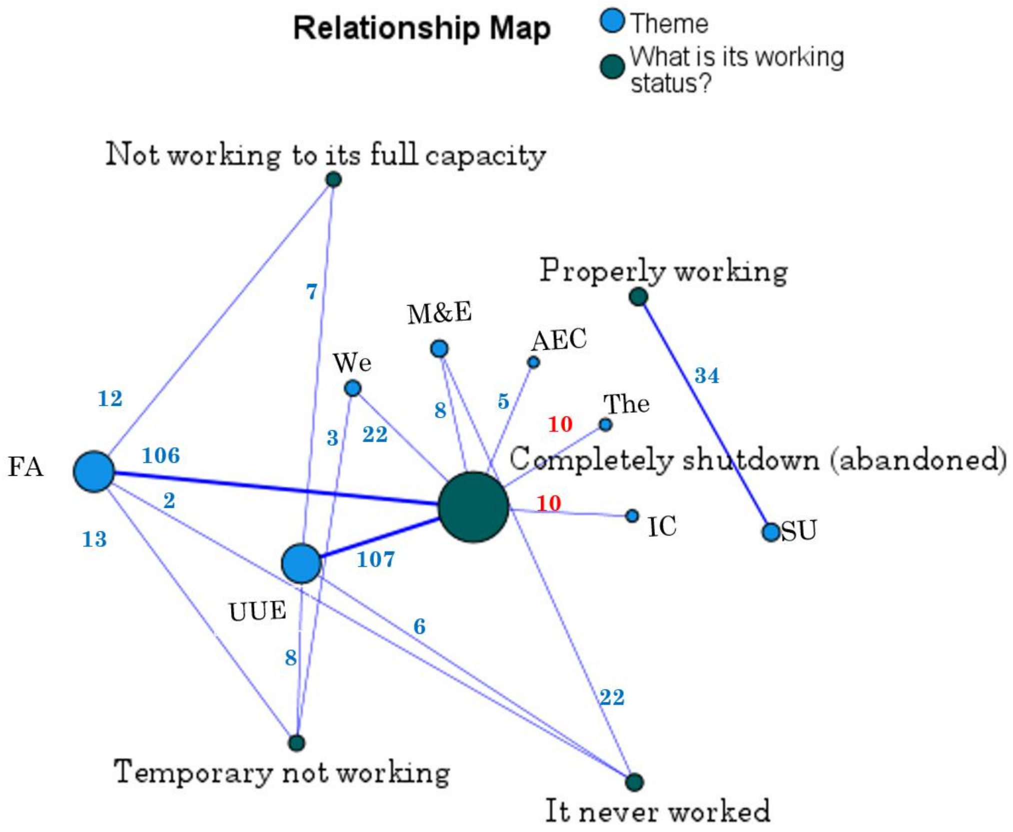

Fig.15. Relationship map for plants categorical working statuses and thematic linkages (source: author) [52]

Unmet Users' Expectations (UUE); Households expected biogas to cover daily cooking energy needs. Contrary to their expectations, users reported that biogas often failed to meet the requirements of heavy dishes that involve prolonged simmering, such as the long boiling (e.g., *isombe)* and staple dishes that require continuous stirring and high thermal power (e.g., *kawunga*). Prefabricated burners and locally fabricated stoves struggled with firepower and stability, leading to routine fuel stacking. Two respondent groups emerged under this theme: *(i)* households with sufficient feedstock, finance and labour who intentionally abandoned the technology because biogas produced was persistently inadequate, and *(ii)* households that initially stacked to compensate unmet demand but later abandoned due to the unexpected daily feeding burden, periodic maintenance, and unsatisfied cooking needs. Across these groups, 107 cases of technology abandonments are linked directly to *Unmet Users' Expectations (UUE)* [52].

Sustained use (SU); Findings reveal that sustained use was found to be linked to semi-intensive mixed farming with zero-grazing practice, in which users valued bioslurry as high-quality organic manure. Respondents under this category explicitly stated that organic manure from bioslurry motivated the sustained use of the technology. Such findings contrast with the programme's energy-led framing which treated biogas systems as an energy-centric programme within user communities. Alongside agronomic benefits, another group of households under this theme indicate that they sustained biogas use due to its rapid combustion compared to charcoal or fuelwood, valuing its suitability for time-sensitive tasks such as breakfast preparation. This was specific to households with school-aged children. In other households, the sustained biogas use was supported by the combined benefits of a cleaner kitchen environment and slurry use, particularly among households with elderly members assisted by farm or household helpers. Nevertheless, even among these '*positive deviants*', fuel stacking continued for cooking high-energy-demand meals, indicating that cooking service alone rarely sufficed [52].

Monitoring and Evaluation (M&E); Among surveyed household, 8.2% were recorded in official programme databases as biogas users on the basis of approved installations, yet their plants never became operational (e.g., installation remained incomplete due to contract issues or commissioning failed due to potential improper feeding). This mismatch between administrative records and operational reality indicates limitations in programme monitoring and verification, allowing non-operational systems to persist in the database as active installations. Although M&E indicators were only weakly linked to "*abandonment*" and "*never-worked*" outcomes, shortcomings in M&E remain a plausible explanatory factor for the programme's early-stage underperformance [52].

Theft (The); Although a few households reported theft of biogas systems components within the neighbourhood, these incidents were isolated and had limited overall post-adoption trajectories. Theft of water tanks, shades, pipes and valves discouraged reinvestment in some isolated cases. Ten respondents cited theft as a reason for giving up, reflecting perceived insecurity of assets rather than technological limits [52].

Weather (We); Environmental stressors were reported, particularly for flex-bag systems. Prolonged drought and wind exposure accelerated deterioration of shading structures and polyethylene digester bags, increasing the risk of leaks or ruptures, while heavy rainfall contributed to erosion on steeper sites. Although the relationship map indicated a weak linkage between weather and the technology abandonment, weather conditions appeared to exacerbate vulnerabilities where design and siting were already marginal [52].

Alternative energy carrier (AEC); Among respondents, only five households reported switching from biogas to LPG. These households were relatively better resourced, financially affluent and cited the *no-labour* advantage of LPG, alongside its improved availability and supply chains in Rwanda. This therefore reflects a limited, affluenceassociated pathway from biogas to LPG. It is rather a broader trend of technology abandonment within the sample [52].

Isolated cases (IC); sporadic cases were documented from sampled HHs. These included rodent damage to polyethylene biodigesters, operator ill-health or ageing, and COVID-19 restrictions that limited technician access. Disruptive household circumstances were also linked to bereavement, intra-household conflict, or neighbourhood disputes. These factors explain only a small subset of technology abandonment cases and are best interpreted as idiosyncratic shocks rather than systemic drivers of post-adoption use trajectory [52].

4.2.2. Thematic results from household livelihood framing

Linking the survey results, auxiliary measured and quantified data to the thematic results emerging from interpretive phenomenology rooted in household livelihood analysis revealed 12 sub-ordinate themes, clustered into four super-ordinate themes that explain how household livelihoods shape the household biogas systems use, as indicated in Fig.16.

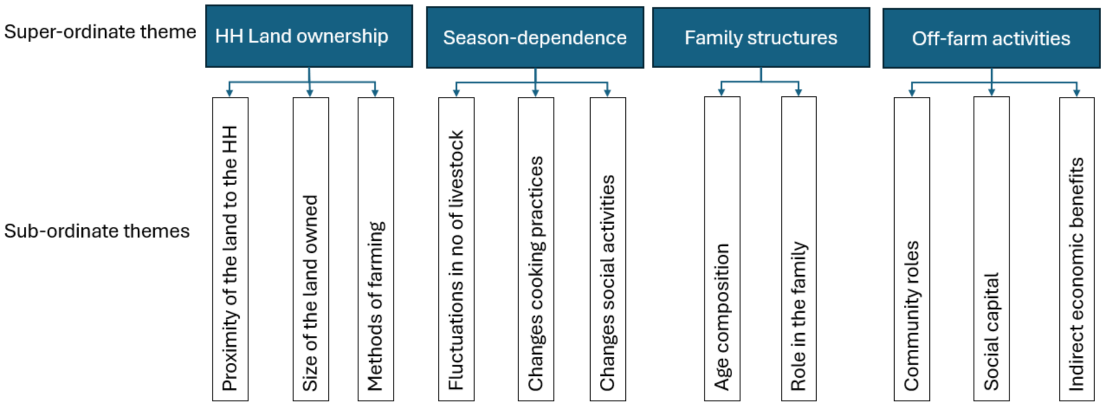

Fig.16. Thematic results from livelihood data analysis and biogas utilisation patterns (source: author) [41]

Household land ownership (consolidated vs fragmented); households with consolidated landholdings used for their living (residence, livestock, and crops co-located) had sufficient time and proximity needed for more consistent digester operation and biogas use, whereas fragmented (often cultivating on distant pieces of land and keeping cattle at the homestead) revealed less consistent technology operations and inconsistent technology use. This closely confirms findings from the countrywide survey indicating that land-use changes (e.g., plots rezoned from farming use to housing use) prompted households to move cattle off-site, making dung collection impractical, hence abandoning the technology.

Season-dependence; the dry season introduced livelihood shifts that reduced effective use, especially for households with fragmented land through seasonal changes in livestock availability/management. This also closely confirms findings from the survey indicating that households who lived in more 500 *m* from a water source, 3,000 *l* rainwater harvest tanks were provided, but during 3–4 months dry seasons the stored water was insufficient due competing demands from livestock and domestic uses. Reliable availability of cheaper fuelwood, which substituted for biogas, together with dry season shifts in meal preferences and cooking practices, was observed to reduce household interest in using the technology. This agrees with results from the survey indicating that biogas often failed to meet heavy-dish requirements (e.g., long boiling of dry beans and "*isombe")* and staple dishes that require continuous stirring and high thermal power (e.g., *kawunga*). During the dry season, increased social activities and time away from home (e.g., weeding events and extended visits to distant families) were observed to disrupt regular feeding and biogas use, contributing to inconsistent operation and lower overall utilisation.

Family structures; biogas use depended on household composition and role allocation, whereby households dominated by school-aged children had lower day-to-day participation in operation/maintenance. During school holidays (overlapping with the dry season), biogas tended to be used selectively for "lighter" tasks while solid fuels remained common. In contrast, households with stable multi-age presence and/or available labour showed more consistent operation and steadier use. The link between the family structures and required family labour for consistent technology operation was also reported from survey results indicating that households who initially stacked to compensate unmet cooking energy demand later abandoned the biogas use due to the unexpected daily feeding burden.

Off-farm activities; community roles and social obligations competed with time for system management, contributing to irregular operation in some cases. Although not formally employed, some household heads were actively involved in community and local social networks, including village committees and agricultural cooperatives, which often provided social capital and indirect economic benefits. However, where household arrangements could not compensate for their absence, particularly in the management of the technology operations, system functioning was negatively affected. Time constraints and shifting priorities led to irregular feeding schedules, resulting in inconsistent biogas production and use. Furthermore, household heads often retained stronger links to alternative fuels, particularly fuelwood and charcoal, which were readily accessible through nearby trading centres. As a result, when biogas production declined, households tended to revert to fuelwood use rather than prioritise efforts to restore biogas system performance.

4.3 Axillary findings

Auxiliary findings not only enhanced interpretation and explanation but also revealed insights on technology utilisation; 2,172 m^3 of biogas were consumed and 135 m^3 were vented by the four selected households in a seven-month period, leading to a 16:1 use-to-venting ratio. Site-level venting were 44.5 m^3 (*EKF*), 36.4 m^3 (*SJB*), 28.3 m^3 (*WMT*) and 25.6m^3 (*NGT*). No biogas leakage was detected during the study period. Vented gas translated to 33–56 $kgCO_2e$ per household per month, derived from recorded vented volumes with altitude/temperature-adjusted gas densities and standard global warming potential (GWP) factors [46]. Temporal patterns indicated that venting was typically higher in June, November and December as Indicated in Fig.17. Utilisation declined July–early

October (dry season), linked to intermittent under-feeding, and leading to less gas production but also reliable supply of fuelwood [46].

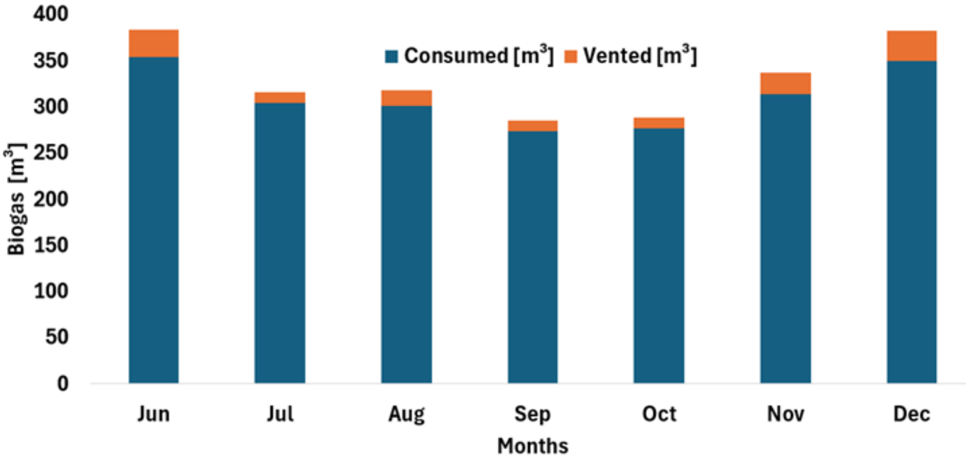

Fig.17.Monthly biogas consumption and venting from the four HHs (source: author) [46].

Segregated auxiliary fundings helped to explain the divergency in system utilisation at respective HHs as presented in Fig.18. The average daily consumption segregated by month was 3.6–3.8 m^3 (*SJB*) and 3.0–3.5 m^3 (*EKF*) versus 0.92–2.30 m^3 (*WMT*) and 1.2–2.40 m^3 (*NGT*). Further, all households continued fuel stacking. The recorded venting ranged from 0.04 to 0.39 $m^3\ day^{-1}$, equivalent to 4–9 % of daily production, underscoring how household livelihood shape the HH biogas systems outcome [41]. Follow-up probing to clarify the drivers of the observed patterns indicated that locally fabricated biogas stoves often lacked sufficient heat output and mechanical robustness for preparing staple foods that require vigorous stirring and prolonged simmering. As a result, households under-utilised available biogas, contributing to venting even when gas was available.

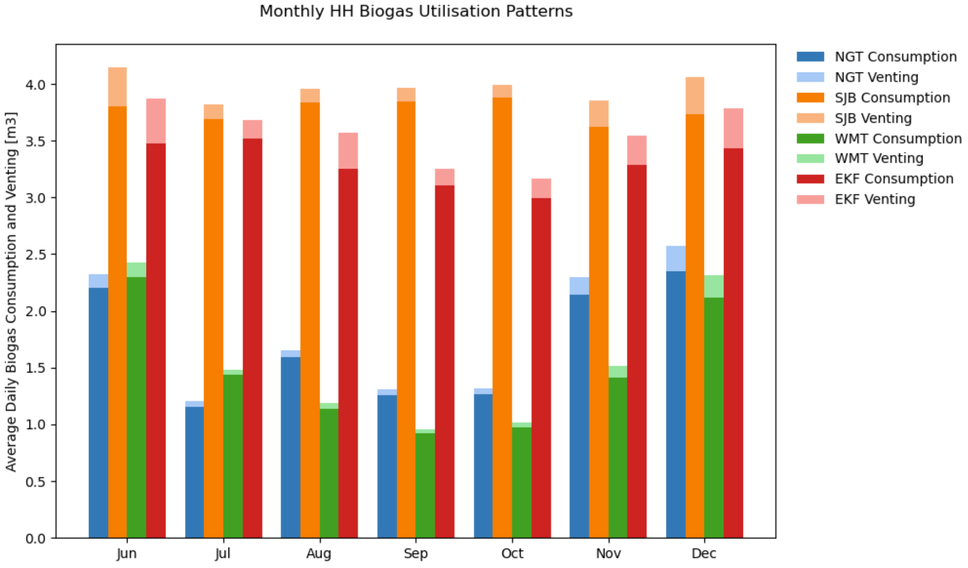

Fig.18.Monthly average biogas consumption and venting patterns per HH. "SJB, EKF, WMT, NGT" represent the coded participating households (source: author).

5. Discussion

This chapter reflects on four interrelated research questions central to the understanding of the post-adoption dynamics of household biogas technology in Rwanda. It examines the trajectories of household biogas systems after adoption, the factors associated with technology abandonment, the conditions underpinning sustained use, and the role of household livelihoods in shaping biogas production and use. By bringing these dimensions together, this discussion presents an integrated interpretation of the uneven outcomes of household biogas production and use beyond initial uptake.

Evidence shows that the divergence between installed systems and realised benefits cannot be adequately understood through technical potential or adoption metrics alone. Rather, household biogas use emerges as a socio-technical phenomenon in which technological performance is shaped by everyday practices, household routines, and the conditions under which systems are expected to operate. This is consistent with literature showing that energy technologies produce outcomes through their interaction with users, practices and infrastructures rather than through technical artefacts alone [57,58].

A first point of the discussion concerns the distinction between deployment and service delivery. The survey evidence showed that the presence of a household biogas plant does not imply effective or continued use. A substantial share of systems had been abandoned, while only a small proportion remained fully functional. This finding is significant because much of the literature on household biogas and clean cooking has often treated adoption or installation as a proxy for success [59,60]. Yet studies across low- and middle-income settings increasingly show that access does not automatically translate into sustained use, and that post-adoption trajectories require closer analytical attention [61]. The thesis therefore adds to this literature by demonstrating that underuse and abandonment of the household biogas technology in user communities are not marginal issues, but central to the understanding of actual energy service delivery in these energy-poor communities.

A second point concerns the explanation of divergent outcomes. The findings suggest that variability in household biogas performance is not best understood as a matter of isolated user choice or technical malfunction alone. Instead, continued use and abandonment can be analysed in relation to how the technology fits within household livelihoods and everyday routines. Land arrangements, livestock management, labour availability, seasonality, and cooking practices all shape whether a biogas system can be fed, maintained and productively used over time. This interpretation resonates with literature that frames energy transitions as shaped by social practices and domestic routines rather than by technology adoption alone [62]. It also aligns with household biogas studies showing that operational success depends on local institutional and livelihood conditions, not merely on technical suitability [63].

Evidence shows that simplified eligibility criteria for selecting potential technology users, such as livestock ownership and water access, were insufficient to predict sustained use. These criteria may identify basic technical potential, but they do not capture the wider household dynamics that determine long-term operation. The feasibility-assessment deficits contributed directly to later discontinuation. This observation complements earlier work showing that domestic biogas programmes often rely on generalised assumptions about feedstock while giving limited attention to context-specific constraints [64].

The findings also raise important questions about the framing of household biogas as a clean-cooking intervention. The results consistently show that cooking service alone rarely anchored sustained use. Even where systems remained operational, complete displacement of biomass was uncommon, and fuel stacking persisted. More strikingly, sustained users often attributed continued operation not only to the value of biogas for cooking, but also to the agronomic benefits of bioslurry. This supports previous work showing that the benefits of household biogas frequently extend beyond cooking to include nutrient recycling, waste management and agricultural productivity [65]. At the same time, it challenges energy-centric framings that evaluate household biogas mainly in terms of fuel substitution.

The measurement and monitoring findings add an important supporting dimension to this discussion. By making household biogas systems observable under real-use conditions, the monitoring work addressed a major limitation of perception-based evidence–the inability to verify actual use patterns over time. The logged data revealed underutilisation and venting patterns that could not be confidently inferred from user accounts alone. This does not displace the interpretive findings; rather, it strengthens them. The value of measurement in this thesis lies not in producing a competing explanation, but in substantiating that household-level divergence is real and not merely a matter of subjective reporting. This is consistent with recent work arguing that metered and digitally monitored approaches can improve the credibility of claims around decentralised energy services and clean-cooking outcomes [66,67].

The venting results are important in relation to the environmental claims surrounding household biogas. The thesis shows that biogas losses can occur when systems are underutilised, and that these losses can be translated into household-level CO_2e implications. This matters because household biogas is often promoted as environmentally beneficial by default, with benefits assumed to follow from installation and fuel substitution [68,69]. However, a growing body of literature has warned that methane leakage and venting can erode, or even negate, expected climate benefits if systems are poorly managed or underused [70–72]. This thesis supports that line of argument by linking everyday use conditions to environmental performance.

Taken together, the thesis shows that household biogas should be analysed and governed as a socio-technical service whose performance depends on sustained use under everyday conditions. The technology does not fail or succeed solely because of its physical design, nor can its performance be inferred from installation counts or generalised assumptions about user benefit. Instead, sustained service emerges where technical requirements, household capabilities, livelihood routines and perceived benefits remain sufficiently aligned over time. Where this alignment breaks down, underuse, venting and abandonment become more likely.

6. Conclusions and recommendations

The findings presented in this thesis indicate that household biogas technology can technically contribute to clean-cooking and broader sustainability goals only if attention shifts from installation targets towards sustained service delivery under real-use conditions. Based on the integrated evidence, policy-and practice-oriented conclusions and recommendations emerged.

Feasibility assessments that rely narrowly on proxies such as livestock ownership and water access overlook household labour availability, land-use arrangements, seasonal dynamics, and cooking practices that materially shape long-term operation. Incorporating bottom-up, household-level assessments into programme design would reduce the risk of post-installation abandonment and improve alignment between technology requirements and everyday realities. Thus, policy frameworks ought to move beyond simplified eligibility criteria for the technology ownership potentials.

Evidence shows that sustained use is frequently anchored in agronomic benefits from bioslurry, with cooking services alone rarely sufficient to motivate continued operation. Policies that recognise and support the agriculture–energy–environment nexus through coordinated planning across sectors are more likely to foster durable engagement and avoid narrow energy-centric performance metrics. Hence, household biogas should be framed and supported as a multi-purpose socio-technical service, rather than solely as a cooking-energy intervention.

Low-power monitoring and smart metering can enable early detection of underuse, operational anomalies, and biogas losses, supporting maintenance and user feedback before systems deteriorate. While not a substitute for contextual understanding, such tools can enhance accountability and help programmes move from assumed to verified service delivery. Monitoring and verification mechanisms should be strengthened to complement interpretive understanding with field-grade evidence.

Persistent fuel stacking, even among sustained users, indicates that current stove designs and system configurations often fail to meet the thermal demands of staple foods. Incremental improvements such as fit-for-purpose stoves, auxiliary storage could reduce underutilisation and venting, thereby improving both user satisfaction and environmental performance. Technology design and supporting infrastructure should be better aligned with local cooking practices.

Translating biogas losses into household-level CO_2e reveals that ineffective use can undermine climate benefits, even where systems are installed. Integrating such indicators into programme monitoring would provide a more realistic basis for assessing contribution to SDG 7 and related goals. Policy evaluation should incorporate post-adoption performance and environmental integrity, not only diffusion metrics.

Overall, these recommendations point to the need for service-oriented, context-sensitive approaches to household biogas systems promotion. Policies that prioritise sustained use, recognise household practices, and combine interpretive insight with targeted measurement are more likely to deliver reliable household biogas system outcomes and enduring sustainability benefits.

7. Contribution

This thesis contributes to the scholarly and technical debates on the role and use of household biogas technology within clean cooking transitions. It explains why widespread installations do not necessarily translated into sustained clean-cooking service. Its central contribution lies in demonstrating and explaining that household biogas outcomes are best understood through post-adoption trajectories rather than through installation or adoption metrics alone. By analysing its sustained use, intermittent use, suspension, and abandonment, the thesis demonstrates that discontinuation is not incidental, thereby repositioning post-adoption dynamics as a central concern in household biogas research.

A second contribution is the explanation of what sustains use under everyday conditions. The thesis shows that continued operation is often anchored not in cooking service alone, but also in the perceived agronomic value of bioslurry, while persistent fuel stacking indicates that biogas rarely functioned as a complete substitute for solid biomass in practice. This finding refines dominant energy-centred framings of household biogas by showing that the technology is sustained as part of a broader household livelihood system rather than solely as a cooking-energy intervention.

A third contribution is the demonstration that household livelihood conditions materially shape biogas production and use. Land and livestock arrangements, labour availability, seasonal routines, and household roles are shown to influence whether systems can be regularly fed, maintained, and used. In this respect, the thesis provides empirical evidence that simplified feasibility criteria, such as livestock ownership and water access, are insufficient to explain long-term outcomes. This offers a more grounded account of why apparently similar systems diverge after installation.

A further contribution concerns use-phase environmental performance. Through longitudinal smart metering, the thesis makes household biogas use observable as a service and quantifies utilisation patterns beyond self-reported proxies. Building on these measured data, it identifies and quantifies venting as a real operational phenomenon and translates vented gas into household-level CO_2e. In doing so, the thesis highlights an environmental consequence of ineffective household biogas use, and potential negative and unintended outcome.

Methodologically, these contributions are enabled by integrating survey evidence, phenomenological inquiry, observation, and monitoring within a single interpretive synthesis. This combination allows for analysing household biogas systems not as isolated technical artefacts, but as a socio-technical service whose realised outcomes depend on how technology, practice, and household conditions interact over time. This approach offers a transferable lens for examining other household-scale clean-energy interventions where installed capacity diverges from realised service.

8. Future work

This thesis indicated that despite the dominant cases of the technology abandonment, there are HHs who still use biogas and have sustained its use for years. These users can serve as learning cases within communities. Nevertheless, a key knowledge gap remains regarding whether the benefits are sufficient to attract private-sector investment without ongoing public support. This triggers two important inquiries:

(i) Although bioslurry co-production for crop production emerged as a key co-benefit underpinning sustained technology use among mixed-farming households, further research is needed to assess whether the benefits realised under these conditions are sufficient to maintain continued use without ongoing public support.

(ii) Although this thesis addressed research questions on post-adoption trajectories and how HH livelihood dynamics influence the use of the technology, broader synthesis is required explain *what* works, for *whom*, in *which* contexts, and *why*?

The future work picks from these two underlying questions. The intention is to develop a '*realist synthesis*' through the context, mechanisms and outcome (CMO) framework for the sustained use of the technology [73]. This will help to explain *what* works, for *whom*, in *which* contexts, and *why*? The synthesis will be developed across macro, meso, and micro levels to provide a comprehensive contextual understanding, identify actionable and triggerable mechanisms, that support sustainable outcomes. To address the question of whether the sustained use benefits can survive without public support, the future work intends to develop a cost–benefit analysis (CBA) for identified sustained-use cases, grounded in potential technology improvement packages. These packages include customised stoves, basic gas purification with locally available materials, low-pressure storage to reduce venting losses, and improved system operation. Benefits will be monetised through fuel and time savings, bioslurry agronomic value, avoided CO_2e, and potential revenues from voluntary carbon markets.

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