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Not quite cooking on gas: Understanding biogas plant failure and abandonment in Northern Tanzania

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ABSTRACT

The potential for biogas to fulfil an integral role in promoting sustainable energy solutions, particularly in the Global South, is evident, and especially pertinent in the Sustainable Development Goal era. Internationally, multiple initiatives driven by private, public and third sectors have resulted in a significant growth in the numbers of biogas plants constructed. These processes are highly visible in Tanzania, which has witnessed considerable investment across the sector in recent decades leading to a proliferation of biogas systems. However, research suggests that many of these plants experience failures which can lead to the ultimate abandonment of the systems, eroding the potential benefits of widespread biogas adoption.

This research explores some of the main drivers of biogas plant failure and abandonment in Northern Tanzania through a rapid review of the literature identifying current sector best practice and a series of semi-structured interviews with key stakeholders including: biogas plant owners, operators, constructors, government officials and private enterprises. The analysis reveals a range of clear and, at points, interrelated themes associated with biogas failure which can be largely grouped under the following banners: poor construction and installation, sub-optimal feeding practices, operation and maintenance issues, and training provision and knowledge erosion. By illuminating the subtleties surrounding each challenge, this paper is designed to stimulate a re-evaluation of how long-term, sustained and successful use of biogas plants can be fostered through a reduction in failure and/or abandonment. This is particularly important given that the biogas sector continues to evolve and expand across the globe.

1. Introduction

Biogas is derived from the anaerobic digestion (AD) of biomass and organic waste material and can be burned directly, used in combined heat and power units to generate electricity, cleaned to create bio-methane for use in national grids or as a transport fuel. It is also recognised as having significant value for managing waste, while the digestate produced as a by-product of AD is widely valued in farming communities for its potential to reduce reliance on chemical fertiliser [1,2]. Reflecting efforts to reduce greenhouse gas emissions from the global energy and agricultural sectors, biogas has received significant recent attention as part of global strategies to increase reliance on renewable fuels, de-carbonise energy supply, mitigate climate change and reduce reliance on fossil fuels [3–5]. It is also valued for its potential contribution to Sustainable Development Goal 7.1.2's aim of achieving 'universal access to clean fuels and technologies for cooking' by 2030 [5]; particularly in light of slow progress to date in the uptake and sustained (exclusive) use of cleaner cooking solutions [5–9]. There is also a need to reduce the health impacts associated with household air pollution from burning biomass, particularly given that cooking with traditional solid fuels is estimated to cause approximately 4 million premature deaths annually [10].

In the decades after Tanzania's independence in 1961, the country's energy landscape has been driven by "hydropowered industrialisation" [11]. However, this source of power now only constitutes 1.2% of the total energy consumption (with petroleum 7.8% and natural gas 2.4%) [12]. Moreover, despite 84% of the final total energy consumption being through renewable energy, and with 38% of the population having

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access to electricity (Urban 73%, Rural 18%), 90% of Tanzania's population still rely significantly on burning biomass as their primary source of energy [13,14] In Tanzania, as well as more broadly across sub-Saharan Africa, off grid areas, where biomass fuels are the primary sources of household energy, there is a lack of infrastructure to support transitions to electricity or LPG. As such, small-scale biogas units have the potential to improve access to clean modern energy sources for cooking, heating and lighting whilst helping to substitute for fossil fuel based alternatives like LPG [15–19]. In China, small-scale biogas systems have been widely promoted for over 30 years [20], while India's National Biogas and Manure Management Programme promoted AD for improving household access to clean cooking and lighting fuels [21,22]. More recently, the Africa Biogas Partnership Program (ABPP) has promoted small-scale biogas in Kenya, Uganda, Tanzania, Burkina Faso and Ethiopia with 51,000 units being constructed since 2015. As key potential beneficiaries of biogas as a clean cooking fuel [23], the ABPP has sought to train women in the construction and maintenance of biogas plants [24].

Biogas technology was first introduced in Tanzania by the Small Industries Development Organisation (SIDO). In 1975, in collaboration with a number of Non-Government Organisations (NGOs) it was expanded with the support of the Centre for Agricultural Mechanisation and Rural Technologies (CAMARTEC and the Dutch not-for-profit international development organisation SNV [25]. Further support for small-scale AD plants came from the Tanzania Domestic Biogas Project (TDBP), implemented through the ABPP, which oversaw the construction of over 12,000 biogas plants between 2009 and 2015. In 2016, the TDBP received nine billion Tanzanian shilling ($3.9 million USD) worth of funding from the governments of Tanzania, Netherlands and Norway for the TDBP to install 10,000 subsidized rural biogas plants by December 2017 [26,27]. Progress in Tanzania and across east Africa slowed after the second phase of the project closed in 2019 [28] and more recently due to the effect of the COVID-19 pandemic. The scheme was targeted particularly at farmers with livestock who could use animal manure and other organic wastes as feedstock for their AD plants and focused especially on northern regions of Arusha, Kilimanjaro and Manyara, due to their high proportion of cattle rearing households [25,29].

While biogas technology has become increasingly visible through such national initiatives coupled with global efforts to promote clean energy sources and mitigate climate change, these positive changes have been somewhat undermined by the lack of sustained use of many small-scale biogas systems or their subsequent failure or abandonment [30–33]. Understanding some of the factors responsible for this is a key focus of this paper and reflects growing interest within the household energy sector on barriers to the sustained and exclusive use of clean energy sources rather than just their initial uptake [6–9,34]. The aim of this paper is thus to build a qualitative understanding of the key factors responsible for the abandonment of small-scale biogas plants in Northern Tanzania and to suggest evidence based, user-identified, solutions to reduce biogas plant abandonment. This aim is realised through two Research Objectives (RO) where emphasis is placed on both the technical and social components of this multidimensional process, exploring new and underreported factors which contribute to these failures:

- RO1 - Conduct a rapid literature review of small-scale biogas plant literature to identify common barriers to initial adoption and sustained use and inform initial interview guides and identify stakeholders for RO2.
- RO2 - Conduct qualitative interviews with key biogas plant stakeholders to understand perceptions of small-scale biogas plants, shed light on key reasons for their failure in Northern Tanzania, and present user-identified solutions to small-scale biogas plant abandonment.

In response to calls to bridge gaps between 'hard' technology-based and 'soft' social science based approaches with more human-centred research [35,36], our contribution to the small-scale biogas plant discourse is twofold. First, to create a holistic and multi-dimensional understanding of the context specific behaviours and attitudes of people in Northern Tanzania who engage with biogas plants on a regular basis; especially owners or operators whose interactions with these systems are integral to their everyday lives and routines. Second, to understand the lived experiences of such individuals and to shed light on the hardware and software issues that underlie acceptance and use of biogas plants or their failure and abandonment. The paper's novelty lies in the use of qualitative research to obtain the end-user perspectives that are so often neglected from technology-focused research and innovation [37]. The focus on barriers to sustained use of small-scale biogas rather than just initial uptake provides important insights into why 'back-sliding' from clean to polluting energy sources occurs; complementing studies of this phenomenon in relation to other fuels and technologies [38]. The paper's significance lies in its potential to inform future small-scale biogas interventions, enabling them to better meet end-user needs whilst promoting more sustained and sustainable access to clean energy in communities that currently lack this. The findings are likely to be of interest to practitioners, policy makers and academics with interests in increasing access to clean, renewable energy in low- and middle-income countries (LMICs).

The structure of the paper is as follows: Section 2 outlines the methodological approaches used. To provide context for the qualitative results, Section 3 draws on existing literature to identify the main barriers associated with small scale AD systems in a range of different regional, agro-ecological, climatic and institutional contexts. The findings are presented n Section 4, and include user perceptions of biogas as a cooking fuel, user perceptions of the causes of poor functionality and failure of biogas plants and user-identified solutions to biogas plant failures. The paper concludes, in Section 5, by offering a number of practical actions which seek to address some of the more common issues associated with biogas plant failure which, if implemented, have the potential to significantly reduce abandonment rates in Northern Tanzania and beyond.

2. Methods

The methodology for this research contains two elements. The first is a rapid literature review of the small-scale biogas plant failure and abandonment literature which sets out the current state of knowledge and sector understanding. The second draws on 30 interviews to capture a qualitative portrait of five biogas stakeholder groups whose lived experiences are critical in understanding the underlying issues which cause biogas plant failure and or abandonment. These two elements are linked through the use of findings from the rapid review to shape discussions with the five biogas stakeholder groups.

2.1. Phase 1: Rapid literature review of small-scale biogas plant failure literature

The rapid review methodology provides "a type of knowledge synthesis in which components of the systematic review process are simplified or omitted to produce information in a short period of time" (p.2) [39]. This enables researchers to identify key literature quickly and effectively in narrow fields of study in time-limited contexts [40,41].

Whilst the wider energy sector and other energy technologies such as solar PV and improved cookstoves have received significant attention in low-income settings, small-scale biogas plants have in some cases been overlooked in previous energy studies [32,33,42]. This, due to the complexity of biogas plant implementation (as discussed in this paper) as it requires a detailed understanding of the complex socio-cultural preferences of end-users, further narrows the literature search and lends itself to the rapid review method. Both published and grey literature were drawn upon but the search was not further limited by restricting publication date or journal type. The rapid review started by drawing on the extensive knowledge of the researchers to establish widely cited systematic reviews that outlined the user-perceived barriers to small-scale/household/decentralised biogas plants. Then using literature databases such as Science Direct [43] and Connected Papers [44], references in the widely cited systematic reviews were extrapolated to follow the narrative through other publications and grey literature.

2.2. Phase 2: A portrait of lived experience in northern Tanzania

Based on the research objectives, a qualitative research pathway was developed, with individual interviews with a range of stakeholders, as outlined below. Semi-structured interviews with respondents enabled researchers to keep discussions focused on biogas specifically while allowing respondents to share their own views as to how such plants are integrated into their everyday lives. Direct observation of the biogas plants in the field helped provide an additional layer of context in terms of understanding the way in which biogas plants were constructed, used and maintained in an active environment. Interviews were facilitated with the assistance of ECHO (East Africa Impact Center), a Christian NGO, with an office based on the outskirts of Arusha in Northern Tanzania. The organisation's network of stakeholders specific to the biogas sector was also drawn upon for organising interviews and undertaking biogas plant visits in October 2017. This organisation has a strong developmental and agricultural focus and concentrates on a variety of issues related to improving rural livelihoods, with an explicit overarching objective of reducing poverty amongst the rural poor.

2.2.1. Data collection

In total, 30 interviews were conducted with five stakeholder groups (Table 1) across three different areas in Northern Tanzania: Arusha, Kilimanjaro and Manyara regions. This number of interviews enabled the research to create a broad understanding of a range of factors associated with biogas plant failure that were specific to this geographical location. These key stakeholders were identified by project partners using purposive sampling based on their extensive experience in the Tanzanian biogas sector.

The questions asked during the interviews varied by stakeholder type but included enquiries about different types of biogas plant design (as presented in Fig. 1 and Fig. 2), common challenges associated with their maintenance, the efficiency of gas production as well as the broader political and economic environment surrounding the biogas sector. Ethical approval was obtained from the University of Nottingham, Faculty of Engineering Research Ethics Committee. All participants provided informed consent knowing that all their data would be anonymised and held confidentially. All consent forms and participant information sheets were verbally translated into Kiswahili. Where discussants were unable to provide a written signature their consent was represented in the form of a thumb print or audio recorded statement.

Fig. 1. Concrete fixed-dome biogas digestor.

Fig. 2. Plastic bag biogas digestor.

Table 1
Stakeholder groups.

Stakeholder Group	No. of Interviews	Detail.
Owners of Operational Systems	12	Farmers and a small number of other institutions, such as schools
Owners of Non-Functional Systems	10	Included to elicit a wide range of views around system failure and barriers to sustained use
Government Representatives	2	Representing departments responsible for the development of agricultural technologies
Biogas Plant Constructors	3	Biogas plant manufacturers – predominantly focused on plastic-based systems (floating dome and bag) – and constructors (known locally as masons) who mainly built concrete, fixed-dome digesters
International NGOs and Consultants	3	Involved in the development of Tanzania's biogas sector and whose activities ranged from increasing educational awareness to supporting the development of new biogas businesses.

2.2.2. Data analysis

All interviews conducted were transcribed before being qualitatively examined using a thematic analysis approach [45] to elicit dominant narratives emerging from the interview process which built on core topics identified in the rapid reviews.

2.2.3. Limitations

Phase 1, the rapid review method, has a number of limitations, such as issues around transparency and reflexivity [41] Issues of unconscious bias and positionality as European researchers are also acknowledged [46]. The most significant limitation of this method is that it may not capture more obscure literature as a systematic review would, however the extensive experience of the authors in the small-scale biogas sector helps to mitigate these issues.

In phase 2, the role of positionality, bias and outsider status need to be acknowledged in relation to the data collection and analysis process. Issues surrounding the role of outsider status [46] were mitigated by using existing connections and partners based in these regions of Northern Tanzania. Most notably, this was achieved through connections with the aforementioned NGO ECHO which has a long established community presence in and around Arusha. Through ECHO, it was possible to connect with the Tanzania Domestic Biogas Programme and long-established international development organisation SNV who have worked extensively in this field, specifically in this geographical space. Such institutions were able to connect the authors with biogas stakeholders in the community, from users and advocates to constructors and maintainers. In cases where the stakeholders were non-English speakers, interviews were conducted with the support of a reputable translator identified by the project's in-country partner, ECHO.

The authors were acutely aware of their positionality as external researchers and therefore interviews were selected as the key methodological approach to allow the discussion of issues that most affected stakeholders on the ground. This was in contrast to the structured, externally driven or quantitative approaches, which could have been employed and would have been centred much more actively on existing Western understandings of the failure and abandonment of biogas plants, in addition to other cleaner energy solutions. The focus was to present a neutral and receptive framework for understanding the strengths and challenges associated with biogas production in these communities, centred firmly on the lived experiences of those currently engaged.

3. Findings: Small-Scale biogas plant failure

Globally a number of research studies have been designed to explore the primary factors which result in a loss of functionality or failure and subsequent abandonment of biogas plants [6,33,47,48]. However, despite a recent increase in literature on broader 'socio-cultural or 'software' factors influencing household priorities; especially regarding cooking and fuel use [6,8,49,50], research on biogas – and on energy more broadly - has tended to be dominated by a focus on more technological or 'hardware' factors [35].

3.1. The why (user perceptions of biogas as a cooking fuel)

While the technological aspects of biogas operation and maintenance issues are quite well documented, the economic and socio-cultural 'software' factors underpinning them are spatially varied and less well studied, despite their importance in explaining a loss of biogas plant functionality. From a user perspective, a lack of biogas production to anticipated levels is frequently linked to a lack of sustained use and subsequent failure or abandonment as it necessitates the 'stacking' of additional fuel sources [8,51,52]. In areas where these alternative fuels such as wood are cheap or easy to obtain, this can result in prolonged periods of biogas plant inactivity and loss of function as well as fewer health and environmental gains as users continue to collect and burn biomass [6,18]. Fuel stacking may also be encouraged by user preferences for food to be cooked in a specific way or if additional, more aspirational fuels such as electricity become available [30]. In Ethiopia, the inability to connect biogas units to traditional stove types discouraged sustained use [52], while in other areas the visual appearance of some plants discouraged their use [30]. Software factors including cultural resistance to the use of animal and human waste for energy creation can also act as significant barriers to the long term integration of biogas technologies, as exemplified in Bangladesh [35], Sri Lanka [30], Ghana [53] and elsewhere in sub-Saharan Africa [54].

3.2. Four common themes of biogas plant failure from the literature

3.2.1. Theme 1: Construction and installation quality

Reflecting a focus on hardware factors, the first themes in the literature on small-scale biogas plant failure concerns poor quality installation including the use of inappropriate technology for particular geographical locations. The application of biogas plant technology that is inappropriate for use in sub-Saharan Africa accounts for a lack of long term sustainability [33]. Similarly, in Sri Lanka, a lack of consideration of soil conditions, vibration patterns and the correct positioning of the digester during the construction phase have led to cracking and leaks[1] [30].

3.2.2. Theme 2: Sub-optimal feeding practices

Other difficulties include the occurrence of system malfunctions due to solid digestate incrustation floating in the main tank, reducing the production of biogas [55] or the failure to keep anaerobic digesters within certain pH parameters (ideally close to pH neutral) which can reduce their efficiency and ultimately result in their abandonment [56]. In some cases, this reflects a lack of user-training in operation and maintenance issues, or poor understanding of basic troubleshooting [30]. Drawing on innovations in developing sensor technologies to record the performance of a range of household energy systems [21,22,34,57–59], there is potential to address some of these problems through on-site monitoring and transmitting data on biogas plant performance and functionality for remote analysis [34,59,60].

3.2.3. Theme 3: Operation and maintenance

The lack of a regular, continuous supply of feedstock (such as animal waste) throughout the seasons or the time-costs associated with collecting feedstock in nomadic or free grazing systems may constitute significant barriers to sustained biodigester use [30,31,33,47]. Deaths of animals, climatic variations, reductions in grazing lands or abandonment of animal husbandry may also cause a lack of the necessary levels of biomass to input [30].[2] The failure of users to employ the correct ratio of animal manure to water, either through lack of knowledge or the unavailability of water, has also caused processing problems [6,33]. Location-specific and climatic factors may also play a role in impairing the digestion process and reducing gas production. These include the inability to add sufficient quantities of water in seasonally dry areas [6] or interruptions to digestion caused by low winter temperatures in more mountainous regions [54].

Where mechanical failures are responsible for poor functionality, the inability to quickly and cost-effectively source and fit spare parts can have major implications for the continued use of biogas plants, particularly within rural settings [30]. In Zimbabwe, a large-scale clean energy project designed to demonstrate the sophisticated nature of biogas systems, collapsed, in part, due to the lack of availability of spare parts [48]. In the same arena, an absence of trained technicians in the locality of biogas plants exacerbates these issues in low-income African countries [33].

3.2.4. Theme 4: Training provision and knowledge erosion

Further difficulties are evident in the day-to-day operation of the biodigester and the labour required for this. Some systems require daily cleaning, which has proved to be too onerous for some users [6,61] while others require loading at height which can complicate the feeding process [30]. In sub-Saharan Africa, instances whereby an insufficient desire on the part of users to maintain the digester effectively led to biogas units becoming deactivated [31,42]. In some cases, the departure of young men in the family to pursue other work has, at times, left a maintenance void that other family members have been unable to fill [30].

From an organisational standpoint, a lack of project monitoring or post-installation follow-up has contributed to a lack of understanding of how hardware and software factors intersect to cause poor functionality

[1] The improper construction may be as a result of tight time schedules underpinned by target-driven instillation practises though does not give specific examples [30].

[2] The input of other materials to supplement waste materials due to shortages has also generated problems with the biodigester leading to plant failure [30].

or abandonment of biogas plants. Failures have also been attributed to a lack of focused energy policy in low-income countries which have experienced growth in the biogas sector [31]. Inadequate awareness amongst users as to the advantages of the technology (some users requested biogas systems to solve issues with waste disposal without any intention to use the biogas) can be traced to poor information exchange [30]. Additionally, successful biogas installation and continued use is built upon institutional arrangements and appropriate policies which ensure that products on the market are of high quality [31]. The marketplace needs to be organised efficiently and facilitate the flow of these high-quality products and ensure comprehensive information exchange between stakeholders to reduce the threat of biogas plant failures.

3.3. *The research gap*

These issues do not represent an exhaustive list of factors which can result in the failure of small-scale biogas plants in LMICs. Additional factors are likely to have been substantially overlooked in previous literature on the subject, whilst others play a less visible role including factors linked to biogas plant adoption rather than a lack of sustained use or failure once installed. Generally, users' financial limitations are considered more of a barrier to the adoption of rather than the sustained use of biogas technologies [31,33,54,61], yet labour and maintenance costs imply longer-term financial and time commitments that may become unsustainable. Another important dynamic is that of land ownership, since the fixed nature of many biodigesters, especially those built into the ground, present issues around ownership and responsibility in situations where land is either rented or contested leading to potential conflict and abandonment [33,62].

Given the range of factors influencing biogas plant failure across the global South, it is difficult to identify a single prominent driver. Rather there is a diverse and often context-specific patchwork of factors responsible for a lack of sustained use, loss of functionality and abandonment. Identifying which of these issues are evident in Northern Tanzania, and the underlying processes which have produced these conditions as well as how to overcome these challenges are presented in the following section.

4. Findings: Evidencing lived experience of biogas plant users

This section explores the key themes which emerged from the interviews conducted, examining user experiences of both cooking with biogas and maintaining small-scale biogas plants along with the perceptions of different stakeholders on factors contributing to a lack of sustained use, loss of functionality and abandonment. Lastly, it highlights some user-based priorities and suggested solutions for addressing biogas functionality problems that were identified during the interviews.

4.1. *User perceptions of biogas as a cooking fuel*

On the subject of biogas as a cooking fuel, responses were generally positive, with biogas described as quick and simple to access as it only required opening a tap and lighting the flame rather than the more labour-intensive process of starting a fire with biomass. Interviewees agreed that given a choice of cooking with biogas or other fuels, biogas was their preferred option. This was mainly down to smoke production, particularly in confined spaces with one respondent noting:

> 'My husband has a problem with his eyes when I'm cooking, he doesn't dare even come into the kitchen … but when I'm using biogas, he can come to the kitchen and we cook together' (Interview 5).

Biogas was particularly valued for heating water in the morning (when biomass fires would normally require lighting from scratch) and also for cooking soft items like vegetables.

Despite a general enthusiasm for cooking with biogas, however, key themes arising from the interviews indicated problems associated with poor functionality, insufficient gas production and, in some cases, complete plant failure that hindered a sustained and exclusive shift to the use of clean cooking fuels. Echoing studies elsewhere [6,18], the failure of biogas plants to fully meet users' cooking needs was linked to a tendency to 'stack' fuels, with biogas frequently being supplemented with firewood (either collected or purchased), charcoal or LPG. In many cases, interviewees expressed frustration that they couldn't rely on biogas for more of their cooking needs:

> 'So the worst thing is to be out of gas when cooking' (Interview 4).

> 'If you could be able for the production of the biogas to be like more longer to use it, the people would not even think even to use the firewood or charcoal' (Interview 22).

> 'It's not like much. It's not like using [a] long time. Sometimes [we] use the gas, sometimes [we] use the firewood because there's not enough gas to use to cook everything' (Interview 3).

For some users, temperature variations associated with the changing seasons were identified as a cause of seasonal fluctuations in biogas yields (and increased reliance on biomass fuels for cooking), with the response below typical of the sentiment:

> 'The problem [is] between changing seasons of the year. Because during the rainy season, the plant is going to be like cool. It's no more like gas production' (Interview 22).

Because of the relatively consistent temperatures across the year in this part of the country, however, minimal disruption to gas production was reported on the whole[3] and even where plants were affected by cold weather, users reported that the rate of gas production slowed rather than ceased altogether. Nevertheless, users still felt constrained in the type of cooking that they could do with biogas. Some respondents noted that their biogas units failed to provide sufficient gas for the preparation of local dishes such as Ugali or Makande that required lengthy periods of slow cooking.[4] A reliance on traditional fuels was also encountered including the use of firewood and charcoal to cook 'heavier' foods, such as maize or beans, which form the basis of local cuisine.

4.2. *User perceptions of the causes of poor functionality and failure of biogas plants*

Reflecting wider literature on the *causes* of sub-optimal biogas yields, poor functionality and biogas plant failure [6,51,54], key themes that emerged from the rapid review have been linked to interviewees' explanations of issues related to poor construction and installation, sub-optimal feeding practices, basic operation and maintenance and training-related issues.

4.2.1. *Theme 1: Construction and installation quality*

The failure of biogas plants was linked back repeatedly by owners to initial mistakes made during the installation phases which fell into several specific categories. Firstly, a few biogas plants were observed which were either no longer used or in need of repair due to issues of subsidence. This can be caused by factors including the system being built on unstable land, using soil of the wrong consistency or poor choice of site location. This issue is particularly difficult to remedy, since

[3] NB. It cannot be ruled out that biogas users at higher altitude (for example, deeper into Kilimanjaro region) suffer more from temperature variations which could affect gas production. However a number of sites visited were at significant altitude and were not adversely impacted.

[4] For a typical six cubic metre plant, enough gas to cook for 2–4 h per day was widely reported by users when the plant was fully operational.

addressing structural failure can be both costly and time consuming, especially for biogas systems out of warranty.

Secondly, cracks in the digester, for those made of both concrete and plastic, were identified as an important contributor to system failures, which biogas plant owners predominantly linked to poor installation. Cracking can lead to multiple problems including loss of pressure inside the digester, drying out of material inside the system and disruptions to flows of slurry from inlet to outlet. However, the cause of such cracking was contested among stakeholders as while biogas users tended to believe installers were responsible, those building the systems, as well as some government representatives, indicated that cracking could be a sign of user neglect rather than poor workmanship. Either way, the loss of functionality or limitations on gas production caused by these issues at the installation phase were clearly influential in the failure or abandonment of some systems.

Thirdly, problems associated with piping were routinely identified as contributing to biogas plant failure. Again, these can be categorised into two main issues, both deriving from the installation. Leakages of gas from the pipes, resulting in less gas for end users, was a significant problem. Poor workmanship, particularly in relation to points of connectivity between digester and pipe, was identified by biogas plant owners as the cause of these leakages. This challenge was exacerbated, at times, by the significant distance between the biodigester and kitchen. Similarly, users highlighted rusting on the pipes connecting the biogas digester with the kitchen as a factor responsible for reduced functionality which sometimes contributed to abandonment, as the material and labour costs associated with replacing damaged or rusting pipework was deemed prohibitive. Such rusting is primarily attributed to cost-cutting at the point of installation, with iron pipes being used instead of higher quality materials, such as plastic.

By contrast, representatives from the government department mentioned that they had not observed the use of iron pipes in biogas installations and did not recommend this given the potential for rusting and associated challenges around gas leakage. While liability for issues such as subsidence, cracking and rusting because of errors in the construction or installation phase (either wilful or otherwise) remain contested, the fact that some systems were not built to the necessary standard was clearly a contributing factor around biogas plant failures and abandonment in Northern Tanzania. Users also linked these issues to plants producing significantly less gas for the end user than would have been expected prior to installation.

4.2.2. *Theme 2: Sub-optimal feeding and maintenance practices*

A second theme arising during discussions of the causes of insufficient gas yield, poor plant functionality and failure concerned sub-optimal biogas plant feeding and maintenance practices. Echoing the literature on biogas plant operation and maintenance [6,30,31,47,52], most apparent were issues related to the feeding of the biodigester. These can be categorised under several key themes related to the behaviour of those responsible for ensuring that the system is used correctly and their access to the resources they needed to feed the plant.

To create the correct consistency of material for input to the digester, animal waste is mixed with water[5] in order to facilitate a smooth flow of material through the digester. Depending on the digester design, location and climate, this mixture is usually to a specified ratio; for example, two buckets of waste to two buckets of water with two or three buckets of each needed per day for a six cubic metre plant. This requires not only good access to these resources but also to the labour required to feed the plant regularly to ensure that the feedstock flows at the correct speed through the digester. Without the correct consistency of material facilitated by this mixing, the digester can become clogged, its usual flow impeded and, as a direct consequence, little or no gas production is recorded.

Through both discussions with users about their feeding routine and examination of the inside of the digester, it was evident that users were, in many instances, not feeding the digester with the correct ratios of waste to water. The suboptimal production of gas is likely to be linked directly to this issue. Less common but nonetheless noteworthy was the tendency of some users to add inappropriate materials including grass to the digester to supplement the animal waste, which in a limited number of instances affected the supply of gas. Additionally, even where the feedstock type and mixture was correct, the inability of users to feed the digester regularly enough was identified as a factor in the breakdown or reduced production in some of the plants visited. For the plant to work most efficiently, a steady flow of materials must continuously move through the system, allowing for the anaerobic digester to produce the gas and to create and maintain the necessary gas pressure to force the slurry through the outlet. Therefore, a regular feeding pattern (either once or twice per day dependent on the system, at around the same time each day) is required to maintain this process.

In some cases, seasonal variations in water availability interrupted the regularity of feeding patterns or contributed to the use of incorrect waste to water ratios. It was evident that some users found it difficult to access water during the dry season:

> 'After rainy season ended we start the problem of having water. We need to travel from home to [water source], it's like 400m. So when go and back it's like 800m. Every day.' (Interview 4).

> 'Yes, we've had that problem [lack of water] because we use tap water. The water we trap from the mountains. So we had the problem of not having water here. So it's took us like two weeks without using the biogas' (Interview 1).

Although the research did not suggest that water shortages were in themselves significant contributors of biogas plant failures, they clearly created temporary challenges for users and were linked to periods of paused feeding or plant inactivity which in turn had an impact on gas yield.[6]

4.2.3. *Theme 3: Operation and maintenance*

A third key theme that emerged in explanations for biogas plant failure and poor functionality concerned the responsibility of the user to operate the plant appropriately and perform basic maintenance. Particular attention was drawn to the ongoing issue of water forming in the pipe connecting the digester with the kitchen and the need to remove this water, through the regular opening and closing of a purpose-built tap on the piping, to prevent reductions in the flow of gas.[7] While most users were aware of the need to remove water in this way, this knowledge was not universal. Frustration with a perceived lack of gas production, at times led to abandonment, even when the supply was simply being blocked by the presence of water. This represents an issue with a straightforward resolution, yet equally is one which has the potential to have a serious impact on gas production and plant functionality. A simple solution for this problem may already be in existence. SimGas, a private sector biogas plant construction company, provide a two-year warranty against structural failures, and such a mechanism can provide reassurances to potential customers who are naturally wary of the ability of poor installation to undermine their investments. It is unlikely that all plants will be constructed perfectly, therefore providing such support is critical to preventing system failure, especially in the

[5] Animal faeces can also be mixed with urine instead or water. However, this was only realistic in cases where cattle were subject to zero-grazing, which only accounted for approximately 50% of biogas users interviewed.

[6] Again, this is geographically sensitive and represents the situation in Northern Tanzania. Given the country's size and climatic variation, such issues may be more or less prominent in different regions.

[7] Regular in this instance was dependent on the amount of water forming but for a plant operating to potential, weekly removal was typical.

first years after installation.

4.2.4. Theme 4: Training provision and knowledge erosion

The evident lack of such knowledge among some users echoed a fourth key theme emerging from explanations of biogas plant failure which concerned the training of biogas plant users and the erosion, over time, of knowledge obtained during such training. During interviews with biogas plant owners, it became clear that the installation of their plants was usually accompanied with some form of user training on how the system should be operated to maximise efficiency and lifespan. Both the Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC), the government department overseeing biogas development in Tanzania over recent decades, and private sector biogas businesses have offered training to households in how to operate their new biogas system efficiently. Training typically covers how to feed the plant (amounts, timings, ratios etc.), how to address simple issues, such as extracting water from the pipe using the tap, and the uses for bio-slurry.

Despite this comprehensive training, biogas plant failures due to operator error represent a significant challenge to their long term use; despite the fact that in most cases users have invested their own funds[8] in the system and value the free fuel it produces. Some broader context is therefore required to understand this outcome. The primary users of biogas technology in this location are farmers who, given their assets such as land and livestock and their investment in biogas technology, are not at the very bottom of the economic pyramid within Tanzanian society. Furthermore, given their slightly elevated economic position, some farmers can afford to employ a small number of workers to assist in the everyday running of their farms. Particularly amongst owners of larger and more sophisticated plants as, although they may have initially invested more in the plant, much of the day-to-day running of the biogas system was done by their employees including: collecting and moving animal waste, mixing it with liquid and feeding the plant, as well as semi-regular plant maintenance such a removing water from the pipe.

It was also clear that some of these workers, at the time of the biogas plant installation, were provided with training on how to use the technology, along with plant owners, as it was envisaged that they were most likely to be directly engaged with the system on a regular basis. However, given the relatively high turnover of such employees, problems tended to arise when they were replaced by new staff and some of the expertise passed on by the departing worker, became lost or misunderstood. Clearly, this has had significant implications for the long-term sustainability of biogas plants in this region and illustrates that while training at the point of installation is self-evidently vital to successful use, it does not guarantee that the technology will be used correctly over its lifespan.

4.3. User-identified solutions to biogas plant failures

During the course of discussions with biogas stakeholders and users, a few notable suggestions regarding the design of small-scale biogas plants were highlighted as having potential to promote their sustained use and long-term viability. Regarding operation and maintenance issues, user convenience was also highlighted by owners as integral to effective operation and maintenance of biogas plants. This issue manifested itself in multiple forms, however central to most observations was the need to make the process of feeding as simple and convenient as possible. For example, if animals were based in a stall with a concrete floor linked to an adjacent inlet of the digester, the waste material could be easily collected and processed by the user. In contrast, it was noted that if the operator had to expend time and energy collecting waste in wheelbarrow, then transport it to the system in a different part of the dwelling; the inconvenience associated with this process had the potential to discourage users. Location of the plant, proximity and ease of process were each cited as challenges which can lead to incorrect plant operation in this environment, all of which feed into the broader theme of ensuring such systems are designed to be fundamentally user-friendly.

In terms of addressing problems linked to insufficient biogas supply, plant owners, especially those who were responsible for cooking with the gas, valued knowing how much gas there was left in the system to enable them to make choices about when and what to cook. Some of the systems were installed with a pressure gauge, which, while technically measuring the gas pressure and not the gas amount, allowed users to estimate the time left to cook with the fuel. Their owners were positive about having access to this basic information as it allowed them to manage their use of gas to best suit their needs. They therefore felt that an expansion of the use of such gauges would allow those cooking to maximise the effectiveness of the gas produced, even if this was below their total requirements.

5. Discussion

The production of biogas from animal waste, when used correctly, remains an excellent way to use existing waste materials at low cost to produce a sustainable fuel which can reduce the damaging impacts associated with household air pollution as well as lowering the rates of biomass burning. Whilst it is encouraging that significant numbers of plants have been constructed in Tanzania, it is disheartening to see so many abandoned by users so soon after installation. It is also disappointing that the effectiveness of biogas promotion initiatives are often undermined by the frequent inability of small-scale biogas units to meet all cooking requirements, necessitating continued reliance on biomass fuels. Also, as even relatively brief interruptions to the use of biogas plants can increase the risk of technical failures, addressing such issues often requires relying on biomass fuels until the biogas plant is operational again. Instead of achieving a full replacement of biomass fuels with biogas, the adoption of such clean cooking technologies is frequently associated continued fuel stacking. This, in turn, undermines potential health gains associated with biogas use whilst making the abandonment of plants more likely than if users had reliable access to sufficient gas from such systems.

It is evident, through both engagement with the literature and the primary research conducted as part of this exploration, that biogas plant failure outcomes can be viewed as a series of software and hardware challenges rather than one single issue. These challenges are visible at multiple stages (installation, operation, maintenance, and training) and include different actors (masons, users and the natural environment), all of whom can contribute to the failure of biogas plants.

Fundamental to the longevity of a biogas plant is the initial construction. Technicians and practitioners continue to debate the most suitable model of system for the Tanzanian context; be that concrete fixed-dome, inflatable bag or plastic covered which can be expanded through 1 m extensions as per the needs of the customer. Whichever design is selected, the requirement to provide some form of insurance against poor installation is essential to ensure that plants are not abandoned as a result. Conflict between constructor and owner in such contexts is likely, and identifying which party is responsible and therefore liable for the repairs is problematic.

The way in which biogas systems are operated on a day-to-day basis is clearly central to their continued viability; a fact which is bought in sharp focus by the significant number of plants which were inactive or underperforming in this geographical region due to operational errors. The lack of appropriate education and training has previously been cited as a driver of biogas plant failures [30,33], however at the vast majority of sites visited, such services were offered at the time of construction. Nevertheless, the current literature fails to acknowledge the erosion of this knowledge over time due to the continuous turnover of those tasked with feeding and maintaining the plant. In general, key instructions,

[8] Some have received subsidies over the years from either government or third sector organisations, but even these usually require some of contribution from end-users.

such as when to feed the digester and what ratio of waste to water is needed, were usually not recorded on paper, with new workers briefed by outgoing staff verbally, if at all. Finding a solution is essential as without broader support, the initial training can have very little long-term value. Potential options include systematic training refresher visits from installers or through other means such as the provision of physical guidelines at the time of purchase or access to online information.

In addition, the disappointment of end users in the limited or less-than-expected production of gas was evident in conversation with owners resulting in biogas having a poor reputation in the area. These problems are often exacerbated by issues outlined around poor construction or incorrect operation, but it is important for those using the gas for cooking to be able to get the most possible use out of the fuel available. The inclusion of pressure gauges provides a welcome addition in many such kitchens, with users able to estimate the time left to cook and consequently which meals can be prepared with the resources available. The availability of such information can help make the system more valuable to the operator and, as a result, users are less likely to abandon them completely.

6. Conclusion

Technology in this field continues to develop at a steady rate and provide significant opportunities for future work especially through solutions using 'Internet of Things' principles. The advancements in sensor technology [63] - which can be monitored either on-site or remotely - have started to be used to record data across a variety of intervention strategies [7,8,34,57,59,60]. For the biogas sector, such developments may prove useful when attempting to keep plants active and production high, with the potential for sensors to monitor output and performance continuously, providing data which can highlight problems with the system before gas production is significantly affected.

This paper presents several key learnings. Fundamental to future policy development around reducing biogas plant abandonment is a focused and accurate understanding of the key reason behind current trends which this research provides. Poor construction and installation, sub-optimal feeding practices, inadequate maintenance issues along with limited training provision and knowledge erosion each contribute significantly to biogas plant challenges, ranging from sub-optimum operation to complete desertion by owner operators. This research provides an evidence-based understanding of the key drivers of such decisions by users, which is vital given the ability of biogas technology to reconcile the existing and continuing political movement to reduce carbon emissions with the need to advance global ambitions around sustained poverty reduction for populations and communities on the economic fringes in developing nations. To conclude, this research recognises that reducing the failure rates of biogas systems in this geographical area is a complex issue, however steps can be undertaken to reduce the impact of some of the most damaging factors which lead to system abandonments. Specifically, this paper represents a call to action to biogas businesses, installers and constructors to rethink the way in which they deliver training as well as further integrating design features which allow users to understand the performance of their biogas plant.

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CRediT author statement

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Declaration of competing interest

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

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