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Exploring the role of biogas systems in sustainable waste conversion and household energy supply

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ABSTRACT

Background: Systema 20 Model biodigesters were installed at Tsangano Market in Malawi and are being promoted all over the country. However, there is limited field-based proof to support their technical performance and social and environmental benefits. Therefore, this study assessed the technical performance of the biodigester and its community benefits. **Methods:** The study used a mixed-methods approach. Waste composition analysis involved randomly collecting and segregating 835.17 kg of market waste to determine its constituents; direct measurements of feedstock and water inputs and biogas and liquid biofertilizer yields were conducted using calibrated tools; household surveys (n = 385) and focus group discussions were conducted to examine cooking fuel use and firewood displacement by biogas; indoor emission reductions were estimated using WHO air quality guidelines; methane reductions were calculated using IPCC (2006) methods; and laboratory analysis and field experiments were conducted to assess biofertilizer quality and its effect on maize production. **Findings:** Organic waste accounted for 99.9% of market waste; biodigester produced 12 m^3 of biogas and 548 litres of biofertiliser daily, with an operational efficiency of 57.7%; the plant has the potential to support 13 households with clean cooking fuel, displacing 37.1 tonnes of firewood annually and reducing indoor PM2.5 from over 300 $\mu g/m^3$ to below 50 $\mu g/m^3$; the system diverted 50.4 tonnes of organic waste yearly, avoiding 28.05 tonnes of CO_2-equivalent emissions; and the biofertiliser (200.02 m^3/year) had the potential to produce 16 tonnes of maize annually, although it performed better under irrigation than rain-fed farming. **Conclusion:** The Systema 20 biodigester is a promising solution to waste, energy, and environmental challenges at the community level. However, further research is needed to address biodigester efficiency and sustainability bottlenecks. **Novelty/Originality:** This study offers the first integrated field-based assessment of a market-scale biodigester in Malawi, linking energy production, environment, and food security.

KEYWORDS: biogas; Systema 20 model biodigester; biofertiliser; waste-to-energy; food security; climate mitigation.

1. Introduction

Rapid economic development and urbanisation experienced around the globe have contributed to improvements in people's well-being (Singh et al., 2014). However, these developments are associated with high consumption of resources (Trivedi et al., 2015), which results in the generation of large quantities of solid waste (Nazombe, 2022; Adetola et al., 2021). Theoretically, waste management is grounded in systems thinking and circular economy principles, which support using resources sustainably by, among other things, reducing waste and recoveringresources from the waste (Geissdoerfer et al., 2017). According to the Ellen MacArthur Foundation (2013), the circular economy model seeks to design systems that, among others, keep products and materials in use. Energy and nutrient

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recovery from waste through anaerobic digestion aligns with this model. Applying these models has become very important at a time when waste management has become a global issue due to its impact on the environment, climate change, health, and sanitation (Singh et al., 2014; Zhang et al., 2024; Ferronato & Torretta, 2019). Municipalities struggle to properly manage solid waste due to a lack of adequate resources, especially in low-income countries, such as Malawi (Rada, 2017; Chikukula et al., 2024). Usually, waste collection and disposal alone accounts for the largest share of the municipality budget, which is estimated to be between 20-50% in Malawi (Nazombe, 2022), yet less than 50% of the waste generated is collected (Cogut 2016; World Bank, 2023). Therefore, most of the waste generated is dumped in open spaces, such as behind buildings (Nazombe, 2022; Chikukula et al., 2024). These huge quantities of MSW accumulating in open space present major health and environmental risks (Cogut, 2016; Rada, 2017). The probability of waterborne diseases, such as cholera and diarrhoea, is very high in such areas, especially during rainy seasons (WHO, 2023). The organic component of the MSW undergoes uncontrollable biodegradation in open space, releasing methane (CH_4) and carbon dioxide (CO_2) into the atmosphere, which contributes to climate change and global warming (Uzodinma, 2018; Zhang et al., 2024). The most dangerous of these gases is CH_4, whose effect is 20-25 times higher than that of CO_2 (Ferronato & Torretta, 2019; Adetola et al., 2021).

Using the resources sustainably is key if the cities are to reduce resource consumption and the generation of waste. However, waste generation is inevitable in urban and marketplaces as long as resources are being extracted and used to produce goods and services for human consumption (Cogut, 2016). Therefore, local authorities and planners are required to adopt sustainable options for managing the waste, which requires a better understanding of the composition of the solid waste generated (Singh et al., 2014; Bovolo et al., 2021). In developing countries, segregation of the waste at the point of generation is almost non-existent. This complicates waste management planning, and it is so difficult for the entrepreneurs to extract different components of waste. However, organic waste in these developing countries accounts for the largest share (Chikukula et al., 2024). Therefore, composting and waste-to-energy are the suitable options for managing large volumes of waste. Anaerobic Digestion (AD) is one example of the biochemical waste-to-energy technology (Budiyono et al., 2018; Adetola et al., 2021), where biogas is produced by the decomposition of organic materials, such as food waste, in the absence of oxygen (Sawyerr et al., 2019; IRENA, 2024). However, recent comparative studies conducted by authors such as Mwirigi et al. (2014), Okello et al. (2021) and Patel et al. (2022) have shown varied performance and impacts in Africa and India, thus providing important benchmarks for evaluating similar technologies in Malawi.

The AD of organic waste has the potential to solve energy challenges facing communities (Nkem & Njoku, 2022; Budiyono et al., 2018). Electricity access at 25% in Malawi is the lowest in the region, and biomass in the form of firewood, charcoal, and agricultural waste accounts for more than 90% of the energy needs (Trivedi et al., 2015; ESMAP, 2023). Alternative sources of energy, such as Liquefied Petroleum Gas (LPG), are inaccessible (Ehimen et al., 2023). Therefore, the majority of the population is dependent on unclean sources of energy for cooking, lighting, and heating. Biomass in the form of charcoal, firewood, and agricultural waste accounts for 99% of the energy demand in the rural areas (Milanzi & Daw, 2018), and the use of these dirty fuels has adverse effects on people's health and environment (Tornel-Vázquez et al., 2024). These dirty fuels are blamed for increasing cases of respiratory illnesses among women and children due to indoor emissions (Longe, 2021; Morgan, 2018). The AD process produces biogas, which is a gas that is made up of CH4, CO2, water (H2O) and other gases in smaller quantities (Uzodinma, 2018; Zade et al., 2019; Budiyono et al., 2018). CH4 is a fuel that can be used for different uses, including cooking, heating, electricity generation, and as fuel for motor vehicles (Trivedi et al., 2015).

The country is experiencing high rates of deforestation as forests are being cleared due to high demand for firewood and charcoal (Milanzi & Daw, 2018; McCauley et al., 2022). Increased demand for forest wood has attracted many unemployed people to venture into charcoal and firewood production, transportation, and retailing. It has become difficult to curb illegal charcoal production in the country regardless of the government adopting regulations because the charcoal and firewood supply chains are providing a source of livelihood to many households. Therefore, deforestation remains a major challenge for the nation, and biomass supply is becoming unsustainable, making the charcoal and firewood not only scarce but also expensive (Tornel-Vázquez et al., 2024). Women and young girls spend more time searching for firewood instead of focusing on development activities, such as agriculture, business, and education, which contributes to gender inequality (Longe, 2021; Nguyen & Su, 2021). In addition, these women and girls are exposed to sexual exploitation as men take advantage of them along the way (McCauley et al., 2022). However, with proper biogas technology delivery models, clean cooking and heating energy can be more accessible to households, protecting them from indoor emissions and helping them save more time for socio-economic activities (Acheampong et al., 2024; SEforALL, 2023). Biogas also can help to reduce deforestation in the surrounding areas (Nkem & Njoku, 2022), while also supporting the decarbonisation of both the energy and waste sectors (Searle et al., 2018).

Food insecurity in the country, among others, is blamed on limited access to farm inputs, especially inorganic fertilisers (Komarek et al., 2017). Over the years, the country has been experiencing a sharp increase in the prices of inorganic fertilisers, making the input less affordable for smallholder farmers (Amankwah et al., 2024). The government has adopted interventions to subsidize the inorganic fertilisers for these smallholder farmers in Malawi (Komarek et al., 2017). However, subsidy programs have placed heavy burdens on the national budget (Gono & Takane, 2019). Therefore, the country has experienced a high demand for organic fertilisers (Nyondo et al., 2021), and many suppliers have flooded the unregulated market with these products. Bioslurry (i.e., biofertiliser) produced as a by-product of the AD process is very rich in soil nutrients. This bioslurry can be used for crop cultivation, thus contributing to food security and nutrition (Mubanga et al., 2022). Controlled biodegradation of the organic waste benefits the environment as CH4, a greenhouse gas (GHG) that is more potent than CO2, is captured and converted to CO2 and H2O. The AD process also has the potential to reduce the volume of waste requiring disposal to 4% (Sawyerr et al., 2019); thus, the technology can play a key role in promoting sanitation and reducing the budget for waste collection and disposal in urban areas and marketplaces (Nkem & Njoku, 2022; IRENA, 2024). Tsangano Market, located in the Ntcheu District of Malawi, is not exceptional to waste management challenges. The market generates huge quantities of vegetable waste such as tomatoes, onions, irish potatoes, and cabbages, which usually are dumped in open space (Chikukula et al., 2024). Managing such waste is a major challenge due to a lack of waste collection services (Nazombe, 2022).

Malawi University of Science and Technology (MUST) and Green Impact Technologies (GIT) developed a 40m3 biodigester that uses the biodegradable waste generated by the market as feedstock in an effort to solve socio-economic and environmental challenges. However, despite these efforts, there is limited empirical evidence to show how the System 20 Model biodigesters perform in local contexts and how they benefit the communities socio-economically and environmentally. Therefore, the main objective of this study was to evaluate the technical performance of the Tsangano biodigester and to assess its social and environmental benefits to the community. To achieve this, the research answered the following specific questions: What is the actual technical performance of the Systema 20 biodigester at Tsangano Market under field conditions? What are the social and environmental benefits of using the biogas and biofertiliser produced by the biodigester? What are the challenges that are associated with operating the biodigester in this context? and How does the performance compare with other countries around the globe?

2. Methods

2.1 Study area

This study was done at Tsangano Market, which is a rural area located in Ntcheu District of Malawi. Households in the area depend on agriculture as a source of livelihood, producing large quantities of fruits and vegetables, which are traded at Tsangano Market. The market supports farmers from both Malawi and Mozambique and serves consumers from major cities of Blantyre and Lilongwe in Malawi. The market generates large quantities of agricultural waste in the form of fruits, vegetables and cattle and goat manure from the animal slaughterhouses. Tsangano Market, just like many other markets located in rural areas, usually lacks waste collection services; thus, waste generated is not properly managed, as evidenced by the dumping of large quantities of waste in public spaces, such as behind buildings, along the roads, and in water drainage systems. In addition, access to electricity is very low in the area; thus, many households rely on solid biomass (i.e., agricultural waste, firewood, and charcoal) for cooking. To address the challenges that people face at the market and the surrounding communities, the MUST, in partnership with GIT, constructed the first commercial biogas plant that utilises agricultural waste generated by the market to produce biogas and organic fertilisers. Figure 1 shows the map for Tsangano Market in Ntcheu District, Malawi.

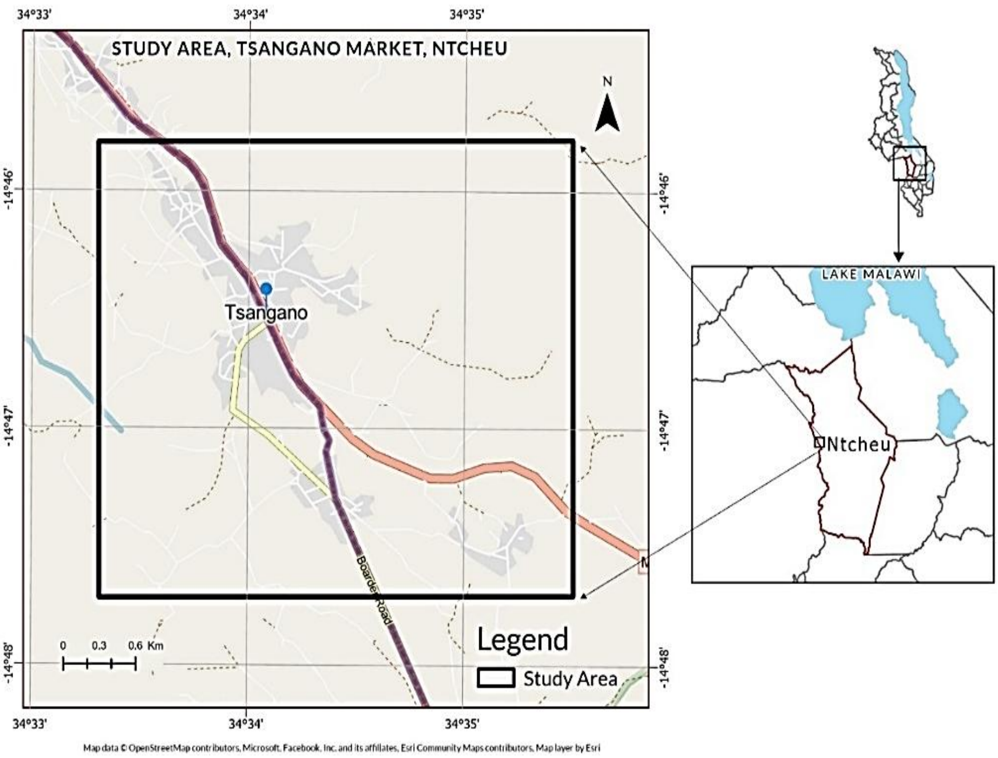

Fig. 1. Map of Tsangano Market in Ntcheu District

2.2 Research design

The study employed a mixed-methods approach to assess the Systema 20 biodigester performance and community social and environmental benefits at Tsangano Market. Data were collected on market waste characteristics, plant feeding, biogas and biofertiliser yield, and household cooking fuel use at Tsangano. Therefore, different methods were used to collect data. Key methods included a waste characterisation experiment, acquisition of technical specifications from the biodigester supplier, direct field performance measurements of the Systema 20 Biodigester, and a household survey supported by focus group discussions (FGDs) to determine the social and environmental impacts of the biogas plant. This comprehensive data collection enabled analysis of the biodigester's performance against manufacturer standards while also helping to understand the social and environmental impacts. The performance of the biogas plant at Tsangano in Malawi was compared with similar plants in other countries, including Kenya, Rwanda, Zambia, Nigeria, Uganda, Tanzania and India.

2.3 Specific methods and techniques

2.3.1 Tsangano market waste composition analysis

The study involved randomly collecting samples of waste from the strategic places. Gawaikar & Deshpande (2006) reported that when handling large quantities of waste, a sample of between 100 and 1000 kg of waste will provide more accurate information regarding waste characteristics. Therefore, during this study, a sample size of 835.17 kg was collected using and random method of sampling and used for characterisation. Waste was segregated manually, and constituents were measured using a calibrated 50 kg capacity scale weighing instrument that was checked for accuracy before sampling.

2.3.2 Biogas performance analysis

The study involved comparing the Systema 20 Biodigester Model performance specifications with the actual performance based on the local environment. Therefore, to determine the actual biogas plant performance, the primary data on biogas plant feeding and biogas and biofertiliser yields were collected over a period of one month. Specifically, a weighing instrument was used to measure the amount of organic waste used to feed the biogas plant every day, and a calibrated container was used to determine the amount of water used to mix with the feedstock every day. The daily biogas yield of the plant was measured by using the biogas backpack, which is also used to supply biogas to the users in the community. Each biogas backpack has a biogas volume of $1m^3$; therefore, quantification of the biogas was based on the number of biogas backpacks harvested every day. The weight of the biogas backpack full of biogas was determined by direct measurements using a weighing instrument. The biofertiliser yield was measured using a calibrated container. The biogas and biofertiliser yields obtained were compared with the Systema 20 Biodigester Model to determine the actual performance. Figure 2 shows a biogas backpack that was used to measure the biogas output.

Fig. 2. A 1 m^3 biogas backpack that was used to measure the biogas output

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2.3.3 Clean cooking and indoor emissions reduction

This study employed descriptive statistics to analysethe data that was collected through the purposive sampling method. Specifically, the study considered the number of households that use biogas for cooking, and data on the average number of hours of daily biogas use for cooking was captured. Biogas usage health impact was assessed using a proxy method, which involves linking the reported household biogas usage with WHO indoor air quality guidelines, which outline safe exposure limits for particulate matter (PM2.5) and carbon monoxide from household fuel combustion (WHO, 2014). During the assessment, it was assumed that biogas produces significantly fewer pollutants than traditional biomass fuels, such as charcoal, firewood, and agricultural waste (Rosenthal et al., 2018). The study used a national average household occupancy rate of 4.6 persons (NSO, 2019) to extrapolate the number of beneficiaries in terms of reduced exposure to indoor emissions. However, during the analysis, it was assumed that all the biogas generated by the plant was utilised despite a noted shortage of biogas backpacks. Thus, this approach represents a best-case scenario rather than actual biogas uptake in the community. Therefore, there is a need for further research, where these limitations should be addressed by using more robust statistical modelling or sensitivity analysis (Creswell & Creswell, 2018). The study also estimated the reduction in exposure to indoor emissions based on the volume of biogas used for cooking by the households and the cooking hours supported, typical emission levels from traditional fuels (i.e., firewood, which is the predominant cooking fuel for households at Tsangano) versus biogas, and the WHO-recommended safe exposure limits.

2.3.4 Deforestation reduction

This study employed a mixed-methods approach comprising household surveys and focus group discussions (FGDs) at Tsangano Market and the surrounding communities to assess cooking fuel usage patterns. Specifically, a sample size of 385 households was calculated using Cochran's formula at a 95% confidence level with a 5% margin of error, which is considered to be more appropriate for unknown populations. The sample was stratified by distance from the market, ensuring households located both near and far from the biogas system had a chance to be interviewed. The survey instrument developed was pre-tested before starting the actual interviews, and corrections were made to remove any errors. To estimate actual biomass use, respondents reported daily firewood consumption. These results were validated through direct measurements of 25 market-sold firewood loads using calibrated weighing scales (Figure 3 a&b). In total, three FGDs were conducted at Tsangano Market, one with biogas users and the other two with non-users to triangulate and validate survey findings regarding households firewood usage and biogas performance in terms of its ability to replace firewood.

a b

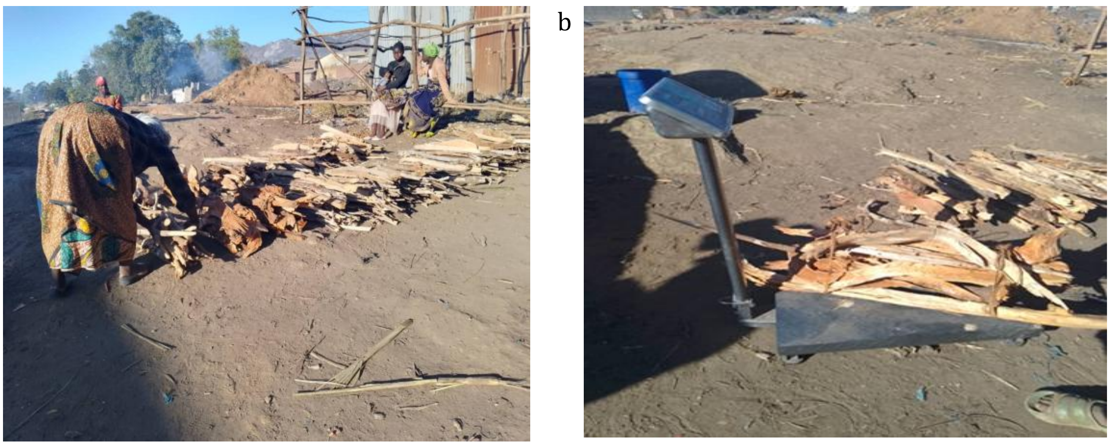

Fig. 3 (a) Loads of firewood sold on the market; (b) Measuring the weight of firewood loads

2.3.5 Sanitation, water access and GHG emission reduction

The study quantified the amount of organic waste that was extracted from the market for biogas and organic fertiliser production. This helped to determine the role of the biodigester in promoting sanitation. The uncollected organic waste usually undergoes uncontrollable biodegradation, releasing CH_4 into the atmosphere. Methane emissions avoided were estimated using IPCC (2006) default emission factors, where it was assumed that there was uncontrolled biodegradation in the absence of intervention. The study used the formula shown in equation 1 to calculate the methane emissions:

$$CH_4 = MSWT * MCF * DOC * DOC_f * F * \frac{16}{12} * (1 - R) * (1 - OX) \qquad \text{(Eq. 1)}$$

Where: *MSWT* is mass of solid waste treated in tonnes; *MCF* is the methane correction factor; *DOC* is the degradable organic carbon in waste; *DOCf* is the fraction of *DOC* that degrades; *F* is the fraction of methane in landfill gas, *16/12* is the molecular weight ratio of CH_4/C, *R* is the recovered methane (i.e., assumed 0 is uncontrolled) and *OX* is the oxidation factor (i.e., 0 for open dump sites). On the other hand, daily water demand of the biogas plant for biogas and biofertiliser production was determined by measuring the volume in liters using a calibrated container. The water demand for the plant was compared with average water access per household in the area.

2.3.6 Bioferrilizer production, use and food security

The biofertiliser produced was analysed to determine its physical and chemical characteristics. Data from the demonstration farm as well as technical specifications of the Systema 20 biodigester model were used to analyse the impact of the biofertiliser on crop production and food security. The performance of the biofertiliser was tested at a demonstration maize farm, and results were compared with the average maize consumption per head per year.

2.4 Data collection methods and analysis

The study used multiple approaches to collecr primary data, which inlcluded conducting a household survey and focus groups discussions (FGD) assess the cooking and heating fuels mostly used in the community, which involved conducting interviews with the household heads and conducting FGDs; direct measurements of the organic waste extracted from the market using the a weighing instrument, measurement of water extracted from the community borehole used for biogas production; using a biogas backpack to measure the amount of biogas harvested from the biogas plant every day; and analysing the physiochemical characteristics if the biofertiliser and quantifying its daily yields using a calibared container. In addition, the study used data provided by the Systema 20 Model Biodigester, which was used to compare with the field technical performance of the plant at Tsangano Market. Data were entered and analysed using Microsoft Excel, where descriptive statistics, such as means, frequencies, and percentages were used to Summarise the data on biodigester performance and community benefits (Creswell & Creswell, 2018). Environmental benefits of the biodigester were estimated using standard conversion factors from FAO (2018) and IPCC (2006) guidelines.

2.5 Research ethics consideration

The study adhered to ethical guidelines and standards as required by the MUST. Therefore, the study proposal was submitted to the MUST Research Committee for a review. An approval was provided by the research ethics committee, where recommendations were given and adopted by the researcher. The study also obtained an approval from the local authority, Ntcheu District Council, to conduct the study in the area. Informed consent was obtained from the research participants, especially during data collection. Data collected was treated with confidentiality, where, among other things, respondents were kept anonymous.

3. Results and Discussion

3.1 Technical analysis of Tsangano Biogas Plant

3.1.1 Waste generation and composition at Tsangano Market

The results showed that cabbage and Irish potato peels at 28.7% and 26.4%, respectively, accounted for the largest share of the waste generated at Tsangano Market (Figure 4). However, 99.9% of the waste generated was organic. This is not surprising considering that the market is well known for fruit and vegetable marketing, serving major cities of Lilongwe and Blantyre in Malawi. Therefore, most of the waste generated is organic. This indicates that the biogas plant, which demands organic waste, has a sustainable supply of the feedstock. However, this may have an implication on GHG emissions, as in open space the organic waste undergoes uncontrolled biodegradation, realising GHGs, such as CH_4 and CO_2. Figure 4 shows waste compositions at Tsangano Market.

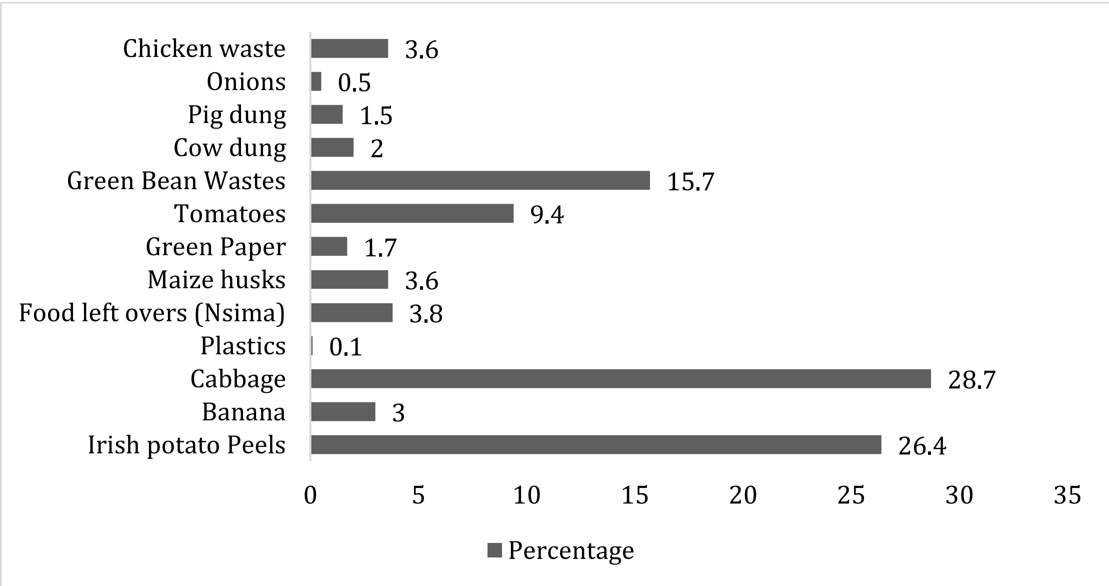

Fig. 3. Tsangano Market waste composition

3.1.2 Overview of the Tsangano Biogas Plant

The Tsangano commercial biogas plant was constructed by the MUST in partnership with GIT with financial support from the Science Granting Councils Initiative and the National Commission for Science and Technology (NCST). The main objective of the project was to address challenges related to energy access, deforestation, greenhouse gas emissions and sanitation at Tsangano. Therefore, the project involved the installation of the biogas plant within the community market that uses organic waste generated by the market as feedstock for biogas and biofertiliser production. The System 20 Biodigester Model promoted by Ecogen Limited in Malawi was the choice for the project implementers. Two biodigesters, each having a capacity of 20 m^3, were installed in 2020. Therefore, the plant has a combined capacity of 40 m^3. Cabbage waste constitutes the largest share of the organic waste used for feeding the biogas plant. Once the fresh feedstock collected from the market is crushed and mixed with water before feeding the plant. The biogas produced is supplied to households and restaurants at a fee, and biofertiliser is sold to smallholder farmers. Figure 5 shows the Tsangano Biogas Plant in Ntcheu District.

Fig. 4. Tsangano Biogas Plant in Ntcheu District

3.1.3 Systema 20 biogester supplier

The model of the biodigesters used at Tsangano Market in Ntcheu District is Systema 20, which is 20 m^3 in size. According to the supplier specifications, this model is suitable for the biodegradation of food waste, cattle manure, and pig manure. The biodigester is supposed to be fed 69 kg of feedstock every day that is mixed with water at a ratio of 1:3. If properly fed, the biodigester is supposed to produce 10.4 m^3 of biogas, which is equivalent to 17.3 hours of cooking. Apart from biogas, the biodigester has the potential to produce 276 litres of biofertiliser per day. However, the performance of this biodigester model is dependent on the temperature, where the optimal yields can be obtained at temperatures above 23°C. Therefore, the biodigester may give different results depending on the local temperature. Table 1 shows the specifications of the Systema 20 model biodigester.

Table 1. Systema 20 biodigester performance specifications

	Unit	Daily	Annually
Feedstock	Kg	69	25,185
Water required	L	207	75,555
Biogas yield	m3	10.4	3,796 (equiv. 17.3 hours of cooking.
Biofertiliser yield	L	276	100,740 (equiv. 2 hectares of crops)

3.1.4 Actaul performance of the intalled biogas plant

Two biodigesters of the System 20 Biodigester Model were installed at Tsangano Market. Therefore, the biogas plant has a combined capacity of 40 m^3. This biogas plant system is fed 138 kg of feedstock every day, which mainly is composed of potato peels, cabbages, tomatoes, food waste from restaurants, and animal waste (cow dung and goat dung). Annually, this biogas plant system uses 50.4 tonnes of biodegradable waste from the market and produces 12 m^3 of biogas and 548 litres of biofertiliser every day. These yields are equivalent to 4,380 m^3 of biogas and 200 m^3 of liquid biofertiliser per year. This shows that the efficiency of the biogas plant at 57.7% is very low. However, these results are based on data collection that was done over a period of 30 days only. Temperature does vary throughout the year; thus, the performance of biogas plants may not be the same, considering that temperature is one of the key factors that affect the biogas yield. Table 2 summarises the performance analysis of the biogas plant at Tsangano.

Table 2. Performance of the biogas plant at Tsangano Market

	Unit	Daily	Annually
Feedstock required	Kg	138	50,370 (50.4 tons)
Water required	L	414	151,110 (151.1 m3)
Biogas yield	m3	12	4,380 (equiv. 9,709 hrs of cooking)
Biofertiliser yield	L	548	200,020

Low biogas yield is one of the common challenges that biogas plants face, which can be attributed to technical challenges. One of the key factors that affect the operationalization of biogas plants is the availability of a sustainable supply of feedstock. The biogas plant is supposed to be fed continuously to ensure that biogas is produced every day. Therefore, the plant is supposed to be located in a suitable place, where it is also economic to access the available feedstock. Generally, the feedstock must be available in large quantities and cheaper to access. The Tsangano Biogas Plant is strategically located at a market that handles large quantities of organic waste, including vegetable and fruit waste and manure for cattle and goat slaughterhouses. Throughout the year, the market generates large quantities of organic waste, which is not properly managed due to a lack of waste collection services. The amount of organic waste being extracted from the market for biogas plant feeding remains a very small fraction of what is being generated by the market, and there is a need for upscaling the biogas plant in the future to properly address waste management challenges at the market. Therefore, there is a sustainable supply of the feedstock for the plant. Regardless of this, the biogas plant is underperforming.

The plant is supposed to produce 20.8 m3 of biogas per day according to the technical specification of the biogas plant model installed. However, currently the plant is only producing 12 m3. Thus, the efficiency of the biogas plant at 57.7% is very low and not economical. This does not come as a major surprise considering that regardless of biogas technology being well established (Kougias & Angelidaki, 2018), there is still a need for more studies on biogas yield optimisation as biogas generation is affected by many factors, such as temperature, hydraulic retention time (HRT), organic loading rate (OLR) and physical and chemical characteristics of the feedstock. Generally, biogas yield is affected by a number of factors, such as temperature, loading rate, carbon to nitrogen ratio (C/N ratio), mixing, pH, substrate, and hydraulic retention time (HRT). Before developing the biogas plant, it is very crucial that proper studies are undertaken to determine the biogas potential. However, it was noted that before developing the biogas plant, the implementers did not do a comprehensive study. There is no clear explanation as to why the biogas yield of the plant is very low. In the long term, this reduces the number of beneficiaries that can benefit from using this clean cooking fuel. Therefore, there is a need for the operator of the Tsangano Biogas Plant to consider undertaking a comprehensive study on how biogas yield can be optimised, which, among other things, will involve determining the physical and chemical characteristics of the feedstock used and suitable feedstock ratios for optimal biogas yield. Other feedstock can be used for cogeneration to maximise biogas yield. A detailed study needs to be done to optimise biogas yield, which is key to augmenting the community benefits.

3.2 Biogas plant social impacts

3.2.1 Clean cooking, reduction of exposure to indoor emissions

Only 3.8% of the households have access to grid electricity at Tsangano Market. Alternative cooking options, such as LPG, are also not widely accessible in rural areas. LPG is less affordable; thus, the households have no other option but to use cooking fuels that are available at a lower or no cost (Tornel-Vázquez et al., 2024). Therefore, this explains why most of the households depend on dirty fuels for cooking, such as firewood and agricultural waste, because they are affordable. This explains why the use of firewood, charcoal, and agricultural waste is very common in a rural area, such as Tsanganio Market. The study findings show that 99% of the households use biomass (i.e., charcoal and firewood) for cooking at Tsangano. Table 3 shows cooking fuel usage at Tsangano.

Table 3. Cooking fuel use at Tsangano

Ranking	Fuel type	%
First	Charcoal	75%
	Electricity	1%
	Firewood	24%
	Maize Cobs	0%
Second	Charcoal	21%
	Electricity	2%
	Firewood	75%
	Maize Cobs	1%
Third	Briquettes	17%
	Charcoal	17%
	Electricity	50%
	Firewood	17%
Fourth	Maize Cobs	100%

To estimate the health benefit of biogas, the study considered a recommended exposure threshold for a proxy approach by linking household biogas usage with World Health Organisation (WHO) indoor air quality guidelines, which set recommended exposure thresholds for PM2.5 and CO in domestic environments (WHO, 2014). Biogas, which burns with a blue flame, is regarded as cleaner than traditional fuels, and its use contributes to improved indoor air quality. However, dirty fuels are associated with indoor emissions that are blamed for respiratory illnesses (Longe, 2021; Morgan, 2018). Households normally spend up to 2 hours in the kitchen preparing food (Monsivais et al., 2014). It is during these hours when women and young children are exposed to indoor emissions because of using dirty fuels. Reducing their exposure to these harmful gases requires replacing these dirty fuels in their kitchens with clean cooking fuels. Biogas is a clean source of cooking energy that burns with a blue flame, and its use helps to reduce the exposure of the users, especially women and children, to harmful gases.

The Tsangano Biogas Plant produces 12 m^3 of biogas every day, which is equivalent to 4,380 m^3 of biogas per year. The biogas is adequate enough to provide 26.6 hours of cooking per day, which is equivalent to 9,709 hours every year. Therefore, 13 households can be protected from indoor emissions that cause respiratory sicknesses every day because biogas is cleaner. Considering an average household occupancy rate of 4.6, it means that almost 60 people are protected from the indoor emissions every day. The study also found that traditional biomass fuel (i.e., firewood) usage PM2.5 exposure ≈ 300–1,000 $\mu g/m^3$ in kitchens using firewood, which exceeds the WHO limit of 25 $\mu g/m^3$. Thus, for women and young children to be exposed to this risk during the 2 hours of cooking is a significant health risk. On the other hand, the use of biogas for cooking by the same households helps to reduce the PM2.5 exposure to <10–50 $\mu g/m^3$, which is within the WHO's acceptable range. Therefore, switching to biogas for cooking has a positive impact on the health of the households, which eventually will help to reduce the pressure on the health services in the surrounding communities. Table 4 shows a comparative analysis of using biogas and firewood in terms of exposure to indoor emissions.

Table 4. Estimation of indoor emissions exposure reduction due to biogas usage

Parameter	Value	Source
Daily biogas production	12 m^3	Field data
Biogas energy per m^3	~6.0 kWh	IEA (2021)

Cooking energy required per household per day	~1.5 kWh	WHO (2014)
Number of households using biogas	13	Based on the data collected at Tsangano
Cooking hours per household per day	2 hours	Monsivais et al., 2014
Average household size at Tsangano	4.6 persons	NSO, 2019
Firewood stoves PM2.5	~300–1,000 μg/m^3	WHO, 2014
biogas stoves PM2.5	<10–50 μg/m^3	World Bank, 2020; Rosenthal et al., 2018
WHO safe PM2.5 exposure limit is 24 hour mean	25 μg/m^3	WHO, 2014

3.2.2 Time saving for other social-economic activities

At Tsangano Market, just like in many other communities in Malawi, women and girls are tasked with searching for firewood (Longe, 2021; Nguyen & Su, 2021). Women and girls coming from high-income and medium-income households may not necessarily be impacted by this, considering that most of them have access to clean and modern energy sources, such as electricity and LPG. However, for low-income households that struggle to access cooking energy, the burden is on women and girls, who are supposed to use most of their precious time to search for cooking fuels and water (Morgan, 2018). Currently, most of the forests have been cleared at Tsangano Market and the surrounding communities; thus, firewood has become scarce and less affordable. Therefore, these women spend more time searching for cooking fuel (Acheampong et al., 2024). At Tsangano, it was determined that, on average, a woman spends up to 2 hours every day searching for cooking fuel. Thus, women spend up to 730 hours (i.e., 30 days a year) searching for cooking fuel. This prevents them from participating in other socio-economic activities in their communities, which contributes to gender inequality (Tornel-Vázquez et al., 2024). Therefore, the Tsangano helps to save a total of 730 hours every year for women belonging to each of the thirteen households that may have the opportunity to use the biogas produced. These women will have an opportunity to engage businesses, agricultural activities, and education, thus helping to improve their socio-economic status, which is key to promoting gender equality. Figure 6 shows a woman cooking using biogas at Tsangano Market.

Fig. 5. Household use of biogas for cooking at Tsangano Market

3.2.3 Sanitation and water access

Tsangano Market generates large quantities of waste, which remains uncollected due to a lack of waste collection services. Generally, the local authorities lack adequate resources to collect and properly dispose of waste. Therefore, most of the waste remains uncollected and is usually dumped in open spaces, such as along the roads (i.e., mainly drainage systems) and behind the buildings. The uncollected market waste presents major health and environmental risks to the people who patronise the market. However, the biogas plant contributes to sanitation by using the organic solid waste extracted from the market as feedstock. The study findings showed that the 40 m^3 biodigester uses 138 kg of biodegradable waste as feedstock for biogas and biofertiliser production every day, which is equivalent to 50.4 tonnes annually. The biogas plant has a lifespan of 10 years; thus, it is expected that 500.4 tonnes of waste will be cleared from the market during its lifetime. Biogas plants also demand a lot of water, which is mainly used for mixing the feedstock. The plant currently requires 414 litres of water every day, which is equivalent to 151.1 m^3 of water annually. Tsangano is a rural area where many households do not have access to portable water. Therefore, diverting 414 litres of water every day to biogas and biofertiliser production may increase the strain on community water access. However, the plant has a borehole, and a solar water pumping system was installed, which supplies water to the market as well as the biogas plant. The provision of water to the market considerably improved access to water as well as sanitation within the market.

3.2.4 Biofertiliser use and food security

The inorganic fertilisers are becoming less affordable to smallholder farmers as the prices keep on rising in Malawi (Komarek et al., 2017; Amankwah et al., 2024; Nyondo et al., 2021). This has the potential to contribute to food insecurity and malnutrition. Therefore, over the years, the demand for biofertiliser has been on the rise. Therefore, the installation of the Tsangano Biogas Plant came at the right time. The biogas plant produces 200.02 m^3 of biofertiliser annually, which can be used to cultivate 4 hectares of crops. This is equivalent to a 16-tonnemaize yield per year. Per capita consumption of maize in Malawi is at 133 kg (Mkondiwa & Apland, 2022); thus, the 16 tonnes of maize are enough to make 120 people food secure in Tsangano. The chemical analysis of the biofertiliser was undertaken at Chitedze Research Station in Lilongwe to determine its nutritional value. The analysis showed that the nitrogen, phosphorus, potassium, sulphur, calcium, and pH percentages were 0.3, 0.00015, 0.0025, 0.03, 0.00, and 8.03, respectively (Table 5). The biofertiliser contains a moderate level of nitrogen and sulphur, but it is deficient in phosphorus, potassium, and calcium. Its alkaline pH may help to improve the acidic soils. However, supplementary fertilisation would be required for nutrient-intensive crops.

Table 5. Chemical characteristics of the biofertiliser produced at Tsangano and results interpretation

Parameter	Value	Interpretation	Reference
Nitrogen (N)	0.3%	Moderate level; supports plant growth but may not meet high nitrogen-demand crops	Möller & Müller (2012)
Phosphorus (P)	0.00015%	Extremely low; limited value for improving P-deficient soils	WRAP (2016)
Potassium (K)	0.0025%	Significantly below average; insufficient for K-demanding crops	FAO (2013)
Sulphur (S)	0.03%	Within expected range, and is beneficial for enzyme and protein synthesis	Güngör-Demirci & Demirer (2004)
pH	8.03	Alkaline; good for neutralizing acidic soils, may not suit acid-loving crops	Alburquerque et al. (2012)

The biofertiliser was tested at a demo garden located close to the biodigesters at Tsangano Market, where the results were determined to be satisfactory. However, high performance of the biofertiliser is dependent on the season. The results showed that the liquid biofertiliser is suitable for irrigation agriculture, where the amount of water applied to the crops can be controlled. On the other hand, during rainy seasons, the liquid biofertiliser can easily be washed away by flooding water. Increased adoption of this biofertiliser for irrigation agriculture in Ntcheu District, where irrigation agriculture is common, can have a significant impact on improving food security and nutrition, impacting urban areas, especially Lilongwe and Blantyre, which are dependent on the Tsangano Market for fruits and vegetables. Figures 7 (a) and (b) show maize in a demonstration farm located close to a biogas plant at Tsangano Market in Ntcheu District.

a b

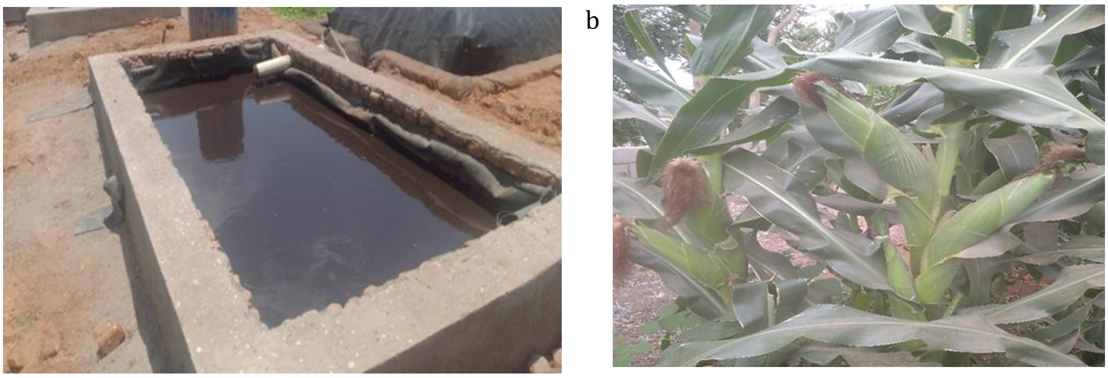

Fig. 7 (a) Biofertiliser harvesting; (b) Maize in a demonstration garden

3.3 Environmental benefits

3.3.1 Greenhouse gas emissions

The waste sector is one of the major sources of GHGs, especially in developing countries like Malawi, where the waste is not properly managed. With no proper waste collection services at Tsangano Market, traders and consumers dump waste in any place, including water drainage systems, behind buildings, and along the roads. It is common to see heaps of waste in different places within the market. However, organic waste dumped in open space usually undergoes uncontrollable biodegradation, releasing GHGs, such as CO_2 and CH_4. Out of these two, CH_4 is proven to be a GHG that is more potent than CO_2. It is proven that the impact of CH_4 on climate change and global warming is much higher than that of CO_2 (Ferronato & Torretta, 2019; Adetola et al., 2021). The Tsangano Market the composition of organic waste is 99.9% (Figure 4), which contributes more to GHG emissions. Using the IPCC (2006) methodology, this study estimated that 50.4 tonnes of organic waste (i.e., the amount of organic waste that is used to feed the plant at Tsangano per year) dumped in open spaces would generate approximately 1.005 tonnes of methane (CH_4) per year, assuming that there is no intervention to recover the methane through controlled biodegradation. When converted to carbon dioxide equivalents using a global warming potential (GWP) of 27.9 (IPCC AR6, 100-year horizon), the reduction is approximately 28.05 tonnes of CO_2e per year Table 5 shows the role of the biogas plant in capturing CH_4 from the organic waste at Tsangano Market.

3.3.2 Deforestation

In Malawi, firewood and charcoal remain the dominant sources of cooking and heating energy, accounting for over 90% of total household energy use. However, in rural areas, the reliance on biomass is even more pronounced, as it is estimated that biomass accounts for 99% of the energy use, and Tsangano Market is not exceptional. As shown in Table 3, 99% of the respindents considered biomass in the form of charcoal and firewood as their most prefered cooking fuel. This overreliance on biomass is linked to accelerated deforestation. However, the introduction of biogas systems at Tsangano presents an opportunity to displace the use of biomass, which is blamed for deforestation and helath risks. The survey results and direct measurement showed that on average households consumes approximately 7.82 kilograms of firewood per day. This means that if the 13 households can consistently use biogas for cooking, an estimated 37.1 tonnes of firewood would be displaced annually. This has the potential to positevely impact the environment in the long term through a reduction in deforestation. However, there is a need to upscale these initiatives to ensure that more households are able to use biogas considering that currently the existing plant has the potential to supply gas adequate for only 13 households.

3.4 Comparative insights from international biogas development: Lessons for Malawi

Comparative analysis of biogas technologies in Kenya, Uganda, India, Tanzania, Rwanda, Ethiopia, Zambia, and Nigeria reveals varied performance. India and Rwanda demonstrate strong adoption due to structured programs. However, Kenya and Tanzania face operational and scalability challenges. Socio-economic benefits for the beneficiary users and communities include clean energy access, reduced deforestation, and use of bio-slurry in agriculture. Key lessons for Malawi include the need for capacity building and integration of energy-agriculture-waste systems to enhance sustainability. Table 6 shows performance of biogas systems in other countries.

Table 6. Biogas systems performance and impacts in other countries

Country	Author	AD system physical characteristics	Performance	Socio-economic and environmental impacts
Kenya	Mwirigi et al. (2014)	Small-scale; digesters uses livestock waste.	Systems face maintenance challenges.	Waste-to-energy potential is being underutilized; Benefits limited by scalability and user training gaps
Uganda	Okello et al. (2021)	Household and institutional AD; cow dung and agro-waste used as feed.	Moderate gas yields (0.25–0.45 m^3/kg VS);	Supports SDG 7 and 13; improved sanitation
India	Patel et al. (2022)	Fixed-dome and portable digesters	Widespread use, implying success.	Energy substitution, nutrient cycling, and waste reduction
Tanzania	FAO (2023)	Community and farm-scale AD projects, where crop waste and manure are used as feedstock.	Variable success; low maintenance and lack of technical capacity in rural areas to operate and maintain the systems.	Climate-smart agriculture applications.
Rwanda	NIRDA (2021)	National Biogas Programme and standardized household digesters	Relatively high uptake; but there are challenges in biogas storage and use efficiency.	Bio-slurry is used for crop cultivation; biogas helps to replace dirty fuels.
Ethiopia	Wassie & Adaramola (2020)	Household-scale AD, where cow dung is used as feedstock	Efficiency between 0.3–0.5 m^3/kg VS; but sustainability is affected by the lack of spare parts.	Bio-slurry increasingly used in crop cultivation.
Zambia	IRENA (2022)	Pilot AD in farming cooperatives and schools	Lack of skilled technicians hinders adoption	Crop cultivation through the use of biosulrry; promotes fuel substitution.
Nigeria	Akinbami et al. (2001)	Different digester types; Municipal solid waste and cow dung are used for biogas production	High biogas potential	Helps to achieve agriculture and climate change targets.

4. Conclusions

This study has provided a better understanding of the Systema 20 model biodigester at Tsangano Market, highlighting both its technical performance and impact on the community. The findings showed that the biodigester successfully demonstrated the ability to convert waste into useful products, namely biogas and biofertiliser, but the biodigester is currently underperforming. This limits its efficiency and reduces the number of beneficiaries it can support. This underperformance underscores the urgent need for more research work in the future to investigate the operational challenges, which threaten the sustainability of biogas plants. Despite these operational bottlenecks, the biogas plant offers substantial social and environmental benefits to Tsangano Market and the surrounding communities. It reduces waste accumulation within the market, thus improving sanitation and mitigating greenhouse gas emissions.

The biogas plant has the potential to displace the use of traditional biomass fuels with biogas, thus helping to reduce deforestation and exposure to indoor air pollutants, which are linked to respiratory illnesses, especially among women and children who spend more time in the kitchen preparing food. The use of biogas for cooking also has the potential to free up time that was previously spent collecting firewood, thus allowing women and girls to engage more in economic activities in the community. In addition, the biofertiliser produced presents a sustainable alternative to costly chemical fertilisers, which have become less affordable for smallholder farmers. Overall, the development of the Systema 20 biodigester at Tsangano Market shows the viability of the solution to multiple community challenges, including waste management, energy access, environmental health, and agricultural productivity. However, the water-intensive nature of biogas production may pose a challenge in water-scarce areas, potentially impacting household access; thus, there is a need to consider water accessibility when planning the development of biogas systems. In addition, for the technology to realise its full potential, there is a need to improve the efficiency of the system. In promoting the technology, Malawi needs to learn from successful biodigester programmes in countries such as Rwanda, Kenya, and India, where similar programmes are supported by community capacity building and integrated policy frameworks.

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