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# Improvement of Biogas Quality and Quantity for Small-Scale Biogas-Electricity Generation Application in off-Grid Settings: A Field-Based Study

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**Abstract:** Small-scale electrical power generation (<100 kW) from biogas plants to provide off-grid electricity is of growing interest. Currently, gas engines are used to meet this demand. Alternatively, more efficient small-scale solid oxide fuel cells (SOFCs) can be used to enhance electricity generation from small-scale biogas plants. Most electricity generators require a constant gas supply and high gas quality in terms of absence of impurities like $H_2S$. Therefore, to efficiently use the biogas from existing decentralized anaerobic digesters for electricity production, higher quality and stable biogas flow must be guaranteed. The installation of a biogas upgrading and buffer system could be considered; however, the cost implication could be high at a small scale as compared to locally available alternatives such as co-digestion and improved digester operation. Therefore, this study initially describes relevant literature related to feedstock pre-treatment, co-digestion and user operational practices of small-scale digesters, which theoretically could lead to major improvements of anaerobic digestion process efficiency. The theoretical preamble is then coupled to the results of a field study, which demonstrated that many locally available resources and user practices constitute frugal innovations with potential to improve biogas quality and digester performance in off-grid settings.

**Keywords:** biogas quality; biogas quantity; anaerobic digestion; electricity generation; pre-treatment; co-digestion; user practices

## 1. Introduction

Biomass is a traditional source of energy for resource-constraint communities, which are disconnected from the central grid [1]. However, combustion in low-cost furnaces often leads to health and environmental concerns [2]. Biogas production from biomass could mitigate these negative health and environmental effects, while safeguarding energy access for disadvantaged communities, especially if local residues such as faecal matter and animal waste are utilized as feedstock. Until recently, biogas from small-scale digesters has been predominantly used for thermal energy generation for cooking purposes. However, concomitant with the demand for rural electrification, there has been a growing interest in small-scale electrical power generation from biogas as a complementary solution to PV-battery-based systems [1].

Electricity production from small-scale biogas installations using conventional technologies such as internal combustion engines (ICEs) can be economically advantageous compared to subsidised costs of electricity from fossil fuels, which require large-scale infrastructure [3]. With the introduction of state-of-the-art small-scale solid oxide fuel cells (SOFCs) with a power output of less than 5 kW [4], a significant electrical efficiency gain could be made that could accelerate the integration of biogas in rural electrification schemes. However, from our previous reviews [5,6], small-scale electricity generation using biogas as a SOFC fuel would require a different biogas quality compared to ICEs. For the SOFC, macro-pollutants like $CO_2$ and water vapour have no negative impact and may be used for dry and steam reforming, thereby omitting the need for biogas upgrading. However, the SOFC is much more sensitive to trace impurities such as $H_2S$, siloxanes and other volatile organic compounds (VOCs) compared to conventional electrical generators, including its processing equipment. For example, ICEs have a reported tolerance as high as 150 ppm for $H_2S$ [7,8], whereas a 2 ppm(v) for $H_2S$ and ppb level for siloxanes have been reported to negatively affect SOFC performance, depending on the operational conditions [9,10]. It should be noted that both technologies will require biogas cleaning since reported $H_2S$ concentrations in biogas may reach values as high as 2000 ppm, depending on the used feedstock [9,11].

Quantitatively, electricity generation from biogas through a SOFC and other technologies such as ICEs also has different requirements [5,6] compared to biogas for cooking [12]. This is because, constant power supply is usually required as compared to cooking, which is done in intervals. Likely, more biogas production is required if biogas is used for power generation.

So, to further explore the potentials of biogas-electricity generation systems for rural electrification schemes, both the required stringent biogas quality levels and continuous biogas supply for SOFC and other technologies like ICEs operation should be secured in a local resource-constraint context. Many of the biogas cleaning and upgrading techniques that are commonly proposed in literature are based on technologies developed in affluent societies and/or research environments [5]. The same is true for many of the feedstock pre-treatment methods for enhanced biogas production [13]. The current study takes a new direction and emphasizes the role of local operational practices on digester performance [5] as a first step to prevent or minimize dependency on additional processing equipment, while not compromising on biogas quality or quantity.

In order to do so, pre-treatment and other operational practices that could enhance biogas quantity and quality for small-scale electricity generation from biogas have been identified from literature. With these operational practices in mind, a field study with 48 Ugandan digesters was performed to identify promising local operational practices and resources. Afterwards, field observations were compared to literature and the most beneficial opportunities were derived and integrated into a proposal for a frugal biogas-electrical generation system. A Frugal innovation is a design innovation process in which the needs and context of citizens in the developing world are put first in order to develop appropriate, adaptable, affordable, and accessible services and products for emerging markets.

## 2. Materials and Methods

### 2.1. Identification of Operational Practices and Reactor Designs Suitable for Small-Scale Digesters

The study was carried out through literature review of potential feedstock pre-treatment, co-digestion and user operation practices that can potentially enhance the anaerobic digestion (AD) process's efficiency. Innovative design and operations in small-scale digesters that can potentially enhance the AD process's efficiency were also reviewed.

### 2.2. Observation of Local Operational Practices and Reactor Designs through Field Study

The theoretical framework is coupled with the field survey of 48 digesters (Table 1) in central and western Uganda to investigate the locally available opportunities for enhancing the AD process's efficiency in small-scale digesters. Common user practices were monitored during one-multiple day site visits and observations were classified based on the parameters defined in results Section 3.2.

**Table 1.** Type of feedstock used and the size of the digesters visited during the fieldwork in Uganda.

| Type of Feedstock | Number of Digesters Depending on the Type of Feedstock | Size of the Digesters ($m^3$) | Numberof Digesters Depending on the Size |
|---|---|---|---|
| Pig dung with water as solvent | 6 | 6 | 11 |
| Pig dung with urine as solvent | 1 | 9 | 24 |
| Chicken droppings | 1 | 13 | 9 |
| Cow dung and human waste * | 4 | 30 | 1 |
| Cow dung with urine as solvent | 15 | 40 | 2 |
| Cow dung with water as solvent | 21 | 60 | 1 |
| Total | 48 | | 48 |

* Toilet linked digesters.

During these site visits, digester users were asked inquiry questions; meanwhile, their operational practices such as feedstock storage were observed and digesters were visually inspected. Analysis of feedstock and slurry pH and biogas composition in terms of $H_2S$, $CH_4$ and $CO_2$ was also performed during field visits. The $H_2S$ content in the biogas from various digesters was measured at the cooking side using a hand sampling pump (Dräger accuri, Luebeck, Gemany) equipped with various $H_2S$ measurement tubes (Dräger, Luebeck, Germany). The measurement range of the different $H_2S$ Dräger tubes was from 0–2000 ppm and 0–7%. The biogas major composition of $CH_4$ and $CO_2$ was also analysed using a portable gas analyser (Geotec Biogas 5000, Chelmsford, United Kingdom). Gas samples from the cooking side, which were taken from a disconnected gas pipe normally connected to the stove, were captured using gas lock-syringes which were connected to the portable gas analyser for analysis. Temperature and pH of feedstock and slurry were measured using two portable pH meters. One was Greisinger G 1500 series, Regenstauf, Germany with pH resolution of 0.01 and temperature of 1 °C. Second was Ohaus ST10, Nänikon, Switzerland with pH resolution of 0.1 without a temperature sensor.

Samples of feedstock, slurry and urine were collected in the field and their sulphur and elemental content were analysed in the laboratory using ICP-OES 5300DV (Perkin Elmer Optima, Waltham, MA, USA). Samples were diluted to 50 mL with demineralised water and $HNO_3$ to facilitate the destruction process. All 50 mL samples were destructed in the microwave. The destruction time in the microwave was 60 min at a maximum power of 1300 W.

### 2.3. *Towards a Conceptual Frugal Small-Scale Design for Uganda/East-Africa Context*

Evaluation of the observations were compared to literature and the consequences for reactor performance were deduced qualitatively. For each aspect, one or multiple modifications were proposed, culminating in a conceptual frugal design of a small-scale digester adapted to the resource constraints of the local situation.

### 2.4. *General Description of Ugandan and East African Climate Conditions Affecting Bio-Digestion*

The rural areas in Uganda that were chosen for this field study are characterized by abundant solar irradiation reaching 4–6 $kWh/m^2.d$, few clouded days and an ambient temperature between 20 and 25 °C year-round [14]. Precipitation ranges between 1 and 60 mm daily [14]. These areas are home to many farmers that have cattle, but also agricultural production of crops is common. There is ample vegetation and agriculture such as plantation of cassava, banana, mango and jack fruit. Biomass residues of such plantations are easily accessible for co-digestion. Some farmers have their own pastures and practice zero-grazing, while for others, their cattle roam freely, but often can spend the night together in a kraal (shade where cows sleep) near homesteads. Over the course of years, NGOs have been actively disseminating fixed-dome digesters that are commonly used in rural areas. We consider the climatic conditions representative of many other global sunbelt locations.

## 3. Results

### *3.1. Literature Identification of Operational Practices and AD Reactor Designs Suitable for Small-Scale Digesters*

Literature on biogas is extensive and the influence of many parameters on the quality and quantity of biogas produced from AD have been described in various textbooks [15,16]. The aim of this section is to derive hypotheses for the relevance of parameters given the local physical and socio-economic conditions.

### 3.1.1. Pre-Treatment, Co-Digestion and Other Operational Parameters Can Enhance Biogas Quality and Quantity

Physical pre-treatment such as milling, chipping and gridding may lead to diversification of feedstocks for small-scale biogas plants. If pre-treatment, such as using a simple mechanical grinder, is encouraged, then the availability of feedstock for co-digestion with the animal and faecal waste would be increased. Further, irradiation from the sun can be used as a freely available photothermal or photochemical pre-treatment option in small-scale applications. Solar irradiation contains UV radiation that can enhance lignin disruption within the substrate and subsequently enhance its biodegradability [17]. In the presence of a catalyst such as $TiO_2$, solar irradiation can enhance photo-oxidation of lignin, which yields more easily biodegradable compounds [18]. Even in the absence of a catalyst, UV light pre-treatment has been reported to enhance biohydrogen production [19]. Solar energy can also be utilised to supply thermal energy input for low temperature (55–100 °C) pre-treatment [20].

Co-digestion is another freely available technique to increase the efficiency of AD processes and hence improve the biogas production rate and concomitantly reduce $H_2S$ content in the biogas [21,22]. From Tables S1 and S2 (Supplementary Materials), co-digestion can greatly reduce $H_2S$ content in the gas as compared to single feedstock.

Specific heavy metals are indispensable as micro-nutrients for anaerobic bacteria and archaea [23]. Locally available additives, such as green leaves and biochar, contain these trace metals and can supplement microorganisms with these micronutrients [24]. Mentioned additives are freely available in off-grid communities and if they are used in the right proportions, they can indeed enhance biogas production rates and also reduce on $H_2S$ concentrations in the biogas [25–27].

In addition, micro-aeration has been reported to enhance the hydrolysis of hardly biodegradable materials, meanwhile reducing the $H_2S$ content in the biogas [28–31].

The extensive literature study and systematic discussion on the relevance of specific parameters for small-scale digesters and biogas-electricity generation systems, considering these local socio-economic conditions, is presented in Supplementary Materials. From this analysis the following most relevant topics were derived that have been taken into account in the field study: (i) pre-treatment methods, (ii) co-digestion, (iii) additives for enhanced biogas quality and quantity, (iv) reactor pH, (v) reactor mixing, (vi) substrate particle size, (vii) seeding, (viii) micro-aeration, (ix) temperature and (x) design of the reactor. Their theoretical effect on the performance of AD systems has been described in Table 2.

### 3.1.2. Small-Scale Digester Design Parameters

In rural conditions, particular attention should be paid to the digester design to ease operation and prevent unnecessary maintenance. Therefore, the following section is dedicated to different small-scale reactor designs that have been reported to affect the efficiency of the AD process and have an influence on the biogas quality and quantity.

For small-scale applications, a self-agitation bio-reactor was proposed [32]. Such a reactor can minimize the need for mechanical mixing and enhance the quantity of biogas generated at the same time. Martí-Herrero et al. [33] proposed the use of Polyethylene Terephthalate (PET) rings from soda bottles in a tubular plug-flow digester to increase solids retention and the effective surface area. The incorporation of PET rings was found to increase COD removal and the specific biogas production rate. Additionally, it enhanced process stability and allowed for a higher loading rate [34].

The integration of solar thermal energy into the AD process was proposed to increase the efficiency of the digesters [35]. In addition, the integration of a greenhouse and a solar thermal energy system for AD was effective in enhancement of the digester temperature [34,36]. Application of the greenhouse above the digester was reported to increase the slurry temperature by over 9 °C above ambient temperature [33,37]. Additionally, a simple passive solar design of a low-cost plug-flow digester constructed with double tubular polyethylene layer was able to increase the slurry temperature by 8 °C above the ambient temperature [38]. Simple digester modifications in terms of covering the gas holder with transparent polyethylene that acts as a greenhouse can potentially increase the digester temperature and hence, increase the biogas production rate [39,40]. For underground digesters, the slurry temperature greatly depends on the temperature of the soil surrounding the digester [41] and hence keeping this temperature elevated using a greenhouse would, in turn, enhance the digester temperature. Since polyethylene is readily available in most countries, the construction of greenhouses surrounding the digester seems to be a suitable approach for resource-constrained settings. The increase in temperature, which enhances the biogas production rate by the use of solar energy, is likely to increase the economic returns of the biogas digesters. Even at the household level, a solar-assisted biogas system was proven to be economically feasible [42]. A temperature increase from 20 °C to 35 °C can significantly increase the biogas production rate in the case of manure [43]. However, for this feedstock, increasing the temperature beyond 35 °C may not significantly enhance the biogas production rate [44].

Apart from a greenhouse structure, several researchers have investigated the use of solar thermal in AD using various techniques such as concentrated solar power and rooftop solar collectors. Earlier researchers developed innovative solutions such as the use of a solar collector as a rooftop for the digesters, which they reported as a potential technique to reduce thermal losses [45]. El-mashad et al. [35] investigated the use of a solar water system for thermophilic AD. A solar heating system with a flat-plate collector in AD is technically feasible, although it increases the capital and operational costs of the system [35]. Hao et al. [46] studied the feasibility of integrating a concentrating photovoltaic/thermal (C-PV/T) hybrid system into a biogas plant to achieve more efficient bio-methane production by temperature enhancement. An improvement of 1.7% in bio-methane production was obtained; however, this was less than the regular error margin. Moreover, Colmenar-Santos et al. [47] analysed the hybridization of concentrated solar power (CSP) and biogas plants, which was found to increase the profitability and environmental advantages. As well, Vidal et al. [48] studied the integrated AD/solar photo-electro-Fenton (SPEF) process for the treatment of slaughterhouse wastewater. Results showed that the combined process reduced the costs associated with slaughterhouse wastewater treatment and improved the removal efficiency of influent COD by more than 90%. In addition, a solar-driven hydrothermal pre-treatment system was investigated as an alternative energy-saving approach for the digestion of microalgae slurry. This approach improved the bio-methane potential by 57% compared to that of raw microalgae without pre-treatment [49]. A novel integrated solar PV and thermal AD system has been recently proposed by Hao et al. [46]. Such a system would meet both the auxiliary and thermal energy demand of the biogas digester, but its economic feasibility in small-scale systems is rather doubted.

Solar energy, apart from enhancing biogas production, can also be used to enhance pathogen removal from the digested slurry when faecal matter is used as feedstock [50]. Sun-drying of the digested slurry was found to increase pathogen (*F. streptococcus*) removal up to 3 log units. Further, in digester effluent that operated at a temperature of 45 °C, *E. Coli* and total coliforms were found to be between 2–3 log units, which is lower than the world health organisation (WHO) guidelines for digested slurries [51]. Solar drying of digestate can reduce its total nitrogen concentration by volatilising ammonia, thus resulting in balanced chemical composition for fertilizer application [50]. As reported before, solar radiation can also be used for pre-treatment to enhance lignin degradation [18] and hence further improve the efficiency of AD. Therefore, countries which receive a large amount of annual radiation can consider solar energy as a source of heat to enhance the AD process efficiency and also as a feedstock pre-treatment option. Moreover, the usual feedstock for small-scale digesters, namely cow dung, contains a considerable fraction of lignocellulosic material [52]. Hence, the possibility of using the freely available solar radiation as a pre-treatment method for digester feedstock such as cow dung seems advantageous to enhance the biogas production rate of small-scale digesters.

**Table 2.** Effect of operational parameter on AD and their optimal conditions.

| **Parameter** | **Theoretical Effect to the AD Process/Optimal Range** | **Actual Situation Described in Literature on Small Scale Digesters** | **Recommendation for Improved Quality or Quantity in Small-Scale Biogas-Electricity Generation System Based on This Field study** |
|---|---|---|---|
| Physical pre-treatment-milling, chipping and gridding | Increases the particle surface area available for enzyme attack [53] | Not recommended for small application due to some drawbacks which include high energy consumption [53] | For small-scale application, manual milling can be considered. This can result in feedstock diversification |
| Physical pre-treatment-Irradiation and low-temperature pre-treatment | Irradiation improves lignin degradation [18]<br>Low temperature (55–100 °C) pre-treatment enhances thermal solubilisation of particulate matter thus enhancing hydrolysis [20]. | No solution suggested<br>No solution suggested | Solar can be used as a source of irradiation for pre-treatmentSolar can be used as a source of heat (thermal energy) for low temperature treatment using parabolic solar concentrators. |
| Co-digestion | Co-digestion complements feedstock characteristics and hence balances its composition within non-toxic ranges for microbial growth [54,55]. | Commonly cow dung and pig dung are used and less attention was given to other feedstocks | Other materials such as plant waste can be used if physical pre-treatment such as milling is encouraged. |
| **Parameter** | **Theoretical Effect to the AD Process/Optimal Range** | **Actual Situation Described in Literature on Small Scale Digesters** | **Recommendation for Improved Quality or Quantity in Small-Scale Biogas-Electricity Generation System Based on the Field Study** |
| Metals | Nutrient to bacteria and increases organic matter degradation and biogas production [23,26,27] | No solution suggested | Additives such as green leaves can be used to increase metals in the feedstock. |
| pH | 6.8–7.8 [56] | pH is not controlled and recommendations are given with focus on microbial performance | Upper limit 7.5–8.0 would be preferred since it also improves biogas quality, in particular it reduces $H_2S$ concentration in biogas. Dilution of feedstock with hydrolysed urine could keep the pH in the upper limit [57] |
| C/N ratio | High C/N ratio results in insufficient nitrogen for microorganisms and hence lower biogas production. Optimal range is 20–35 [53] | No solution suggested | The use of urine as a dilution can be used to balance the C/N ratio |
| **Parameter** | **Theoretical Effect to the AD Process/Optimal Range** | **Actual Situation Described in Literature on Small Scale Digesters** | **Recommendation for Improved Quality or Quantity in Small-Scale Biogas-Electricity Generation System Based on the Field Study** |

**Table 2.** *Cont.*

| | | | |
|---|---|---|---|
| Organic loading rate | Optimal value depends on the type of feedstock and reactor [58] | This is not controlled, but feeding schemes are proposed | For small scale Biogas-SOFC, this can be easily controlled by providing feed bucket with specific dimensions |
| Hydraulic retention time | Lower retention time results in lower biogas quantity [59]. | In fixed dome reactors, this is controlled passively by the pressure | Needs to be more thoroughly controlled as observed feeding schemes are all very different |
| Mixing | Ensures intimate contact between feedstock and microorganism [39] and improves biogas production rate | Self-agitation has been proposed in literature [32] through a new design | Mixing was not observed, but can easily be done by incorporating mechanical mixing in the reactor design. This can be complemented by varying gas pressure and flow of feedstock [32] |
| Substrate particle size | Large particles are very slowly hydrolysed and may lead to clogging | Small particles are preferred since they provide a large surface for microorganism adsorption, but for small scale rural digesters no solution is proposed | Feedstock is usually taken as it is. For plant waste feedstock, manual milling could improve hydrolysis and increase biogas quantity |
| Solids concentration | Increased biogas yield if it is in optimal range of 7–9% [39,60] | No solution suggested | Co-digestion with plant waste can be used to balance the solids concentration. |
| **Parameter** | **Theoretical Effect to the AD Process/Optimal Range** | **Actual Situation Described in Literature on small Scale Digesters** | **Recommendation for Improved Quality or Quantity in Small-Scale Biogas-Electricity Generation System Based on This Field Study** |
| Seeding | Enriches microorganisms into the digester to accelerate the start-up [61] | Wood ash is recommended although this is more of an additive [61] | Wood ash is readily available and can be used as additive |
| Temperature, thermophilic (50–60 °C) and mesophilic (30–40 °C) | The higher the temperature, the faster the hydrolysis and the higher the loading capacity [44,59] | Mesophilic operation is proposed as it is less intensive in terms of operation and maintenance. The use of solar energy is proposed to increase operational temperature by using a greenhouse (covering the gas holder with transparent polyethylene) [39,40] | Mesophilic situation is not achieved and systems operate typically well below 35 °C. Abundant solar energy can be used to enhance the digester temperature. Waste heat from electricity generators such as SOFC can be used to increase the digester temperature and increase biogas quantity. |
| Type of the reactor | Reactor type affects solids retention time | Designed in such a way to optimize organic loading rate and retention time. | If waste heat or solar thermal energy is to be used, it should be with good thermal insulation properties. |

### *3.2. Field Observations That May Influence the Quality and Quantity of Biogas from Small-Scale Digesters*

After defining the key parameters, the field survey was carried out to verify the outcome from literature for off-grid small-scale digesters and biogas-electricity systems. A total of 48 digesters across Uganda were visited. The observations carried out during the field visit corresponded to the following categories: (i) Pre-treatment (irradiation due to feedstock storage), (ii) co-digestion, (iii) co-feedstock and additives such as passive mixture of feedstock with leaves, soil, and feedstock dilution using urine instead of water, (iv) reactor pH, (v) reactor mixing regime (feeding frequency and mixing by stirring) (vi) substrate particle size (solid materials), (vii) seeding, (viii) micro-aeration, (ix) temperature and (x) type of reactor.

### 3.2.1. Current Pre-Treatment Observed

Physical pre-treatment-irradiation and feedstock storage: It was observed that some farmers store the feedstock for several days before it is fed into the digester (Figure 1a). It was noted that the feedstock is normally exposed to open irradiation from the sun. Other farmers, due to limited feedstock, always use fresh dung.

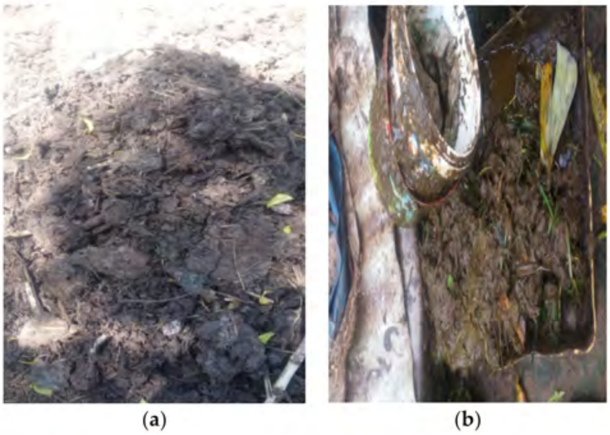

(**a**) (**b**)

**Figure 1.** (**a**) Stored cow dung and (**b**) fresh cow dung.

### 3.2.2. Co-Digestion Observed in the Field

It was observed that some farmers were practicing co-digestion. Out of the 48 digesters visited, 11 were co-digesting feedstock. Some of the farmers added toilet waste to the digesters, while others used pig and cow dung due to the presence of more than one type of animal. It was evidenced that co-digestion of animal dung and food or agricultural waste is not practiced in off-grid settings for the visited digesters.

### 3.2.3. Observed Co-Feedstocks and Additives with Biogas Quality and Quantity Enhancing Potential

It was observed that during cow dung collection, a mixture of leaves and grass is also collected (Figure 2a), however, this depends on the collection site. Sometimes, when grass is not present, soil is likely to be collected together with the cow dung (Figure 2b). If the un-cemented-kraal [1] (Figure 2b) is located in a clay area, this can constitute a passive clay additive to the feedstock. During field research, it was also observed that wood-ash is readily available and hence can be used as part of the additive material.


(**a**)

**Figure 2.** *Cont.*

**Figure 2.** (**a**) Cow dung mixed with green grass and leaves, (**b**) Un-cemented kraal where cow dung mixes with soil and (**c**) Cemented kraal with minimal chances of cow dung mixing with soil.

#### 3.2.4. Other Observed Digester Operational Practices Which Can Potentially Affect the Quality and Quantity of Biogas

Dilution of feedstock with urine: In Uganda, some farmers dilute the feedstock with urine as opposed to water. This practice is widely spread in the central region where most of the cows are kept on zero-grazing, hence the collection of urine is relatively easy. Famers usually collect the urine in a pond which is then later used to dilute feedstock instead of water. Away from the central region, where animal field grazing is the most common practice, farmers usually use water for feedstock dilution.

Analysis of biogas composition presented in Table S2 (Supplementary Materials) in terms of $CH_4$, $CO_2$ and $H_2S$ showed that they were in the range of 47–52%v, 40–47%v and 0–2000 ppm, respectively. It was observed that digesters which had urine as their solvent had higher pH compared to digesters which had water as their solvent (Figure 3b). Digesters with a higher pH and urine as a solvent had relatively lower $H_2S$ content in the gas when compared to digesters with a lower pH (Figure 3a). Figure 4 shows the variation of $H_2S$ content in the gas with effluent pH. It shows that a general decreasing trend in $H_2S$ content was observed as effluent pH increased.

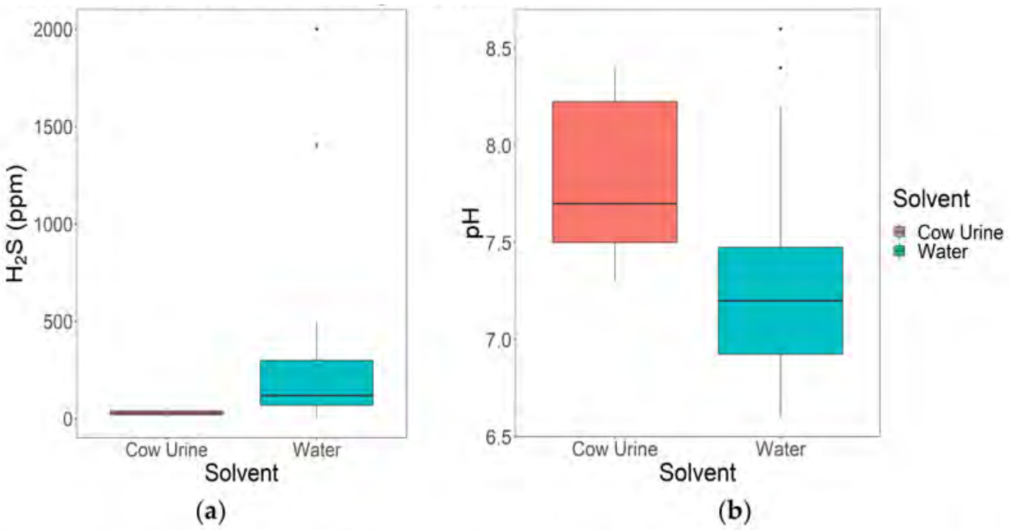


**Figure 3.** (**a**) Effect of solvents on $H_2S$ content in biogas and (**b**) on pH of digesters visited in the field study using either cow urine or water as solvent.

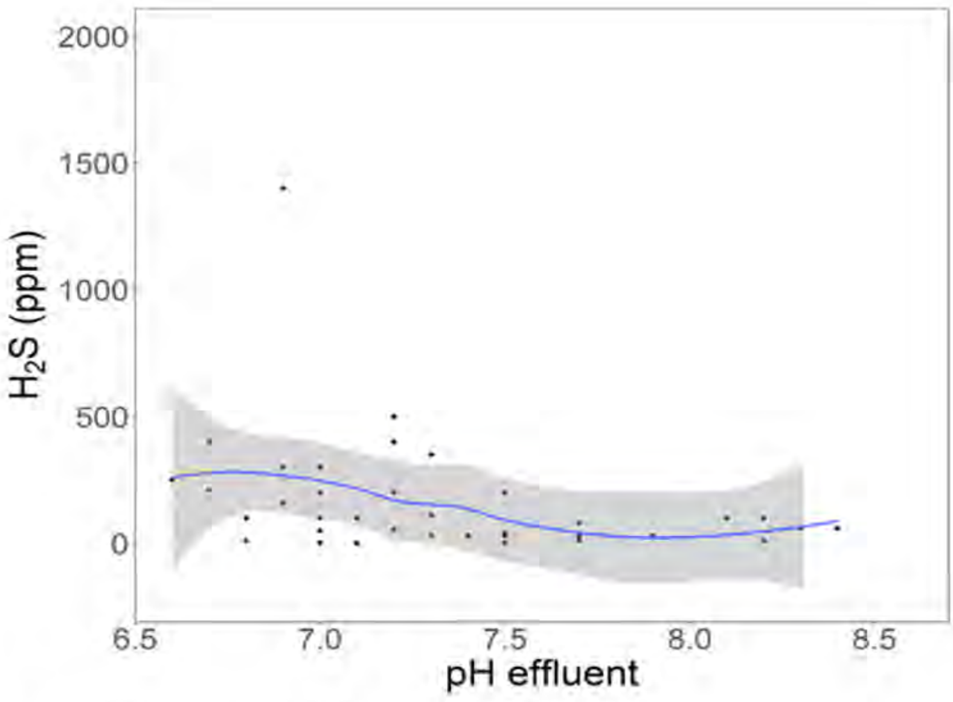
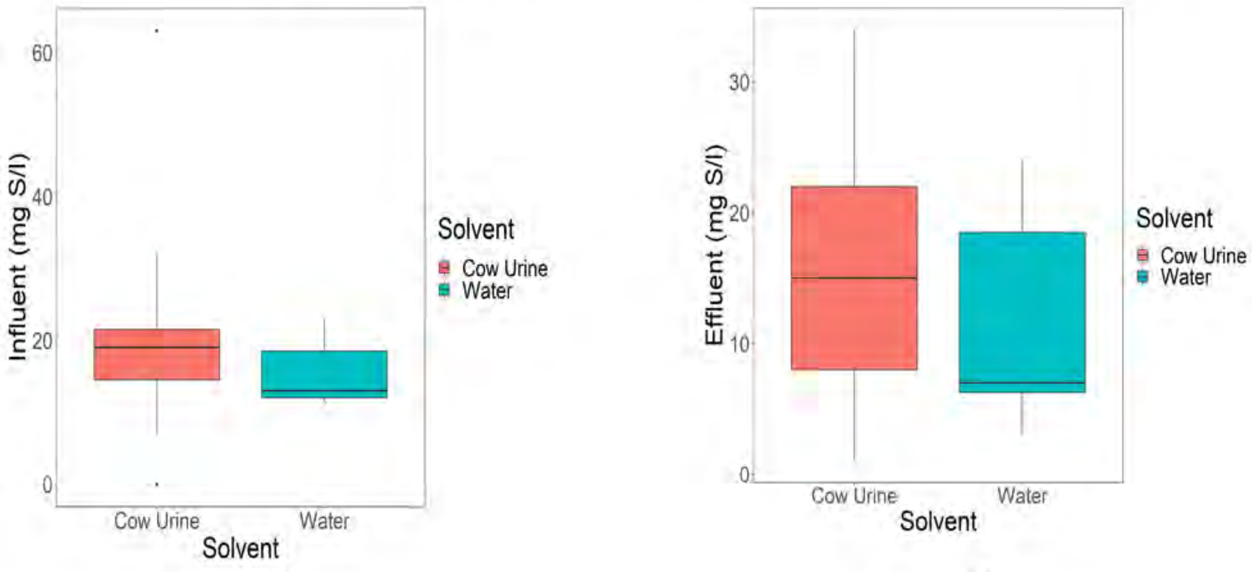


**Figure 4.** Effect of pH on the $H_2S$ content in the gas.

Analysis of the influent and effluent samples (Figure 5) shows that digesters which had urine as their solvent had a relatively higher sulphide concentration compared to digesters which had water as a solvent.



(**a**) (**b**)

**Figure 5.** (**a**) Sulphur (S) concentration measured in the influent and (**b**) effluent (mg S/L) of digesters visited in the field study using either cow urine or water as solvent.

Feeding Frequency: The feeding pattern is one of the operational practices which could enhance mixing and result in a more efficient digestion process. However, it was observed that the frequency of digester feeding varies widely between digesters, as well as for the same digester from time to time. All the digesters visited had no standard feeding schedule. Some farmers fed their digesters once a week, whereas others tried to feed them daily. Further, the ratio for feedstock dilution was not standardised and was usually calculated based on assumptions. In most cases, feeding depended on the availability of feedstock and was not based on protocols related to digester capacity and required retention times.

Mixing by stirring: Mixing by mechanical stirring is generally not frequently practiced in decentralised digesters. All the digesters visited were not agitated by stirring and the operators were not aware of the benefits of such practices. Proper stirring needs to be encouraged since it improves contact between microorganisms and the feedstock, hence enhancing bioconversion.

Solid materials: Solid materials in the concentration range of 7–9% have been reported to enhance biogas production [60]. As mentioned before, it was observed during the field survey that off-grid communities have access to digestible solid material such as banana peels. If such a practice is embraced in small-scale digesters, it is likely to increase the feedstock availability and also enhance the biogas production rate of AD.

Seeding materials: Seeding is not a common practice in off-grid small-scale digesters. None of the 48 surveyed digesters used seeding.

Micro-aeration of anaerobic digester: In small-scale digesters, micro-aeration is not a common practice in Uganda. However, it was observed that passive micro-aeration could occur for some digester designs like fixed-dome (Figure 6), which have an expansion chamber exposed to the atmosphere. This unintended exposure of the slurry to the atmosphere might result in micro-aeration of the slurry, especially during mixing through the expansion chamber.

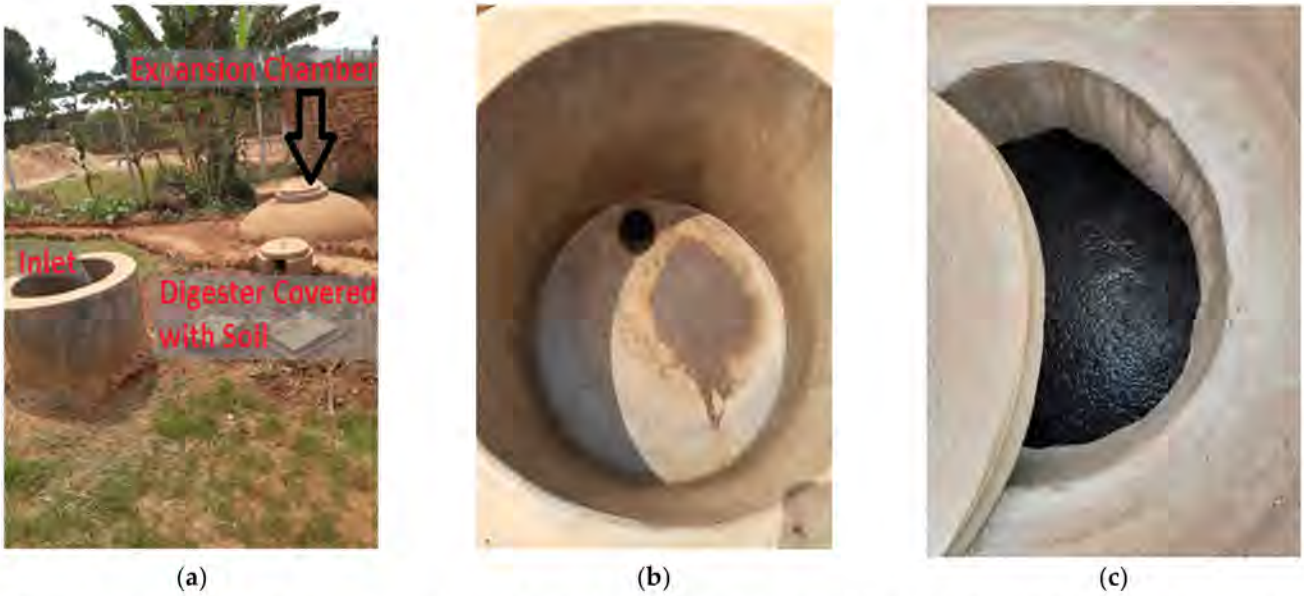


**Figure 6.** (**a**) Side view of the expansion chamber and inlet (**b**) Arial view of the inlet and (**c**) Aerial view of open expansion chamber with slurry exposed to ambient conditions.

Temperature: In small-scale digesters, temperature usually is not controlled and is determined by the environment. In East Africa, most of the visited digesters are fixed-dome (Figure 6), which are usually constructed underground to maintain a constant temperature. However, during the rainy season, it is likely that the temperature will be low due to soil humidity. The average annual temperature which has been reported ranged between 18–25 °C [56]. The measured slurry temperature during field visit ranged between 23–25 °C. Although common for field digesters, this range is below the recommended mesophilic condition of 30–40 °C [44]. Other reactors, such as plastic tubular plug flow digesters, which are usually mounted above the ground, are likely to be affected by temperature variations in the East Africa settings, which range from 17 °C at night to 30 °C during day time [62].

### 3.2.5. Type of the Reactor

It has been observed that most of the digesters which are currently being used in East Africa are of fixed-dome type (Figure 6). Such digesters are usually constructed underground to balance potential temperature fluctuations. Other digesters which are currently used are the balloon type (Figure 7) and plastic digesters. These two types of digesters are usually cheaper when compared to the fixed-dome type, but their lifetime is shorter and they are susceptible to damage and temperature variations during cold nights. According to digester owners in Uganda, a tubular digester of 9 $m^3$ can cost as low as Ugandan Shillings 3,000,000 (USD 842) whereas a fixed dome of similar capacity can cost between Ugandan Shillings 4,500,000 (USD 1250) and 6,000,000 (USD 1667). However, although the capital investment is high for a fixed-dome digester, it has a life of more than 20 years which is more than two times that of a tubular digester [63,64].

**Figure 7.** Balloon type digester.

## 4. Discussion

It was observed during the field survey that there is potential to improve the biogas quality and quantity for electricity generation with alternatives, ranging from physical pre-treatment to user practices such as proper mixing. Note that the observed $CH_4$ and $CO_2$ composition is suitable for electricity generation, especially if dry reforming in SOFCs is envisaged [65–67]. However, $H_2S$ needs to be removed for efficient electricity generation.

Currently in East Africa, some farmers store feedstock under the sun before it is supplied to the digester. Although this is done passively and in an open space, it can potentially increase the rate of biodegradability of lignin-containing material [17], which in turn could increase biogas generation. According to Gong et al. [18], UV radiation from the sun is likely to increase the rate of degradation of lignin material that is present in cow dung. Therefore, solar exposure can potentially affect the rate of biogas production. It should, however, be noted that storing feedstock under open irradiation may require more water for feedstock dilution. In consequence, closed irradiation storage shall be preferred to enhance the biodegradability of feed stock. Water loss can be minimised by storing the feedstock in closed storage, which concomitantly could be used to retain heat for additional thermal pre-treatment. Through this improvement, the feedstock temperature would increase, leading to better efficiency of the AD process. If pre-treatment by solar radiation is embraced in small-scale digesters, it is likely to enhance the efficiency of the AD process.

Although not currently practiced, solar energy can also be used as a thermal energy supply for feedstock low-temperature (55–100 °C) pre-treatment. This method is favourable for feedstock with low carbohydrates [68]. Since cow dung consists of approximately 20% carbohydrates [69], the effectiveness of this method on improving biogas quality and quantity when using this feedstock needs further investigation. It should be noted that with the availability of solar radiation and the possibility of solar thermal concentrators, low-temperature pre-treatment might be well feasible in small applications in sunbelt countries. Nonetheless, the additional capital and operational costs of its incorporation in small-scale applications need further investigation. In addition, sub-Saharan Africa is generally hot with abundant solar irradiance, and thus solar energy could be utilised to optimise the temperature control of the digester. However, its implementation needs to be evaluated concerning increased economic benefits and extra requirements such as a thermal insulation system to be used during cold nights.

A frugal [2] CSP system using Fresnel lenses can be proposed to utilize solar energy and provide heat for both pre-treatment and temperature enhancement for a fixed-dome underground anaerobic digester [70]. Fresnel lenses have become one of the top contenders in the field of concentrated solar energy applications [71]. This can be attributed to their lightweight and small volume properties; furthermore, they are mass-produced at a low cost and can effectively increase energy density [71]. Fresnel lenses achieve a concentration factor of 350–500 at a direct normal irradiation (DNI) of 1 $kW/m^2$ [72], with a conservative estimate of 86% efficiency [73]. This feature makes them good heating sources for various applications [74–76]. Although solar tracking would generate more thermal energy from the sun as compared to a fixed system [77], if moving parts are used, the operational and maintenance costs for small-scale biogas-electricity generation systems will increase. To enhance actual implementation, the digester should be designed in such a way to minimise the heat transfer area and total costs [78]. Instead of heating the entire digester, heating of the feedstock input on daily basis can be considered as an alternative [43]. As reported before, many researchers have proposed the use of a solar water heating system to enhance digester temperature. However, for small-scale applications, such system would require additional auxiliary components like pumps. Overall, this would increase the auxiliary power consumption and operational and maintenance costs.

Milling, chipping and grinding practices were not observed in the field. This is because animal and human waste are currently used as the only feedstock in small-scale digesters. Out of the 48 digesters, 47 used animal waste as feedstock, apart from a few of them in which toilet waste was added in addition to animal waste. It was observed during the field visit that there is under-utilized potential of plant waste, namely banana leaves, as a feedstock for small-scale digesters. If physical pre-treatment is embraced as common practice, this could enhance the use of plant waste as co-digestion feedstock with the usual animal dung in small-scale digesters. Milling, chipping and grinding, although not currently utilised, can be employed as a strategy to diversify feedstock and obtain more biogas. If this practice is embraced in small-scale digesters, it could encourage the use of specific plant waste, namely banana leaves, as co-feedstocks with the usual animal waste.

Physicochemical pre-treatment as reported in Supplementary Materials, primarily refers to thermal pre-treatment. This pre-treatment was currently not utilised in the visited digesters. High-temperature pre-treatment (150 °C–220 °C) may not be readily applicable in small-scale applications. However, low-temperature pre-treatment can be readily applied in small-scale applications using solar energy. However, low-temperature pre-treatment (60 °C–90 °C) was not in use for the visited small-scale digesters, although high solar insolation is available. Nevertheless, the prevailing solar irradiance could be passively applied during open sunlight storage. Other pre-treatments such as ultrasonication, chemical pre-treatment and biological pre-treatment are currently not used in the investigated small-scale digesters.

In off-grid settings, there are a number of potential feedstock co-digestion alternatives which can be supplemented with the available cow dung. Such feedstock includes plant leaves and food peelings, among others which need further investigation on their possible beneficial effect on biogas quality and quantity. Co-digestion is likely to increase biogas quality and quantity and, therefore, should be encouraged for electricity generation from biogas. However, care should be taken to maintain optimal co-digestion ratios, depending on the type of available feedstocks. This can have economic and biotechnological advantages for operating small-scale digesters [79]. Research and development is required to determine the optimal ratio for specific feedstock co-digestion, depending on the available alternatives.

From the field observations, there is passive co-feedstock of green leaves and additives of soil. As reported before, green grass and leaves may contain micro-nutrients of interest, such as Fe [24], which is also among the trace elements found in soil [80]. Such elements have been reported to enhance biogas yield and possibly reduce the $H_2S$ content in biogas [26]. It was also reported that clay contains a significant amount of $Fe_2O_3$ and metal elements [81]. Some parts of East Africa are characterized by the presence of clay soils. This can either positively or negatively affect the biogas quantity and quality in terms of $H_2S$ content for electricity generation applications. It should be noted that adding clay and soil in the digester may negatively impact the digester hydraulics and hence result in malfunctioning. Hence, the use of clay soil as an additive and green biomass as a co-feedstock needs further investigation to establish its benefits concerning biogas quality and quantity as a result of feeding ratio and clay composition.

The use of cow urine for feedstock dilution also acts as another additive to the AD process. Digesters using urine as a solvent had relatively lower $H_2S$ concentration in their gas compared to digesters that had water as a solvent (Figure 3). This, therefore, indicates that the practice of using cow urine as solvent can reduce the $H_2S$ content of the gas, thereby making it more suitable for small-scale electricity generation. With an increased sulphur concentration in the influent (Figure 4), more $H_2S$ content centration in the biogas would be expected for digesters with urine addition as compared to those with water as a solvent. On the contrary, the digesters which had water as a solvent had higher $H_2S$ content centration in the gas. Therefore, this indicates that the relatively high pH for digesters that had urine as a solvent apparently could have played a role in HS-capturing in the liquid phase. These results can be well-explained by the circumneutral pKa value of 7.02 of $H_2S/HS$. The use of urine is currently encouraged to reduce water demand; however, urine also contains metal trace elements which can enhance the AD process's efficiency [82]. The alkali metal and metal elements such as Na, K [82] need to be balanced for an efficient AD process. Therefore, the elemental composition of urine can have a positive effect on balancing the digester stability, meanwhile reducing on $H_2S$ content in the biogas for electricity generation applications. In addition, urine contains a significant amount of urea [83]. If urine is stored, urea is hydrolysed to ammonia and bicarbonate, which increases the pH of urine to values reaching as high as 9 [57]. Therefore, the usage of urine for feedstock dilution can affect the final pH in the system, hence stabilising or compromising the digestion process. As long as the pH does not reach values exceeding 8.0–8.5, the use of urine could be beneficial for the quality of biogas intended for electrical generation applications. Since urine adds additional sulphur and urea to the digester, excess ammonia can inhibit the AD process, particularly at high pH values [84]. Additional sulphur can also increase $H_2S$ in the gas phase. Moreover, the use of urine is likely to affect the C/N ratio of the feedstock which can either positively or negatively impact the biogas quality and quantity. Therefore, the effect of urine for feedstock dilution needs to be carefully investigated in terms of its effect on the pH, C/N ratio, applicable loading and trace element dosage. The dilution of reactor content was recommended to mitigate the effect of excess ammonia and overloading of trace elements [84]. Consequently, the use of diluted urine instead of concentrated urine could have a more positive impact on the efficiency of the AD process. Further research is required to establish the optimal quantity of urine to achieve an efficient AD process.

Other operational practices, such as daily feeding and mixing, need to be encouraged among small-scale digester operators to improve the overall outcome of the AD process. Irregular feeding times, feedstock volume and mixing ratios will affect both the OLR and HRT of digesters, most likely affecting the quality and quantity of biogas. Such practices need to be standardised depending on the size of the digester and the nature of the used feedstock to guarantee optimal biogas generation for the envisaged electricity generation. This can lead to a more controlled OLR and HRT, as opposed to the current practice where feeding is done randomly and compromises the stability of AD. As a consequence of enhanced biogas production, more fuel will be available for biogas-electricity generation applications. Mixing is also likely to enhance the efficiency of AD but it is not currently embraced by off-grid digester operators. Mixing improves the contact between substrate and microorganisms [39]. Therefore, if such practice is embraced in a small-scale digester operation, it is likely to enhance biogas quality and quantity. However, it was noted that according to the design of most digesters, stirring would be a tedious task. Consequently, it is highly recommended that a biogas digester for energy recovery is designed with a stirring mechanism. Additionally, solid materials and additive materials need to be encouraged to enhance the biogas production rate. Solid materials can act as co-digestion substrate, whereas additive materials such as ash contain metal elements such as Fe which can enhance the efficiency of the AD process [85].

Micro-aeration is an example of another practice which should be embraced in small-scale biogas-electricity generation applications. This practice has been proven effective in small-scale digesters [86], but it is not commonly used in East Africa. An improved digester design for high-quality biogas recovery could include air dosage into the digester headspace to oxidise $H_2S$ in the biogas. This practice could contribute to reducing the size of the additional cleaning unit, which, in turn, will help to reduce the capital and operational cost for a biogas-electricity generation system [5].

Thus far, pre-treatment is not commonly applied in small-scale biogas plants, which might be related to the use of animal manure as the main feedstock, which can be relatively easily digested without pre-treatment. There is an increasing interest in electrical power generation from biogas in off-grid communities which already count on other feedstock sources such as plant agricultural waste. An efficient pre-treatment for small-scale applications needs to be re-considered in terms of its technical and economic feasibility. Moreover, it should be a versatile system, such that small-scale biogas plants already in existence, can be coupled with emerging small-scale SOFC technologies and the more conventional technologies such as ICEs. For a biogas-electricity generation system, thermal pre-treatment seems to be feasible if solar energy and the waste heat from conversion devices such as SOFCs is utilised as a source of heat for pre-treatment. Operational practices such as additive addition, mixing, among others need to be revived to enhance the AD process efficiency in small-scale digesters. Furthermore, irradiation from solar energy can also be used as a pre-treatment alternative, especially for countries with high solar irradiation.

## 5. Proposal for Improved Reactor Design

A fixed-dome design would be a good starting point for design modification to minimise daily temperature fluctuations during AD in the current settings. Construction materials that can insulate the digester during cold night conditions can be used during the construction. The enlargement of the inlet to avoid clogging (Figure 6b) and the incorporation of a mechanical stirring device are minor physical adjustments that could improve the digester's performance.

There is potential to enhance the efficiency of biogas production employing locally available resources and straightforward modifications of the existing digesters. For instance, a simple mechanical mixer can be added to the existing fixed-dome design to ensure proper mixing of the digestate to increase the conversion rates. In addition, consistent daily feeding can enhance the mixing in the digester. Micro-aeration can be incorporated for in-situ $H_2S$ reduction in biogas. For countries with abundant solar irradiation, solar-based pre-treatment, temperature enhancement of the AD process and post-treatment of the digestate should be considered. However, further studies on the digestate quality in relation to application as fertilizer are recommended. As a summary of the revised literature and field observations of this study, we propose a small-scale biogas-electricity generation system in Figure 8.

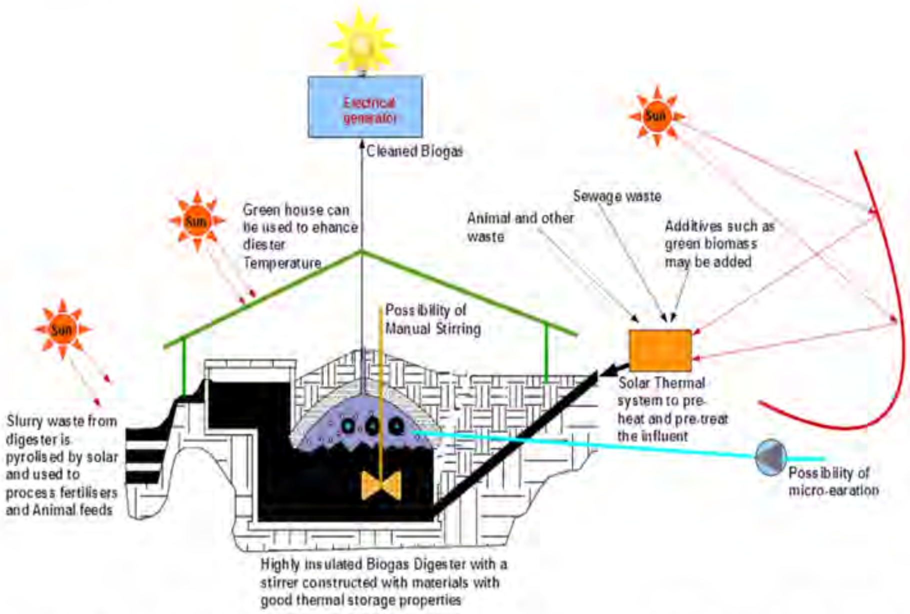


**Figure 8.** Model biogas-electricity generation system integrated with a solar thermal system.

## 6. Conclusions

This study has shown that there is a potential to locally enhance biogas quality and quantity from small-scale digesters via available pre-treatment methods for feedstock, co-digestion, additives and operational practices. However, its small-scale implementation in resource-constrained settings needs to be technically and economically evaluated. Furthermore, field observations have revealed that passive pre-treatments, additives and user practices can potentially impact biogas production. Specifically, our research has established that:

- There are a number of available co-digestion feedstocks in off-grid settings, such as banana leaves, which can be used in addition to the usual animal and human waste. However, this needs additional practice such as milling and gridding to be effective.
- There is passive usage of co-feedstocks such as green leaves and additives such as soil. The usage of these locally available additives in off-grid community settings could potentially enhance the AD process in small-scale digesters. However, their effect on process efficiency needs to be more thoroughly evaluated.
- Urine is currently being used by some digester operators. However, urine could have several effects on the efficiency of the AD process and the quality of biogas in terms of impurities such as $H_2S$. Digesters using urine as a solvent had lower $H_2S$ content compared to digesters that had water as a solvent. Therefore, its use should be carefully evaluated to find out the extent of possible benefits, drawbacks and the optimal dilution ratio to enhance biogas production rates.
- Standard operation of the digesters was not always followed by off-grid digester operators. This has an effect on OLR and HRT, among others. Therefore, good practices for digester operation such as agitation, daily feeding volume and dilution

ratios need to be emphasized during user training to ensure stable operation and efficient biogas production in small-scale digesters.

- Solar energy, though currently utilised passively, if embraced, can potentially enhance digester temperature and also provide freely available thermal energy for pre-treatment of small-scale digester feedstocks. Solar irradiation can also be considered as a feasible alternative if mild temperature pre-treatment is applied in small-scale digesters. In addition, solar energy can be a heat source to increase the digester temperature to an optimal range for the AD process. Its use can have a positive effect on biogas quality and quantity and thus can also enhance the economic feasibility of small-scale biogas-electricity generation systems. Despite the aforementioned advantages, further research and development is required to evaluate the economic and technical feasibility of solar integration with AD for small-scale biogas-electricity generation applications.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/en14113088/s1, Supplementary Material with Table S1. Quality of Biogas from Lab experiments, and Table S2. Quality of Biogas From field measurements.

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