A Low-Cost Tubular Biogas Digester for Rural Households in Malawi

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Abstract

Effective development and promotion of biogas technology can offer numerous benefits to any country. However, development and adoption this technology in Malawi has for a long time been constrained by locally unaffordable biogas digester designs. Hence the aim of the study was to develop biogas digester from locally available materials and assess its performance under Malawian environmental conditions. The study consisted of three pairs of locally constructed tubular polyethylene digesters (same design) that were fed with pig dung, goat stomach waste and kitchen food wastes. One digester in each pair was enclosed in a greenhouse structure made from transparent polyethylene. Gas production onset was quickest in digesters containing pig dung (1 day) followed by those containing goat stomach wastes (3-4 days) and lastly kitchen food wastes (14 days). Average daily gas production from digesters was 35.7 L/day and the average percentage of methane content in the biogas was 62.1 %. We therefore conclude that the overall performance of the tubular polyethylene digesters that were feed with goat stomach waste and pig dung was superior compared to other studies done at similar ambient temperatures. The flame was sustainable and usable for home and industrial purposes as the methane content was above 52%. We therefore further conclude that tubular digesters can be fabricated and used under Malawi conditions.

Key words: *Energy sources, Biogas, digester, methane, design, wastes, Malawi*.

1 INTRODUCTION

Renewable sources of energy are an indispensable ingredient to sustainable social and economic development and no country can achieve sustainable development without ensuring adequate access to energy services for a broad section of its population (Lloyd, 2017; Stout & Best, 2001; Flavin & Aeck 2010). Energy propels the development activities of a country and when it is renewable the greater the assurance of the continued availability. Furthermore, production and utilization activities of most renewable sources of energy are less harmful to the environment hence ensures continuous availability of critical development resources and services provided by the environment.

Malawi is well endowed with a variety of renewable energy resources. However full potential of the renewable energy subsector remains far from being realised due to several structural, operational and institutional challenges. This has resulted in overdependence on firewood and charcoal as a primary source of energy. Current statistics indicate that about 97 % of Malawians depend on firewood and charcoal for their domestic energy requirements (GoM, 2017). In particular, about 99.7 % of the rural population depend on solid fuels such as firewood, charcoal and crop residues for cooking (GoM, 2009b).

Overdependence on solid fuels such as firewood, charcoal and crop residues have several disadvantages such as indoor air pollution when used for cooking (Rehfuess, 2006) and deforestation (GOM, 2017). Because of the high use of solid fuels for cooking, levels of particulate matter higher than those recommended by World Health Organisation (WHO) have been observed in Malawian households (Fullerton et al., 2009; Havens et al., 2018). Heavy reliance on firewood and charcoal has also been one of the major causes of deforestation in Malawi (GoM, 2010). Among other things, deforestation has contributed to firewood scarcity resulting into a situation where women and girls walk longer distances to fetch firewood and in the process waste time that could be engaged in other critical personal and community development activities (GoM, 2010).

Biogas digesters have been tried in Malawi as alternative energy sources for cooking in rural areas. The use of biogas for cooking has also been noted for most developing countries (Cheng et al., 2014; Sasse et al., 1991; Karki, 2005). Biogas has the advantage of providing clean energy, reducing indoor air pollution, reducing deforestation, improving waste management and improving agricultural productivity through use of effluent as fertiliser (Czekała, 2018; Garfí et al., 2012; Dohoo et al., 2013; Fullford, 1988; San Thy & Preston, 2003; Clanak, 2014.). Therefor biogas technology has multiple potential benefits it can offer to Malawi if it is developed and effectively promoted. However, its impact over the years has mainly been constrained by huge cost of the conventional fixed dome and floating drum digester designs that have been used to promote the technology in Malawi. Tubular polyethylene biogas digester is a potential low-cost alternative digester design that can be used to promote biogas technology in Malawi. No attempt however has been made to understand, adapt and optimise its design and performance under local environmental conditions. Furthermore, there are various biogas digester feedstocks in Malawi that are abundantly available. These feedstocks include pig manure, abattoir waste (animal intestine contents) and kitchen food remains. However, the performance of these substrates in a tubular polyethylene biogas digester under local conditions has never been studied and compared. To fill up this knowledge gaps, the present study was conducted.

2 STUDY AREA, DATA AND METHODS

The study was carried out at Chancellor College in Zomba District, Malawi. This site is located at 15.39° S and 35.33° E and at an altitude of 898 m above sea level (m.a.s.l). Zomba experiences a tropical climate with three main seasons: cold-dry, hot-dry and hot-wet, ranging respectively from April to July, August to October and November to March. The hottest months are September, October and November, with average temperatures ranging between 28 ^oC and 30 ^oC. This section describes the methods used in the study.

2.1 Experimental design overview

The study followed an in-situ experimental design approach in which three pairs of tubular polyethylene digesters of same design and size were constructed and installed within a similar microclimate environment (at the same site). One pair of the digesters was fed with pig dung, another pair with fresh goat stomach contents and the last pair with kitchen food wastes. These feedstocks materials where chosen because they are currently available in Malawi as waste. The pig dung is readily available in many households with pigs while the goat stomach contents are available in many slaughter shelters and they are usually not used for any purpose. The kitchen waste is usually available in many local restaurants and hotels.

One digester in each pair was enclosed in a movable greenhouse structure made from transparent polyethylene material while the other was not enclosed in the greenhouse structure. Each digester was inoculated the same type and amount of inoculum, which is partly digested sludge with high amounts of active microbes (Achinas & Euverink, 2019). The experiment was conducted for a period of three months during which data on the temperature of the sludge inside the six digesters was collected at an hourly average using K-chrome thermocouples (± 1.1 C°) and an automatic data logger (Campbell Inc., CR10 model). Ambient temperature and the temperature inside the green houses were monitored at every hour each day for a period of one month using a handheld multi-meter (Brymen, TBM815 model). Volume of gas produced per day was monitored using a water-displacement based system that was improvised from 5-litre empty plastic cooking oil containers and 13-litre buckets. The content of methane in the produced biogas was analysed using the Dragger gas monitor (Dragger Safety AG & Co. KGaA, X-am 7000 model). The pH was measured using both bench (Metrohm, 827 pH Lab Model) and portable (Oakton, Eco-Testr pH2 model) digital pH meters. Gas pressure was measured using a properly hand-crafted and calibrated U-tube manometer. A flammability test was also carried out to see whether the gas that was produced was flammable and an assessment of the quality of the flame was done.

2.2 Digester design, construction and installation

This section explains the design, construction and installation of the digesters. The study used an improved tubular polyethylene digester design methodology by Marti-Herrero & Supriano (2012) as shown in Figure 1. The methodology uses trench cross sectional area and optimisation of trench dimensions with respect to the bottom angles (α) of the side walls (A) of the trench and the relationship between length of the biogas bell (L_{bell}) and the top width of the trench (b) as shown in Figure 1.

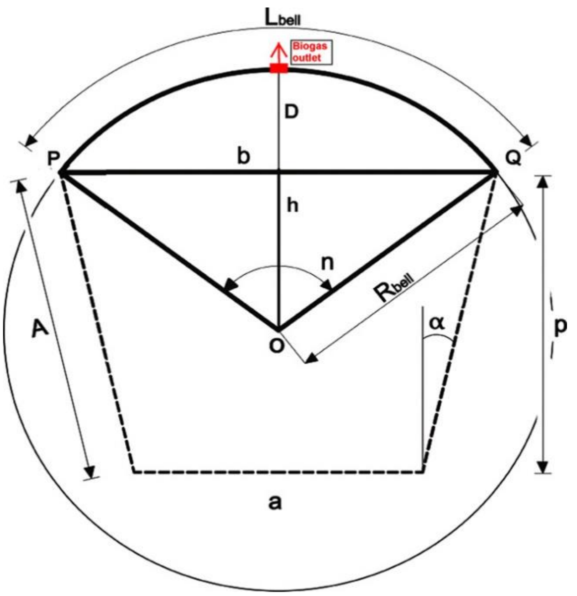

Figure 1: *Cross section diagram of a tubular polyethylene digester (Marti-Herrero & Supriano, 2012).*

This new methodology overcomes the problem of reduction in actual hydraulic retention times that was experienced with older designs whose liquid volume calculations are based on the circular cross-sectional area of the polyethylene tube (Marti-Herrero, 2011).

Sizing of the digester was based on a daily substrate-water mixture loading volume and hydraulic retention time. The study used a daily fresh substrate loading rate of 5 kilograms per day and a retention period of 40 days as design criteria. This amount was chosen for easy collection, sorting and transportation of the substrates to the digester site. The retention period of 40 days was chosen because the digesters were expected to operate at local ambient temperatures of between 28 °C and 30 °C which are within the mesophillic temperature range of 20 °C – 45 °C (Ukpai & Nnabuchi, 2012); Al Seadi et al., 2008). The substrate-water mixing ratio of 1:3 was used to ensure fluency of slurry so as to prevent obstruction (Marti-Herrero & Supriano, 2012). The design daily substrate-water mixture loading volume (V_R) was found by multiplying the sum of substrate (R_s):water (R_w) mixing ratios by the design daily fresh substrate mass loading rate (M_s) and 1 L, assuming that 1 kg of the substrate was equal to 1 L of water as given in equation (1).

$$V_R = (R_s + R_w) M_s L \qquad (1)$$

where V_R is the design daily substrate-water mixture loading volume (m^3/day), R_s is substrate proportion in mixture, R_w is water proportion in mixture, M_s is mass of fresh substrate to be loaded daily (kg/day) and L is 1 litre of water (assuming 1 kg of substrate was equal to 1 litre of water).

From (1), a total daily substrate-water mixture loading volume of about 20 L or 0.02 m^3 was obtained. Figure 2 shows the installation of six digesters.

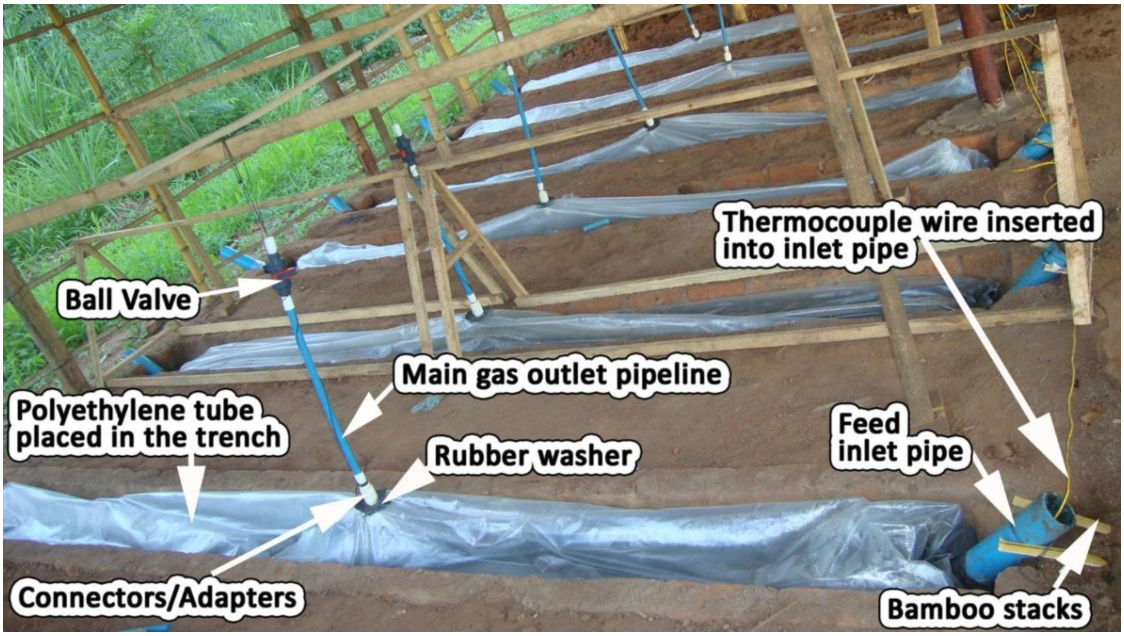

Figure 2: *Installation of the tubes into the trenches.*

2.3 Determination of Biogas Produced Per Day

The amount of biogas produced per day was collected and measured using a displacement system adapted from San Thy & Preston (2003). It consisted of an empty 5- litre cooking oil plastic bottle inserted in 13 litre bucket filled with water. The base of the bottle was open and the mouth was sealed with a stop cork and gum and fitted with small gas inlet and outlet pipes (Fig). The height of the bottle was graduated in into five (5) equal marks each equivalent to a liquid volume one (1) litre. The system was designed to operate under pressure generated from the volume of biogas produced. The gas from the digester was directed into the inserted 5-litre bottle which was floated in the larger 13-litre plastic bucket filled with water. With increase in amount of gas being produced, the gas pressure inside the inserted bottles was expected to increase and displace some of the water inside the bottles. However, since the system was made in such a way that the pressure required pushing the inserted bottle upwards was less than the pressure required to displace the water from the plastic bucket, the increase in pressure inside eventually translated into upward movement of the inserted bottle from its initial position.

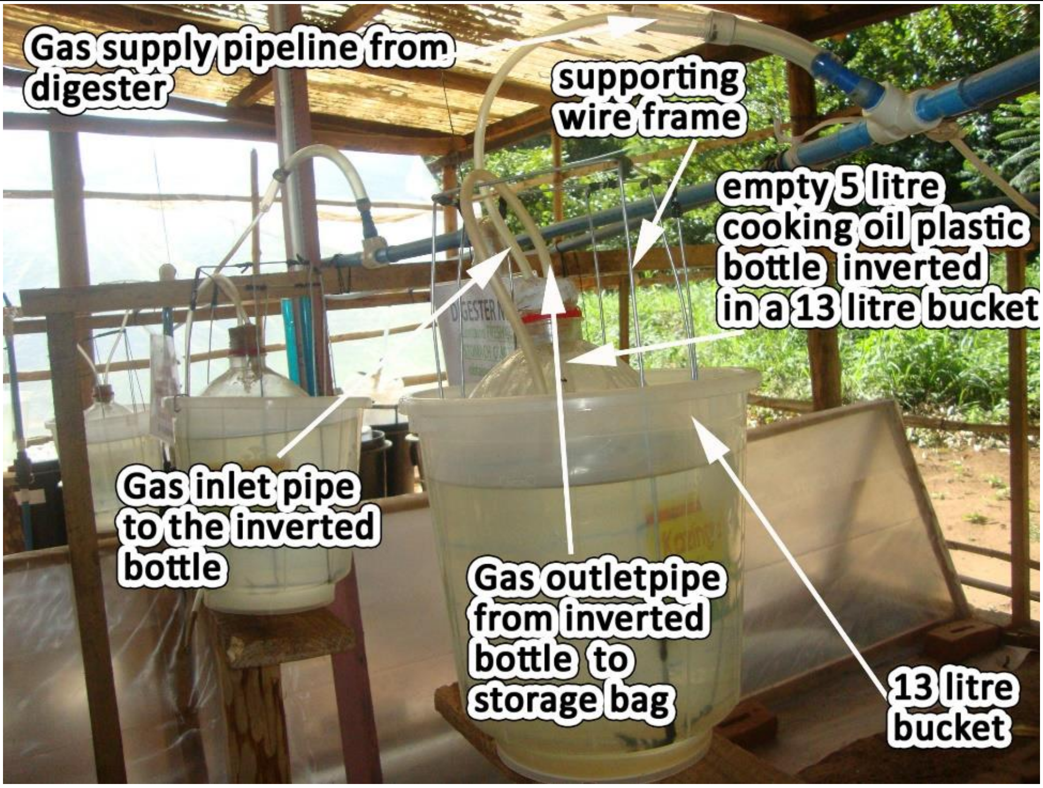

Figure 3: *The displacement apparatus used to measure amount of biogas produced.*

To increase the pressure required to push the inserted bottle upwards, a 16 kg flat piece of wood was wrapped in polyethylene sheet and placed on top of the inflated digesters during measurement of gas produced. The mass was left resting on the digester while the main gas outlet valve was opened to allow the gas to flow to the measurement device where it caused the inserted bottle to rise to maximum graduated mark in litres. The main gas outlet valve was then closed and the inlet pipe to the inverted bottle was also blocked by folding. The outlet pipe on the inverted bottle was then opened to allow the gas to flow to the gas storage bag that was hanged above the apparatus. As the gas was released to the gas storage bag, the inserted bottle went down to rest at its initial position. The valve to the storage bag was then closed. This cycle of events was repeated until the inflated digester became flattened. The number of times the inserted bottle was completely filled was counted and multiplied by the marked maximum reading to obtain the total amount of gas produced in litres for the 24 hour interval. This was done for each digester every morning at eight o'clock for a period of 30 days.   Data was collected for a period of one month.

2.4 Determination of Methane content

The Drager (Dragger Safety AG & Co. KGaA, X-am 7000 model) gas monitor was used to assess the content of methane in the biogas that was produced in the experiment. For each day, a sample of the gas produced was placed in a clear plastic bag that had the gas monitor. The gas monitor was then switched on to measure the percentage of the methane in the gas.

2.5 Measurement of temperature

Temperature data was collected in three categories. There was measurement of sludge temperature inside each of the digesters. This was done using six K-chrome thermocouple wire probes that were inserted into each of the digesters and connected to a CR10 automatic data logger. The data logger was used to measure the sludge temperatures every four minutes and then to further compute the hourly averages of the temperature measurements. The sludge temperatures of the digesters were measured for a period of two months during the three months of the experiment.

The temperature inside the green houses and for the ambient temperature was also measured every hour using a hand-held digital temperature multi-meter (Brymen, TBM815 model) that has a thermocouple wire probe.

2.6 Measurement of pH in the digester

Sludge samples for pH analysis were siphoned from inside the digesters using a 2 m long and 12.7 mm diamteter PVC pipe which was inserted from the end of the effluent outlet pipe. A different sampling pipe was used for each of the digesters. During each sampling schedule, one sample was collected per digester giving a total of six samples. The measurement was done twelve (12) times in the course of the experiment and it was done onsite using the field pH meter (Oakton, Eco-Testr pH2 model) and in the laboratory using a bench based digital pH meter (Metrohm, 827 pH Lab Model) as recommended by American Public Health Association (APHA) APHA (1999).

3 RESULTS AND DISCUSSIONS

We present the result on the gas production by the digesters, quality of the gas produced, temperature variations of the digesters, and the results on pH of the feed material inside the digesters.

Table 4 gives the details of the time taken for each digester to start showing signs of gas generation. The gas generation first started in the digesters that had pig dung as feed material and this was followed by digesters containing goat stomach wastes (after 3 to 4 days). The observation of the generation of the gas was based on the inflation of the digester. Though a specific reason for quick onset of gas production in pig dung digesters may be a subject for further research, immediate gas production from pig manure was also reported by Ferrer et al. (2008). One of the possible explanations can be the fact that despite using the same type and quantity of inoculum, the growth and composition of microorganism populations would vary from feed type to feed type depending, among other things, on the ease of adaptability to the feed type (Al Seadi et al., 2008). It generally appears therefore that in this case, the microbial population may have had less challenges to adapt to pig dung feed type compared to the other feed materials. The other reason is that the pig dung was collected from an old heap of dung and therefore may have already started anaerobically decomposing. The 3 to 4 days lag time in goat stomach wastes digesters may have been due to longer stabilisation of the microbial population in the digesters containing this feed type.

On the other hand, it took 14 days for the digesters containing kitchen food wastes to start showing some inflation as a sign of gas production. The inflation was however short-lived thereby preventing collection of meaningful gas production data. For this reason, these digesters were not included in the gas production quantity analysis. However, the methane content of the little amount of the gas that was collected was analysed. The main possible contributing factor to longer lag time and minimal gas production in kitchen food wastes digesters appears to have been the low pH that was observed. According to Xie (2012) and Dróżdż (2019), low pH values are not conducive to the biogas production process.

Table 4: *Time (days) taken by each feed type digester arrangement to start showing signs of gas production*

Digester Type (feed type and operation environment)	**Period taken to start getting inflated (days)**
Pig dung _Greenhouse	1
Pig dung _Open (Not in greenhouse)	1
Goat Stomach wastes_ Green House	3
Goat Stomach wastes_Open (Not in greenhouse)	4
Kitchen food wastes _Green House	14 days , then digestion stopped
Kitchen food wastes_Open (Not in greenhouse	14 days , then digestion stopped

Table 2 gives the quantities of the gas produced from the pig dung and goat stomach wastes. On average, it can be noted from the table that biogas production from the digesters operated on goat stomach wastes was 39.0 ± 3.0 L/day while from digesters containing pig dung was 32.6 ± 2.5 L/day. The difference of gas production by the two feed materials of pig dung and goat stomach wastes was significant based on the T-test carried out that gave t(118) = - 3.221, $p<0.05$. These results are in agreement with other studies in which biogas production from animal intestine contents is generally estimated to be higher than from pig manure (Al Seadi et al., 2008). Higher quantities of biogas were realised from goat stomach wastes possibly due to higher content of fresh partially digested organic substances and materials which allowed prolonged action of anaerobic bacteria compared to pig dung which was a relatively complete digested material. The yield from a particular feed stock will among other things vary according to energy left in the feed stock and if the feed stock has undergone prolonged storage, it may already have begun to breakdown (Armah et al., 2017).

Table 5: *Biogas (litres) produced per feed type and operation environment per day*

Digester Operation Environment	Type of Digester	
	Pig dung	Goat stomach wastes
Open (Not in greenhouse)	32.8 ± 3.5	37.33 ± 3.5
Greenhouse	32.3 ± 3.5	40.6 ± 4.9
Overall (for open and greenhouse)	32.6 ± 2.5	39.0 ± 3.0

± in the table means standard deviation

With regard to the environment under which a digester was operated in general, an independent T-test was carried out for the digesters containing ping dung to determine if there was any significant difference between the amount of gas produced by the digester operated in the open and that operated in the greenhouse. The p-value of 0.422 was obtained from the two digesters containing ping dung and at 5% significance level, this indicates that the two environments under which the two digesters where operated had no significant effect on the amount of gas produced. Similarly, a t-test was also carried out for the digesters containing goat stomach wastes to determine if there was any significant difference between the amount of gas produced by the digester operated in the open and that operated in the greenhouse. A p-value of 0.148 which at 5% significance level, indicates that the two environments under which the two digesters where operated had no significant effect on the amount of gas produced. This suggests that the environment under which a digester was operated had no significant effect on the amount of gas produced. This can possibly be explained by the observed insignificant differences between the temperature inside the digesters under greenhouse and those in the open (Table 3). This is because higher temperatures are critical for increased anaerobic methanogenic bacterial activities (Karki et al., 2005). Pham et al. (2014) also did not find significant difference in biogas production between insulated and uninsulated digesters with a temperature difference of~ 1°C.

Figure 4 show the variation of the amount biogas produced per day from each of the digesters for a period of 30 days. In general, it may be observed from the graph that from the 1st to the 19th day, there was a large variation in quantity of biogas produced between consecutive days as well as between the environment and feed types. However, between the 20th and 30th day, amount of gas production became less variable between the environment and feed types and from one day to the next. This can be explained in terms of increased stability of physical and biochemical conditions and processes inside the digesters with time thereby enabling more stable anaerobic methanogenic activities (Schnurer & Jarvis, 2009).

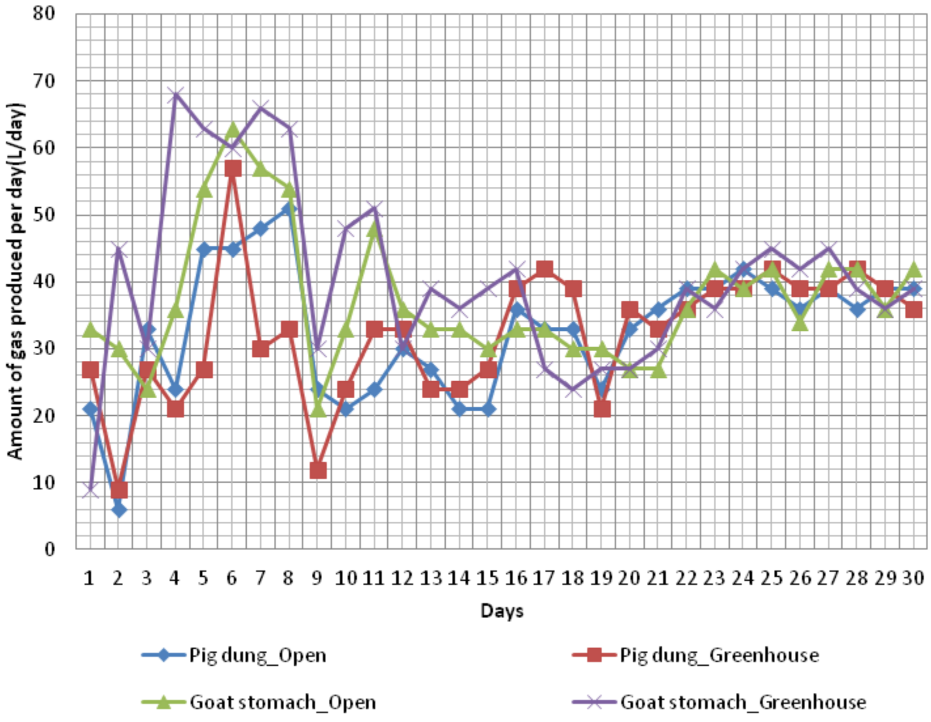

Figure 4: *Biogas generation trends according to feed type and digester operation environment.*

Figure 1 shows the percentage of methane in the biogas (Vol.-%) for the different types of feed material and digester operating environment. On average, biogas from a digester containing goat stomach wastes had 67.3 % methane content while that from pig dung contained 57.0 % methane. This difference can be attributed to the inherent differences in the physical and chemical characteristics of the two feed types. Dublein & Steinhauser (2008) suggests that composition of the substrates can influence methane content in the biogas when he states that addition of long-chain hydrocarbon compounds such as materials that are rich in fats can improve quality of methane i.e. increase content of methane provided that quantities are not too large to avoid acidity.

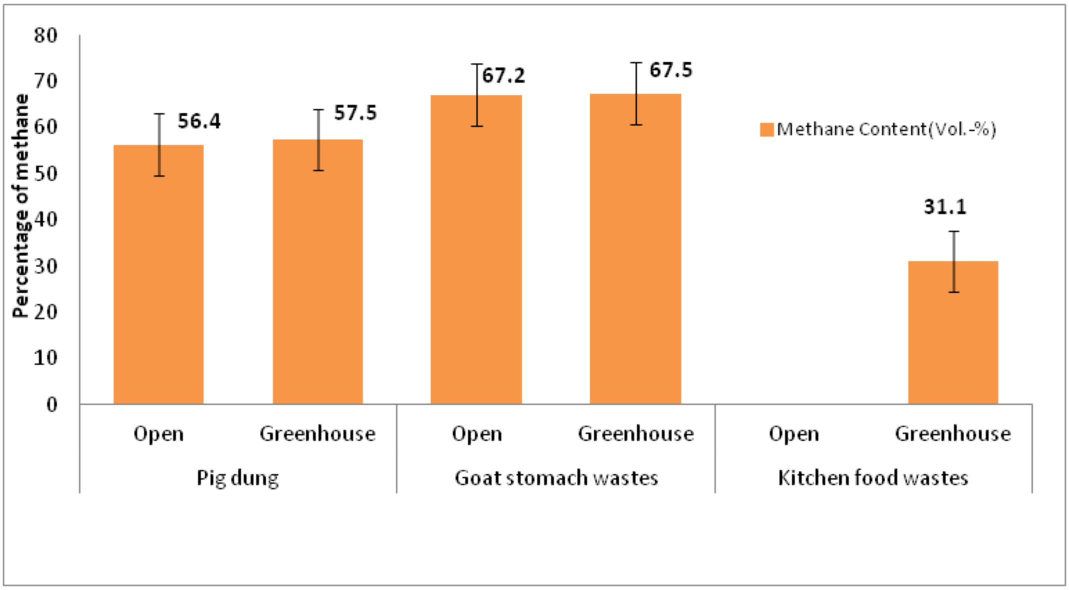

Figure 1: *Average methane content of biogas (Vol.-%) for the different feed types and digester operation environment.*

The percentage difference of methane in the biogas from digesters operated in the open and under greenhouse was found to be 1.1 % for digester containing pig dung and 0.3 % for digester containing goat stomach wastes. The small differences in the content of methane between the biogas from open and greenhouse digesters suggests that the greenhouse environment may have had little effect on the methane content in the gas. On the other hand, the gas collected from the greenhouse digester containing kitchen food wastes had a lowest methane content of 31.1% indicating the inefficiency of the methanogenic processes which eventually came to a halt after 14 days. In general, the values of methane content obtained in the study are much higher compared to other studies done at similar ambient temperatures (Ferrer et al., 2008). This may be due to differences in the digester design and also the power of the inoculum that was used as it has been suggested to have an impact on the composition of the biogas (Hobson & Shaw, 1973).

Table 3 shows that the average hourly temperature inside digesters ranged between 22.5 ± 0.4 C° (goat stomach wastes digester in the open) and 24.0 ± 1.7 C° (pig dung digester in a greenhouse). These temperatures appear to fall on the lower end of the mesophillic temperature range for anaerobic digestion (Al Seadi et al., 2008; Dublein & Steinhauser, 2008). The fact that the experiment was conducted during cooler months of the year may have contributed to this development (Zomba District Assembly, 2009).

Table 3: *Mean temperature inside the digesters according to type of feed material and environment under which it was operated*

Type of feed material used in a digester	Environment under which digester was operated	Mean temperature inside the digester(C°)
Pig Dung	Open	23.8 ± 0.6
	Greenhouse	24.0 ± 1.7
Goat Stomach Wastes	Open	22.5 ±1.5
	Greenhouse	23.0 ±1.0
Kitchen food wastes	Open	23.1 ± 0.6
	Greenhouse	23.6 ± 0.4

Kalia & Kanwar (1998) noted that simple biogas digesters without heating and stirring are influenced significantly by season, especially in cold winter climates. This implies that in warmer months or at warmer areas of the country, higher quantities of gas production rates could be obtained from this digester design since higher temperatures are critical for increased methanogenic activity (Karki, 2005). ANOVA results for the hourly mean internal digester temperature with respect to feed type and environment are summarized in Table 4.

From Table 4, it appears that there was a significant main effect of type of feed material on the average hourly temperature with $F(2, 138) = 13.52$, $p < 0.05$, $\omega 2 = 0.08$, as shown in Table 4. This is no surprise as different feed types are expected to exhibit different temperature behaviour due to differences in physical and chemical properties (Dublein & Steinhauser, 2008). Furthermore, it has also been observed that different feedstocks and temperature inside the digester strongly affected the microbiomes of the digester sludge and this subsequently affects the digestion process (Fontanaa et al., 2016).

Table 4: *Results of univariate analysis of variance of the hourly mean internal digester temperature with respect to feed type and environment*

Analysis of variance (ANOVA) results of the hourly mean internal digester temperature with respect to feed type and environment						
Dependent Variable: Hourly mean temperature inside a digester						
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	38.15369	5	7.631	6.457	0.000	0.1896
Intercept	78458.52	1	78458.521	66386.571	0.000	0.9979
Feed type	31.96131	2	15.981	13.522	0.000	0.1639
Environment type	5.377968	1	5.378	4.550	0.035	0.0319
Feed type * Environment type	0.814417	2	0.407	0.345	0.709	0.0050
Error	163.0944	138	1.182			
Total	78659.77	144				
Corrected Total	201.2481	143				

a. R Squared = 0.190 (Adjusted R Squared = 0.160)

In terms of the environment under which the digesters were operated, results of Two-Way Independent ANOVA showed that there was a significant main effect of environment under which digester was operated on the average internal digester temperature in general, with results of F (1, 138) = 4.55, $p< 0.05$, $\omega^2 = 0.01$(refer Table 4). This explains the observation that the mean internal digester temperature in digesters operated in the open were slightly lower than those operated under greenhouse. The greenhouse environment helped to keep the temperature in the digesters warmer and more stable by allowing incoming sunshine radiation but limiting heat exchange with the external environment. However, it must be noted in this case that the size of the effect was very small ($\omega^2 = 0.01$) which agrees with the small margins of the internal digester temperature differences between the open and greenhouse environments. Similarly, the value of R-squared was 0.19, meaning that only about 19 % of the variation in the temperature between greenhouse and open digesters could be explained in terms of the type of environment under which the digesters were operated (Field, 2005). This also partly explains the insignificant differences in the amount biogas production and the content of methane in the biogas from digesters operated under the greenhouse and in the open. According to Dublein & Steinhauser (2008), a temperature difference of $\pm$ 2 C° is not big enough to affect the anaerobic digestion process drastically. In this study, the average difference in internal temperature between greenhouse and open-operated digesters was 0.4 C° and is well below +2 C°.

The small size of the temperature differences may be explained in terms of the design of the digester in which the liquid portion lays in the underground trench surrounded by a thermal mass of dry soil whose temperature is generally less variable (Farouk, 1981; Phillip & Itodo, 2007). Above the liquid portion in the digester was the gaseous phase whose thermal conductivity is also a relatively poor (Lang, 2014). The warming and heat stabilizing effect of the greenhouse was therefore attenuated by these factors leading to relatively small differences in the values of mean internal digester temperatures between open and green house digesters. It may therefore be concluded that under conditions similar to those in the study, inclusion of greenhouses offers little benefit. Lastly, the Two-Way Independent ANOVA also showed that there was no significant interaction effect between the type of feed material and digester operation environment on the average internal digester temperature, with results of $F(2,138) = 0.345$, $p > 0.05$, $\omega^2 = -0.001$ (refer Table 4). This is important because it gives additional confidence that the observed variation was mainly due to either the feed type or the environment under which the digester was operated and much less by the interaction of these two factors.

With regard to temperature trends inside the digesters, Figs. 6 and 7 give a comparative display of the mean hourly ambient temperature and mean hourly temperature inside the open and greenhouse digesters across a 24 hour period for pig dung and goat stomach content wastes, respectively.

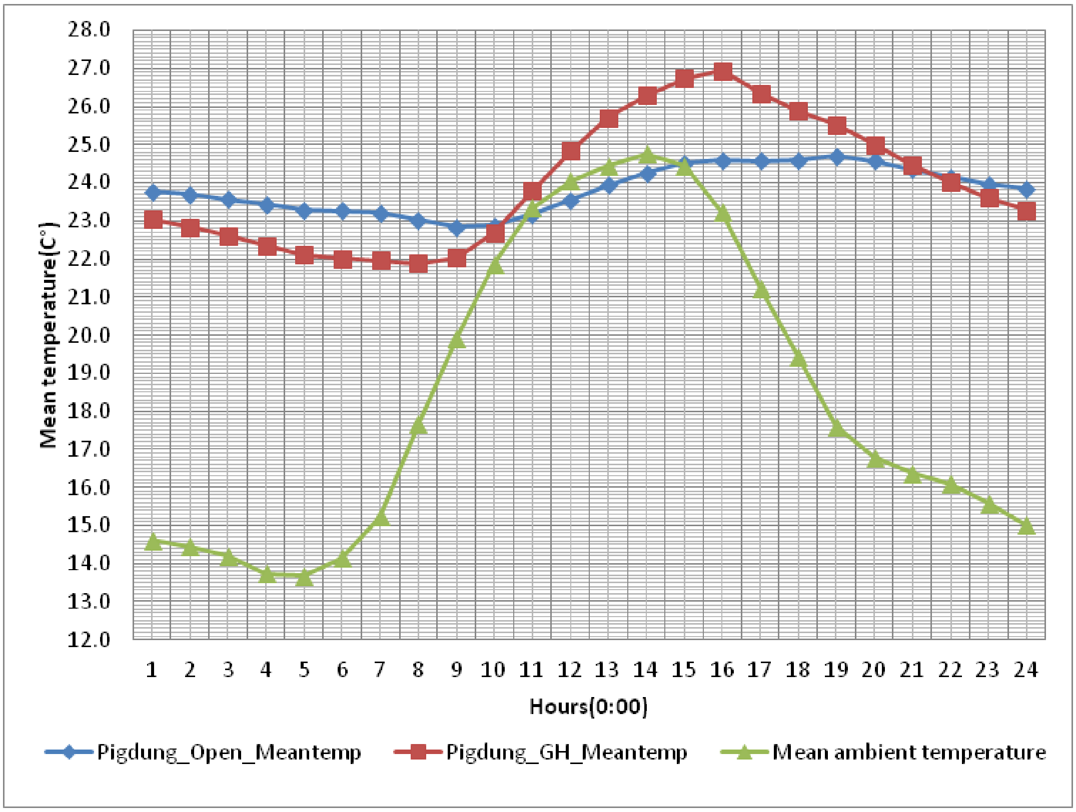

Figure 6: *Mean ambient temperature and temperature inside pig dung digesters operated inside greenhouse (GH) and without a greenhouse (Open).*

It may be observed from Figures 6 & 7 that the temperatures inside the digesters generally tended to be low during early morning hours from about midnight to 05:00hrs in both open and greenhouse digesters. From about 06:00 hrs the temperature began to rise until it reached its peak between 14:00 hrs and 17:00 hrs after which it also started to drop. In general, the variation in both cases appears to be in tandem with the progression of the ambient temperature. In other studies, it was similarly observed that temperature inside simple unheated digesters followed the trend of ambient air temperature with the result that the maximum (peak) temperature was found a few hours after noon (Pham et al., 2014; Perrigault et al., 2012; Park & Riddle, 2010; Khoiyangbam et al., 2004).

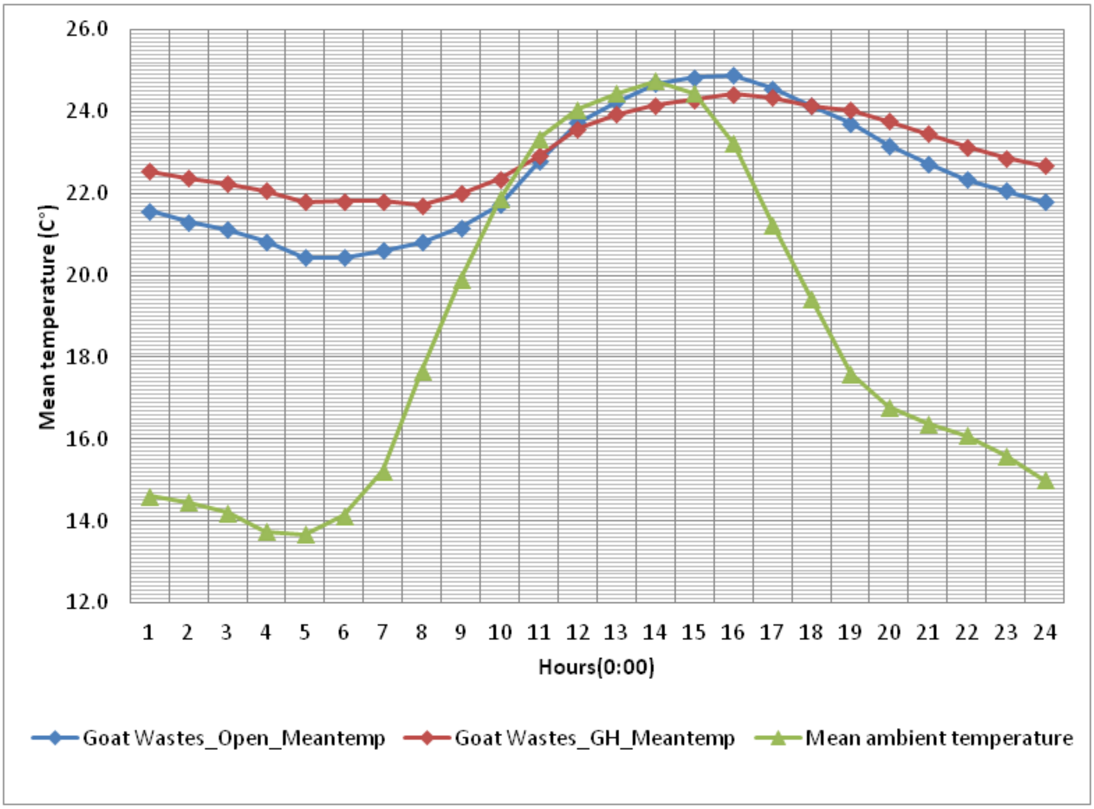

Figure 7: *Mean ambient temperature and temperature inside digesters containing goat stomach wastes operated inside greenhouse (GH) and without a greenhouse (Open).*

There were also marked differences in the behaviour of temperature inside the digesters between those containing pig dung and goat stomach wastes. For instance, in the digesters containing goat stomach wastes, the temperature inside the greenhouse digester was above that of the open digester during late evening hours to early morning hours (Figure 6). For the digesters containing pig dung, the temperature inside the greenhouse digester was below that of the digester in the open during late evening and early morning hours (from about 22:00hrs to 10:00hrs). This is an interesting observation which may require further investigation because according to the greenhouse effect theory (Harrison & Coll, 2007), the temperatures in the digesters containing pig dung were expected to behave more like those in the digesters containing goat stomach wastes. In this study it was additionally noted that the pig dung digesters produced higher peaks of digester temperature than the digesters containing goat stomach wastes. This may have been due to their advantageous positioning at the study site in relation to sun set direction hence got more affected by solar heating.

In the digesters containing kitchen food wastes on the other hand, temperature trends were markedly different compared to digesters containing pig dung and goat stomach wastes (see Figure 8). Firstly, the temperatures in the greenhouse and open digesters did not overlap anywhere across the entire 24 hour period. The temperature inside the greenhouse digester remained on top of that of the open digester across the 24 hour duration. Secondly, the temperature in the digesters containing kitchen food wastes was generally relatively higher than that of the pig dung and goat stomach waste digesters during morning hours. The timing of peak and low temperatures was also different in digesters containing kitchen food wastes compared to the pig dung and goat stomach waste digesters (see Figure 6, 7 and 8). This unique behaviour may be attributed to the minimal microbiological gas production activities in the digesters as the temperature inside a digester is also influenced by the microbial activity on the organic matter (Phillip & Itodo, 2007). As already reported, digesters containing kitchen food wastes did not show signs of gas production until after two weeks and production ceased again shortly afterwards.

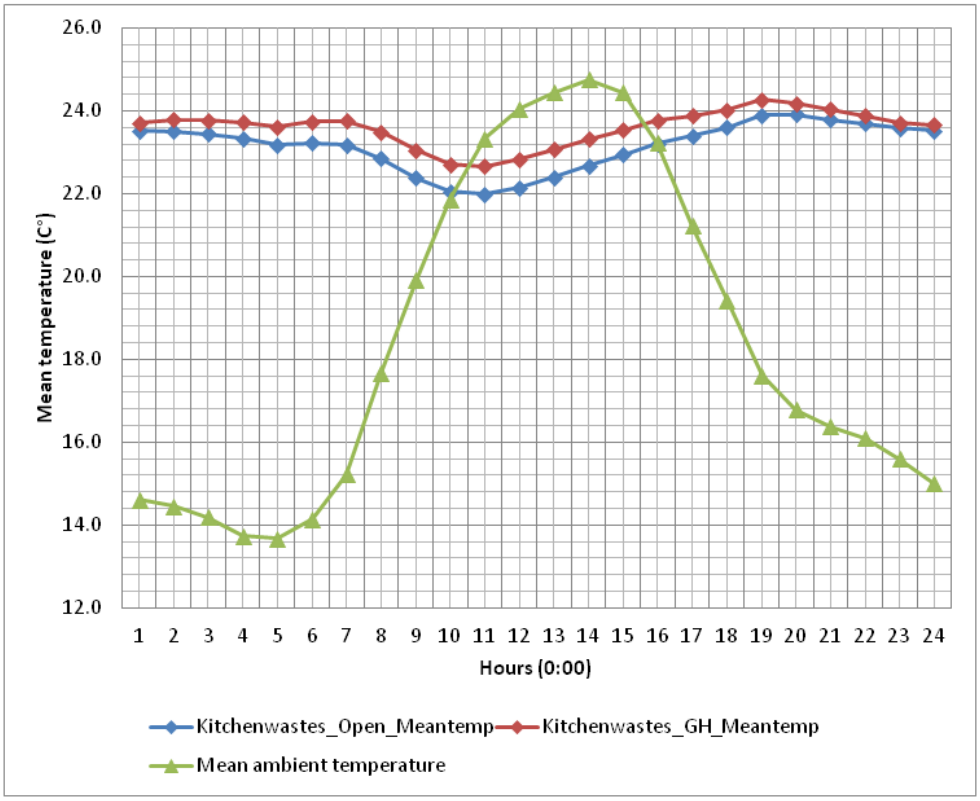

Figure 8: *Comparative ambient and hourly mean temperature trends inside digesters containing kitchen food wastes operated in the Open and greenhouse (GH) environment.*

It may be observed from Figure 6, Figure 7 and Figure 8 that ambient temperature was generally considerably lower than internal digester temperature during both morning and late evening hours but was almost at par with the internal digester temperatures during peak period of early afternoon hours. Thus, unlike internal digester temperature, ambient temperature varied greatly across the day with a mean of 18.4 ± 4 C°, minimum of 13.7 ± 0.5 C° and maximum of 24.8 ± 0.5 C°. In general, the difference between mean ambient temperatures and mean internal digester temperatures was about 4.0 ± 0.5 °C. This agrees with findings by Perrigault et al. (2012), who also noted that temperatures in the soil and in the digester were higher than those in the ambient air

3.1 pH inside the Digesters

Table 5 shows mean pH values of the sludge inside the digesters according to operation environment and feed type. It is observed that the pH was lowest in digesters containing kitchen food wastes with values of 3.9 ± 0.17 and 4.0 ± 0.18 for open and greenhouse digesters, respectively. This may have resulted from the predominantly carbohydrate content of the food left overs that were used.

Table 5: *Mean pH values*

Digester feed material type	Environment Type	Mean pH
Pig dung	Open	7.2 ± 0.17
	Green house	7.7 ± 0.16
	Open	6.9 ±0.07
Goat stomach wastes	Green house	7.1 ± 0.04
Kitchen food wastes	Open	3.9 ± 0.17
	Green house	4.0 ± 0.18

The kitchen food wastes mainly consisted of pieces of *Nsima* (semi solid maize flour porridge). In general, according to Dublein & Steinhauser (2008), biodegradation of hydrocarbons usually happens without release of pH buffering ions as is the case with proteins. Secondly, degradation of carbohydrates increases the hydrogen partial pressure more easily and this happens in combination with the formation of acidic reduced intermediate products. These factors therefore may have easily caused the pH in the digesters to decrease. Despite efforts to control the acidity by applying lime, the pH still remained low throughout the entire period. This situation may have greatly contributed to inhibition of methanogenic microbial activities as evidenced by delay and failure of the digesters to sustain exhibited signs of gas production. Most anaerobic bacteria, including methane-forming bacteria, perform well within a pH range of 6.8 to 7.2 (Gerardi, 2003). Another study by Xie (2012) found that a drop in the pH of the system to 5.9 brought methane production to a complete halt. The pH values in pig dung and goat stomach wastes digesters ranged between 6.9 and 7.7. These levels of pH were able to support methanogenic microbial activities hence the observed biogas production from the digesters.

3.2 Flammability Test

Biogas from both pig dung and goat stomach digesters was able to be ignited by a single match stick on a crudely improvised burner suggesting a reasonable content of flammable methane in it. The gas also burned with a characteristic blue flame. This agrees with results from biogas methane content analysis in which methane content ranged between 56.4% and 67.7%. Kaisu et al. (2008) found that the flame was sustainable at methane content between 52 % – 56 % and above but quenched at the methane concentrations of less than 45 % -54 % for carbon dioxide-methane biogas mixtures. This also explains why the gas collected from the digester containing kitchen food wastes did not burn at all.

3.3 Pressure

Pressure measurement instruments did not yield any useful data because the pressure from the digesters was too low to operate them under ambient temperature and pressure. It was also for this reason that an additional mass was placed on top of the inflated digesters to increase the pressure and enable daily gas production measurements to take place. Other studies also noted this low or variable pressure behaviour of tubular polyethylene digesters (Rajendran, et al., 2012). The ambient temperatures under which the study was carried out may have enhanced the problem. This low pressure phenomenon is however not entirely a setback as it means that the technology can be safely operated at household level with minimal risk of explosion accidents. However, in some areas this problem had been reduced by hanging some weights on the digesters and gas storage bags (Marti-Herrero, 2011).

4 CONCLUSIONS

This study has shown that it is possible to build tubular polyethylene biogas digesters in Malawi using locally available materials. Secondly, the locally constructed tubular polyethylene biogas digesters also performed relatively well even under cooler local weather conditions and feed material types. In particular, digesters containing pig dung were the quickest (1 day) to start producing biogas followed by those containing goat stomach wastes (3-4) days. However, the study also revealed that quantities of gas produced each day from digesters using goat stomach wastes was higher (38.95 L/day) than that from digesters containing pig dung (32.55 L/day). In terms of gas quality, it has been shown that goat stomach wastes had higher percentage content of methane (67.3%) than pig dung (56.95%). However, considering issues of availability, pig dung is more convenient compared to goat stomach wastes. Though production of biogas from digesters operated in greenhouses was slightly higher (36.45 L/day) than those in the open (35.07 L/day), the difference was not statistically significant, suggesting that inclusion of the green house in the propagation of the technology may not be worth it in Malawi. Furthermore, the study also revealed that starting up a digester containing kitchen food wastes mainly consisted of remains of *Nsima* (semi solid maize flour porridge) was not easy because they encouraged development of acidic conditions which inhibited biogas generation. In addition, it has been shown that the temperature inside the digesters was generally higher than ambient temperature by about 4 °C. Furtther, the study has also shown that the greenhouses had an effect on the mean temperature inside the digesters as they increased the internal digester temperature by about 0.4 °C. The size of this effect was however found to be small as evidenced by minimal difference in daily gas production observed between digesters operated in greenhouses and those in the open. It was also observed that internal digester temperature generally varied according to progression of solar radiation during the day, with temperatures being low during early morning hours and high during late afternoon hours after insolation had reached its peak. Thus, if a heating system is to be used with the digester, the heating system should be switched on during the early morning hours in order to optimise the performance of the digester. The study also found that pH in the digesters containing pig dung and goat stomach wastes was between 6.9 and 7.7 which is optimal and the digesters worked properly. On the other hand, the pH in the digesters containing kitchen food wastes ranged between 3.9 and 4.0 and these digesters were not able to sustain biogas production. This finding is critical as such pH values may act as a guide in early detection of malfunctions in the digester. It has also been observed that biogas produced from pig dung and goat stomach wastes was flammable. This implies that, keeping other variables constant, those with access to goat stomach wastes can enjoy cooking with biogas as much as those with access to pig dung as a digester feed material. Finally, the study has confirmed that pressure of biogas produced from the tubular polyethylene digesters was very low. Though this may pose a challenge to effective utilisation of the biogas in gas stoves, it can easily be corrected by having a secondary gas storage bag from where gas pressure to the stove may be enhanced by hanging some weights over it. On the other hand, the low pressure also means that this digester design is relatively safe from pressure induced explosion accidents.

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