International Journal of Energy Applications and Technologies
Available online at
http://dergipark.gov.tr/ijeat/issue/30402
Research Article

IJEAT

Vol. 4
Issue 2
pp. 53-63
Year
2017

DESIGN OF A HOUSEHOLD ANAEROBIC DIGESTER FOR RURAL AREAS IN SUDAN

Hazir Farouk[1,2]*, Andrew Lang[2], Khalid Bakheet[1], Mohammed Salah[1], Mutaz Elobaid[1], Omer Abdelazim[1]

[1]Department of Mechanical Engineering, Sudan University of Science & Technology, P.O. Box 407, 11111 Khartoum, Sudan
[2]World Bioenergy Association, Holländargatan 17, SE 111 60 Stockholm, Sweden

Abstract

This study is aimed at developing an anaerobic digestion system, optimized for economic manufacture and suited to the climate conditions in rural Sudan, which can efficiently produce biogas for cooking purposes at the household level. A lab-scale batch digester was designed and constructed using polypropylene material with a capacity of 20 liters, and with the biogas captured in a floating-top gas reservoir. This initial small-scale construction was mainly to study some important parameters of the anaerobic fermentation process. The parameters studied were: biogas production from various types of organic material, the levels of acidity and dry matter of the organic material, the affect of temperature within the container, along with an evaluation of the time scale and rate of gas production. Four types of organic material were used: fresh and dry cow dung with dry matter content of 20% and 90% respectively, chicken manure with dry matter content of 95%, and food waste with dry matter content of 10%. The results from the lab-scale reactors revealed that the gas production rate was directly proportional to the reactor temperature, and that all commonly available feedstocks produced biogas in predicted volumes, provided the feedstocks were within the recommended carbon: nitrogen balance and were not previously degraded by anaerobic or aerobic microorganisms. Using results from the lab-scale reactor, the digester design was improved and scaled up using a cylindrical water tank with a capacity of 225 liters. Biogas testing covered the methane percentage, calorific value of gas produced and gas consumption rate. The results were that the methane percentage was 57%, the calorific value of the biogas was 20.52 MJ/m^3 and the biogas consumption was 342 liters per hour during a simulation of normal operation for household cooking use.

Key words: *Anaerobic digestion, Biogas, Household, Rural areas, Sudan*

Paper submitted: March 12, 2017

Paper accepted: July 13, 2017

Corresponding author, biodieselgroup11@gmail.com

1. Introduction

One of the main environmental problems of today's society is the continuously increasing production of organic wastes. In many countries waste management, as well as waste prevention and reduction, have become major political priorities, as these are seen as representing an important share of the common efforts to reduce pollution and greenhouse gas emissions, and so the mitigation of global climate change [1, 2]. Production of biogas through anaerobic digestion (AD) of animal manure and slurries, as well as of a wide range of other putrescible organic wastes, is seen as one good option for reduction of greenhouse gas emissions. This is because the putrescible material, instead of just breaking down into freely emitted greenhouse gases, is converted into a renewable energy carrier in the form of biogas, and the digestate residue produced is a natural fertilizer for agriculture and home gardens [1, 3, 4]. The technology for small household-scale anaerobic digesters is proven and used around the world. Some countries leading in this are China, India, Nepal, Vietnam and Indonesia [5-7]. Biogas is also a major source of renewable energy in Europe and the USA. While the development of household scale anaerobic digesters in Africa is not so common, many countries are working in this area – including Kenya, Cameroon, and South Africa [5]

Sudan has high potential for production of biogas as an energy source. It shares some significant common factors with many other countries which have developed a significant energy production using biogas from anaerobic digestion. These common factors include: the high volume of putrescible wastes produced by different communities and industries, the daily struggle of women and children to collect wood for cooking, the large numbers of rural villages which are without access to LPG and are not connected to the main electricity grid, the high deforestation rate due to cutting wood for fuel, and the thousands of graduates who could be gainfully employed in developing this option, and who presently do not have jobs or who are working in menial jobs paying low income.

The aim of this study is to design an efficient and cost-effective household anaerobic digestion system for rural areas in Sudan. The study included a number of specific objectives: to assess the biogas production potential of a number of common likely feedstocks, and to study the effects of the main process parameters of anaerobic digestion.

2. Materials and Methods

This section explains the approach used in this study. It details the methods adopted for design and installation of lab scale biogas digesters, the selection of process parameters and the experimental procedure used for lab scale production of biogas. Based on the results from the lab-scale digesters, a model of biogas digester has been designed for household use. This design has been produced considering the process parameters which were applied in the lab-scale systems. The proposed design of the digester was tested and validated at the last stage of this project. All equipment and tools used during the study work are also shown in this section. The methodology flow-chart adopted is shown in Figure1.

2.1. Materials

The feedstock used in anaerobic digesters of a household will depend on the types of organic wastes (feedstocks) which are available to or produced by families in rural areas. Generally, there are a number of different types of feedstocks available at households in rural areas, and these include cow manure, chicken manure and food waste. In this study the most common types of feedstock available in rural Sudanese households were used in the lab experiments. These were: cow dung in high and low moisture content form, chicken manure, and food waste. Table 1 shows the source, the dry matter and pH of each feedstock used in the lab scale experiment. The feedstock selected for use in the final household digester design was fresh cow dung.

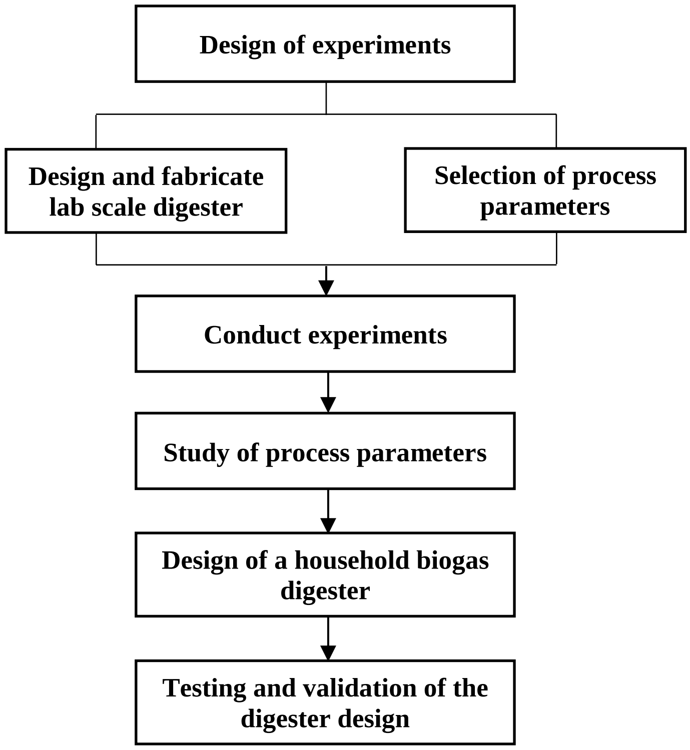

Fig. 1. Methodology flow-chart.

Table 1. Source, dry matter and pH of different types of feedstock.

Feedstock	pH	DM	Source
Cow dung (wet)	7	20%	Cows at College of Agricultural Studies – SUST, Khartoum
Cow dung (dry)	7	90%	Alkalakla Dairy Farm, Khartoum
Chicken manure	7	95%	Poultry Farm in Soba, Khartoum
Food waste	5	10%	Restaurant of College of Engineering – SUST, Khartoum

2.2. Experimental Procedure

2.2.1. Lab-scale digester

Three replicate lab-scale digesters (22 liters each) were assembled and prepared for experimentation at Professor Sabir laboratory for biogas, Department of Mechanical Engineering at Sudan University of Science and Technology (SUST). The main reason for development of this lab-scale digester is to study the anaerobic digestion process in identical batch digesters using different process parameters, in order to optimize these parameters before development of the design of a larger digester. The technology selected for the batch digester design was an above-ground design incorporating a separate floating biogas reservoir tank with a water seal, as shown in Figure 2. This design was selected mainly to simplify the installation and handling of the digester during the experiments, and because the floating gas holder allows easy reading of the daily volume of biogas produced.

Based on the dry matter content of each feedstock the mixing ratio with water was determined, then the required amount of water was added to the feedstock to bring the feedstocks to a standard 10% dry matter content, and subsequent mixing with a hand mixer was then done until a homogeneous mix was obtained. The mixture was placed inside the digester up to the working volume (75% of the total volume), and the digester top cover was tightly closed. Readings of temperature inside and outside the digester, pH and volume of gas produced were measured and recorded on a daily basis.

Fig. 2. Lab-scale digester.

2.2.2. Household digester

An above-ground floating gas reservoir system with gas holder was selected for the design of the household digester, made by modifying a polypropylene water tank commonly available in Khartoum (Figure 3). With this design, the digester should be put at a slightly higher level than the gas holder system. This prevents collection of condensing water vapor in the pipes, because otherwise the condensed water might possibly lead to blockage of flow of the gas produced, preventing it from going into the gas holder. A closed water-filled container allowing one-way gas flow was used between the gas holder and the gas outlet for safety (to prevent burning back of gas along the pipeline) when using the biogas.
It was found that this design is relatively low cost compared to other systems of the same volumes made from different material (i.e., fiberglass). It was also found that the quality is reasonably high, the necessary inlet and outlet fittings are commercially available, it is quite light weight, and the polypropylene material has the ability to withstand minor impact, high pressures and sunlight, and so will have an adequately long life under normal use. Because the digester container is long and of relatively small diameter it also does not need a large amount of space, and can be placed on or slightly into any kind of soil. One of the most distinctive features of this system is that it is easy to install and easy to maintain. This feature enables rural women at their household to operate and maintain the digester without any difficulties or complications.
The dimensions of the water tank selected for construction of the proposed digester are shown in Table 2, while Figure 3 shows the schematic drawing and assembled parts of the digester.

Table 2. Dimensions of the water tanks selected for the final digester construction.

Barrel	Diameter, (Cm)	Height, (Cm)	Volume, (L)
Digester	55.5	93	225
Gas reservoir (part water filled)	56	93	229
Reservoir upper floating tank	44	93	142

2.2.3. Content analysis, calorific value and consumption rate of biogas

While measurement of the methane percentage in the biogas can be done by removal of the carbon dioxide fraction of the mix by a number of methods (by reaction with an aqueous solution of NaOH is the simplest laboratory method), in this study a HSTDX8 biogas detector was used to detect the level of methane in the biogas.
The actual calorific value of the biogas is a function of the methane (CH_4) percentage. By knowing that 100% CH_4 = 10 KWh/Nm^3, the energy content of the methane percentage in the biogas produced in this

study is calculated and then the calorific value of biogas is known. Energy content of biogas produced can be expressed in other units using the energy unit conversion provided in Table 3.

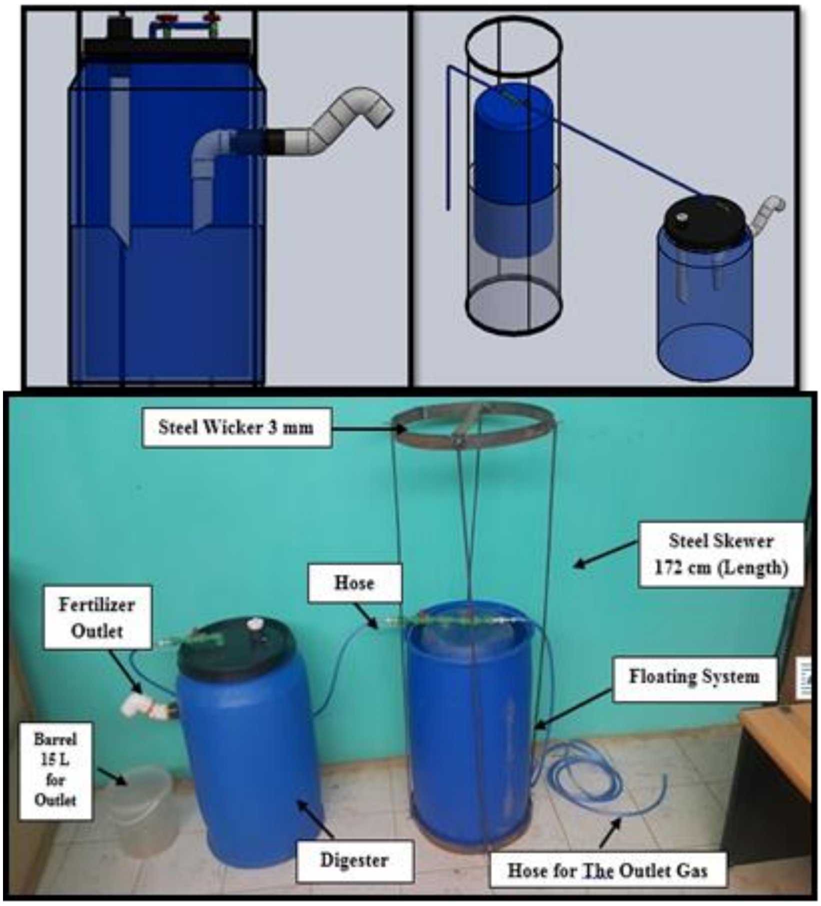

Fig. 3. Schematic sketch and assembled parts of the household digester.

The consumption rate of biogas was calculated by dividing the volume of biogas used to reach the boiling point of water and hold it at a rolling boil for the stipulated period, divided by the time.

Table 3. Energy unit conversions for calorific value.

Energy	KWh	MJ	BTU
1 KWh	1	3.6	3412
1 MJ	0.278	1	947.8
100000 BTU	29.3	105.5	1

3. Results and Discussion

3.1. Lab-Scale Digester

The lab scale digester is an experimental construction with a critical feature being that it is completely airtight and so will maintain the contents in an anaerobic state (absence of oxygen). The digester is also known as a bioreactor or anaerobic fermentation reactor. The design allows measurement of the anaerobic digestion parameters such as temperature and pH. Its design allows accurate measurement of volume of gas produced over time from each feedstock (see Figure 4), and analysis of the biogas components by using a biogas analyser, and for assessment of the time taken until biogas production ceases, known as the hydraulic retention time (HRT), applicable for any feedstock under set conditions.


Fig. 4. Gas holder full of biogas.

This design of the lab-scale batch digester when filled by putrescible materials (including the various manures) under the steady conditions of feedstock, temperature, dry matter content and pH should produce biogas of similar quality in a consistent way over time. The preconditions for satisfactory production of biogas were shown to be that the feedstock had a carbon:nitrogen mix that was within the advised range, and that the feedstock had not already been degraded or previously significantly affected by aerobic or anaerobic microorganisms. The following section discusses the results obtained from the labscale digester using different feedstocks.

3.1.1. Cow dung feedstock (Fresh)

The fresh cow dung used in this experiment had 20% DM, and so the mixing ratio of 1:1 (water to feedstock) was used to bring it to the standard 10% DM. A total volume of 16.5 liters of the 10% DM manure mixture was poured into the lab scale digester and this was then tightly closed to allow the anaerobic digestion (AD) process to start. The gas produced during the process is shown in Figure 5. The starting temperature of the AD for this experiment was low at 21°C but started to increase up to 30°C by the end of the experiment (this was due to increasingly warm daytime temperatures at this time of the year in Sudan). The pH number for the mixture was stable at an average of 7.2 throughout the experiment period and this was expected for the pH number for this type of feedstock.

As shown in Figure 5 there was no gas produced at the first days at low temperature, but the production rate of gas started to increase with increasing in the temperature until it reached the peak at 34 days and 30°C. From this, we can say the HRT was up to 40 days. This was a longer time than expected for this small digester volume. However, we assume this result was due to the low temperature of winter season when the experiment was started. (Retention time expected was less than 30 days). The relatively long period until the start of biogas production is assumed to be due to both lower temperature and so the slow buildup of bacterial population, and also to the need with this feedstock for the breakdown by specialist bacteria types of undigested cellulose in order for other bacteria populations to process this to produce the biogas. Moreover, during the first days of this experiment the lab scale digester and the gas holder were standing in the same level which would possibly affect the flow of gas to the gas holder, and so the gas produced may have accumulated at the top of the digester. The relative levels of the digester and gas holder were changed later in the experiment and this is the most likely reason for improving the gas flow into the holder. This appears to be the best explanation for the brief high spike of gas volume reading followed the period of no gas production as shown in Figure 5. Total gas produced was 17.5 liters in 38 days. It was noted that, despite the slow initial production, the final volume was consistent with the volume produced from dry cow dung (see 3.1.2).

3.1.2. Cow dung feedstock (Dry)

For this experiment, dry cow dung with 90 % DM was used as feedstock for AD. Due to the high DM contents, the mixing ratio used was 7:1 (water to dry cow dung). The total volume of 16.5 liter of mixture was poured into the lab scale digester and this was then tightly closed to allow the fermentation process (AD) to start. The gas produced during the AD is shown in Figure 6. The temperature during the process was constant within the range of 37-38°C. The pH number for the mixture was stable at average of 7 throughout the experiment period, and so approximately the same pH results were obtained as for the

International Journal of Energy Applications and Technologies, Year 2017, Vol. 4, No. 2, pp. 53-63

first experiment trial with fresh cow dung. As stated previously, this was the expected value for this type of feedstock.

It is clear from Figure 6 that the production rate was gradually increasing with time until it reached the peak at 7 days. However, after 7 days the gas production started to decrease until day 15, and then the AD process stopped. Total gas produced using dry cow dung in this experiment was 15 liter in 15 days. And so, the HRT was set to be 15 days which is expected with the small volume of the digester used and the relatively high and constant temperature (over each 24 hour period). The rapid rise to a peak gas production and then several steps of reducing gas production suggests that populations of specialist bacterial populations were breaking down the less accessible organic materials within the digestate, and with the subsequent digestion of these to produce methane.

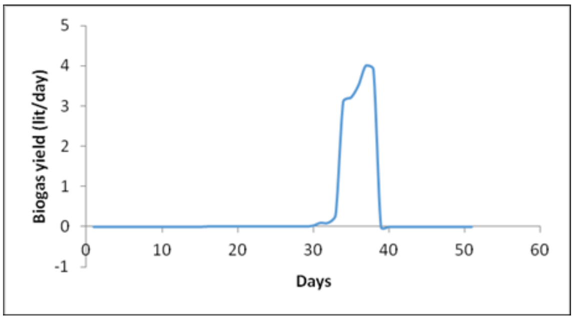

Fig. 5. Daily gas production using cow dung feedstock (fresh).

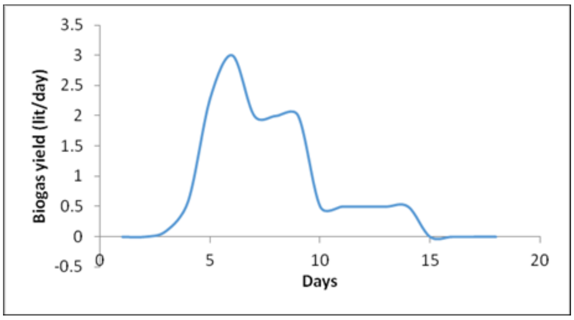

Fig. 6. Daily gas production using cow dung feedstock (dry).

3.1.3. Chicken manure feedstock

Chicken manure feedstock for this experiment had a dry matter content of 95%. Due to this, the mixing ratio was selected to be 9:1 (water to chicken manure) to bring the mix to the standard 10% DM. The total volume of 16.5 liter of mixture was poured into the lab scale digester and this was tightly closed to allow the fermentation process (AD) to start. The gas produced during the AD is shown in Figure 7. The temperature during the process was within the range of 37-38 °C, while the pH number for the mixture was stable at an average of 7.

Chicken manure is regarded as one of the most problematic feedstocks for anaerobic digestion due to the high nitrogen content of the feedstock. Anaerobic digestion of chicken manure means that the carbon:nitrogen ratio is well outside the range required in a normal anaerobic digester and this can mean that the usual pH buffering process is not adequate. This then results in the pH level moving higher than the pH range that the anaerobic bacterial population performs most effectively within. This development of a high pH level is because of production of ammonia. This was the case with this experiment, as when we tested the flammability of the biogas from the chicken manure it was noticeably lower than for biogas from other feedstocks. This was attributed to the gas having a high ammonia and CO_2 content relative to the methane content. From Figure 7, the quick rise in gas production and sudden fall to a low production rate would confirm the suppression of the bacterial activity, as postulated above. Moreover, it is likely that the manure had started to ferment anaerobically within the depth of manure in the chicken shed and then during the storage and transfer.

3.1.4. Food waste feedstock

This experiment was conducted with the food waste that has 10% DM. The selected mixing ratio was 1:1 (water to food waste). The total volume of 16.5 liter of mixture was poured into the lab scale digester which was then tightly closed to allow the fermentation process (AD) to start. The gas produced during the AD is shown in Figure 8. The temperature during the process was constant at range of 37-38°C, while the pH number for the mixture was stable at average of 5. Normally, fresh food waste would be around pH of 7, and so having the sample used in this experiment with pH of 5 that means that aerobic fermentation to acetic acid and CO_2 has started some time before. This level of acidity makes it harder to get a population of anaerobic digestion bacteria to develop. The gas volume produced was mainly CO_2 and there was little or no anaerobic digestion.

In this experiment the gas produced was low compared with other experiments. This may have been partly due to low pH value but possibly due to a low DM content in the feedstock due to an error in adding water when the food waste DM was already 10% when undiluted. The production of gas ceased after the fourth day. This unexpectedly short fermentation period was assumed to be due possibly to bacterial nutrient in feedstock being exhausted, or, more probably, because the pH value was too low to allow the necessary bacterial populations for anaerobic digestion to develop. Total gas produced using food waste in this experiment was 3 liter in 5 days. Clearly it is advisable to get food waste that is freshly produced and has not had time to degrade. It is also important that the dry matter be within the recommended range of 5-15%, though in a household situation it is likely that dry matter content of feedstock going into a digester will fluctuate within this full range without causing any real problem of biogas production.

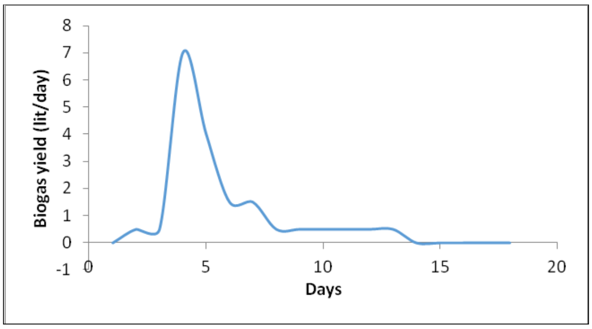

Fig. 7. Daily gas production using chicken manure.

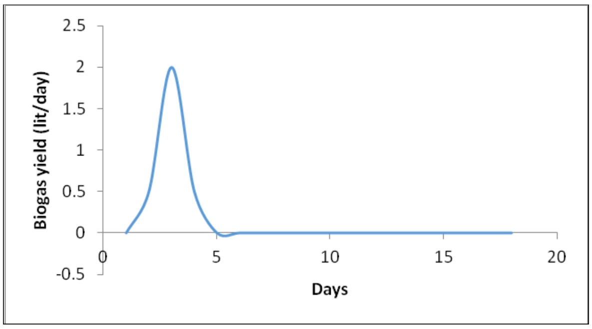

Fig. 8. Daily gas production using food waste.

3.2. Discussion of Trial Results

The laboratory trials of the three feedstocks (with two forms of one feedstock) showed that the bioreactors worked effectively and allowed all necessary measurements to be taken as required. The biogas reservoir with its inverted tank with water seal provided an effective yet simple and cheap system for capturing and measuring daily biogas production, and for seeing when biogas production began and ended. If time and other factors had permitted, it would have been more desirable to have done replicates of production on each feedstock and to have done some mixes of feedstocks (i.e., a chicken manure and cow manure mix) and this would have allowed some improved results, and allowed a refinement of finding dry matter content, and of monitoring of temperature and pH. However, the use of the biodigesters showed that the basic design of a gas tight polypropylene digester connected to a floating gas storage reservoir was an effective design for the most likely feedstocks, and so this basic laboratory reactor design was then upsized for a small-scale continuous-feed household digester.

3.3. The household digester

Once constructed and given an overall check of joints and functioning, the household continuous feed digester was filled with fresh cow manure of 10% dry matter. The biogas storage tank was a larger version of the one designed for the batch lab-scale digester, with the floating reservoir retained within a steel cage, and with its bottom edge sealed by the water in the base container. The gas produced in the 225 L digester constructed is shown in Figure 8. The temperature during the process was constant at range of 37-38 °C, while the pH number for the mixture was stable at 7 throughout the experiment period. It is clear from Figure 9 that the production rate of biogas was started on day 3 and gradually increased with time until it reached the peak at 14 days, then started to decrease again to when it ceased at about 22 days. And so the HRT was 22 days, which is close to the 20-day figure that was assumed in the design calculations. This production curve is satisfactory and similar to what was expected. We assume that the rapid start of fermentation was achieved because of the addition of a small amount of the stomach content of slaughtered cows to the fresh manure used in the mixture, and the initial bacteria population was able to reproduce very rapidly at this very suitable temperature.

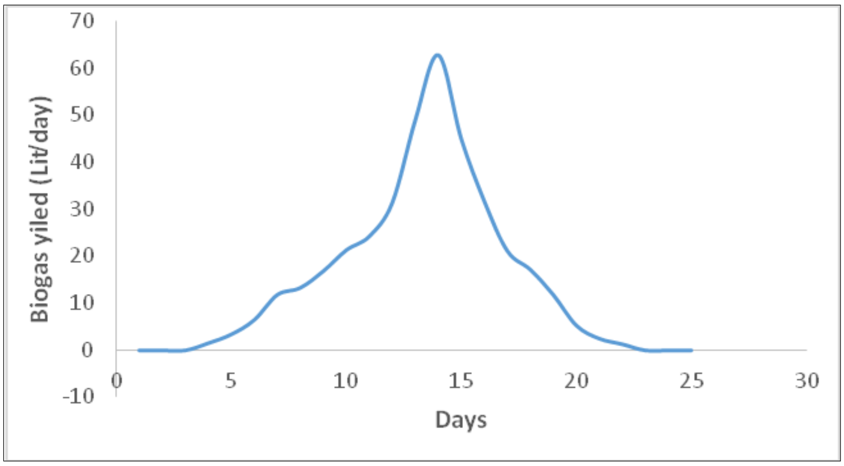

Fig. 9. Daily gas production using fresh cow dung (225 liter digester).

3.3.1. Content Analysis, Calorific Value and Consumption Rate of Biogas

The biogas produced in the digester proposed for the household was analyzed for methane (CH_4) and carbon dioxide (CO_2) contents. The level of CH_4 in the biogas produced was found to be 57% and of CO_2 42.7%. This conforms to the normal range of CH_4 in biogas which has a value in the range of 50% to 70% [8-11]. The biogas produced was used for boiling water on a biogas cook stove burner in a standard biogas burner efficiency test. The consumption rate of biogas was equal to 342 liter per hour. The energy content (CV) of the biogas produced was found to be 20.52 MJ/m^3, which is less than the recognized standard value of 23 MJ/m^3. This is due to the low methane content (57%) compared with the slightly higher methane content of the biogas used for this standard figure.

3.3.2. Construction Cost of the Household Digester

The calculation of the construction cost of the digester proposed in this study was mainly based on the materials and components cost, the construction cost, and the cost of the biogas burner. The total materials cost of the 225 liter digester was found to be USD$120. However, the daily biogas produced by digester with this volume will not be enough for cooking needs of a family of 4-6 members, which means this size needs to be scaled up to a volume that will produce enough gas for household cooking and this is stated to be about 1.5 m^3 of biogas per day. Having more biogas produced requires a bigger digester volume which will lead to more cost. To have household biogas systems adopted widely in rural Sudan it is desirable that the cost is kept low, and so some other options of design and materials should be considered. The largest percentage of the cost is coming from the materials used. One option of reducing materials cost is by using a gas-tight coated fabric bag for gas storage instead of the floating tank system. The same option will be applicable for scaling up to a digester volume that will produce the 1.5 m^3 biogas needed every day by the household for cooking, and the digester volume needed is found to be about 2 m^3. A digester of this volume will cost about USD$300 which considered to be reasonable compared to other available designs available in Sudan. These other possible designs include an in-ground cement digester of Chinese fixed dome design, and a PVC-coated fabric above-ground plug flow design.

4. Conclusion and Recommendations

The lab-scale analysis was done using a batch digester system. Ambient or air temperature is responsible for changes to the raw material temperature inside the small above-ground digester, and this temperature is directly related to the speed of reproduction of the bacterial populations which are performing the different biochemical processes within the overall anaerobic digestion process.

Maintaining the biodigester contents within a relatively narrow temperature range is important, and this is ideally around 35-38 ^{o}C. The production of gas in the lab trials had started quickly for cow dung (dry), chicken manure and food waste because of the ambient temperature (in the summer season) being in this approximate range, unlike in the cow dung (wet) experiment which was done at a much lower temperature.

It is critical for a continuous-feed anaerobic digestion system that the feedstock be consistent and with only very minor changes in composition over time (the moisture or dry matter content changes are not so critical). Of greatest importance is the total exclusion of oxygen from the interior of the digester once the digester is initially filled and producing biogas. The reason that the batch digesters in the lab experiments were not filled totally with the feedstock at the start was to allow a small space above the fermenting mix for biogas to build up, and so to present any digestate being carried out along the biogas tube. While initially this space would contain a few liters of air mixture including oxygen this would not measurably affect the overall result.

The digester design proposed in this study would be scaled up to a volume of 2 m^3. This volume would be suitable for households, as a volume of 2 m^3 could produce up to 1.5 m^3 of biogas (assuming a consistent mixed feedstock of cow manure and some vegetable scraps) and so fulfilling the household needs for cooking, and greatly reducing or eliminating the need to source wood or purchase charcoal.

On the basis of information gained in completing this study, some suggested further experiments could be done using or mixing different types of feedstock. This research was limited to working on a digester design suitable for use in a household. Other research and experiments could be done on the designs and scope for anaerobic digestion at a larger scale (i.e., at slaughterhouses, industrial-scale food processing...etc.). The gas holder can be in the alternate form of a durable gas-tight hemispherical bag as widely used elsewhere in the world. It will be cheaper and the total storage volume will be known.

Acknowledgment

The Authors would like to acknowledge the Deanship of Scientific Research at Sudan University of science and technology for funding this study.

References

[1] Rajendran, K., Aslandzadeh, S. and Taherzadeh, M. J., 2012, "Household biogas digesters – A Review", *Energies*, 5(8), 2911-2942.

[2] Hou, J., Zhang, W., Wang, P., Dou, Z., Gao, L. and Styles, D., 2017, "Greenhouse gas mitigation of rural household biogas systems in China: A life cycle assessment", *Energies*, 10(239), 1-9.

[3] Chen, S., Chen, B. and Song, D., 2012, "Life-cycle energy production and emissions mitigation by comprehensive biogas–digestate utilization", *Bioresource Technology*, 114, 357–364.

[4] Bruun, S., Jensen, L.S., Vu, V.T.K. and Sommer, S., 2014, "Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb ?", *Renewable and Sustainable Energy Reviews*, 33, 736-741.

[5] Cheng, S., Li, Z., Mang, H.P., Huba, E.M., Gao, R. and Wang, X., 2014, "Development and application of prefabricated biogas digesters in developing countries", *Renewable and Sustainable Energy Reviews*, 34, 387-400.

[6] Thu, C.T.T. Cuong, P.H., Hang, L.T., Chao, N.V., Anh, L.X., Trach, N.X. and Sommer, S.G., 2012, "Management practices on biogas and non-biogas pig farms in developing countries – using livestock farms in Vietnam as an example", *Journal of Cleaner Product*, 27, 64–71.

[7] Ho, T.B., Roberts, T.K. and Lucas, S., 2015, "Small-Scale Household Biogas Digesters as a Viable Option for Energy Recovery and Global Warming Mitigation—Vietnam Case Study", *Journal of Agricultural Science and Technology*, 5, 387-395.

[8] Haloua, F., Foulon, E., El-Harti, E., Sarge, S.M., Rauch, J., Neagu, M., Brown, A.S. Tuma, D., 2016, "Comparison of traceable methods for determining the calorific value of non-conventional fuel gases", *International Journal of Thermal Sciences*, 100, 438-447.

[9] Nahar, G., Mote, D. and Dupont,v., 2017, "Hydrogen production from reforming of biogas: Review of technological advances and an Indian perspective", *Renewable and Sustainable Energy Reviews*, 76, 1032-1052.

[10] Abbas, T., Ali, G., Adil, S.A., Bashir, M.K. and Kamran, M.A., 2017, "Economic analysis of biogas adoption technology by rural farmers: The case of Faisalabad district in Pakistan", *Renewable Energy*, 107, 431-439.

[11] Alvarez, R., Villca, S. and Lidén, G., 2006, "Biogas production from llama and cow manure at high altitude", *Biomass and Bioenergy*, 30(1), 66-75.