Sustainable Energy, 2017, Vol. 5, No. 1, 26-31
Available online at http://pubs.sciepub.com/rse/5/1/4

DOI:10.12691/rse-5-1-4

Design and Testing of an Optimized Anaerobic Digestion System

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Abstract This paper presents the design and testing of an optimized anaerobic digestion system by focussing on the thermal, mechanical and chemical aspects of the anaerobic digestion process parameters such as temperature, organic loading rates, air tightness and mixing. Eleven pilot batch biogas digesters were fabricated based on an already existing design and using locally available construction materials. Cow dung and poultry droppings were used as feed materials. The digesters were tested and ran for twelve months. Pressure buildup in the digesters started 24 hours after the initial loading, while combustible gas production was noticed after 72 hours. Tests results showed that the highest biogas yields were produced by poultry ratios 5, 6 and 7. A 7.1℃ monthly average increase in temperature was observed during the period of study. The gas produced was found to be burning cleanly with a blue flame and no smoke. The optimum cow dung/ poultry droppings ratio for better anaerobic digestion performance was obtained and found to fall between 1.4 and 1.6 g VS/L under near thermophilic conditions. Complete digestion of the feed was accomplished within 14 days of hydraulic retention time. Improved biogas generation would greatly influence sustainable development, waste management and economic development in affected communities.

Keywords: *anaerobic digestion, biogas yield, process optimization, temperature, mixing, organic loading rate*

Cite This Article: Oumarou M. Ben, Yakubu B. Ahmad, Abubakar A. Bukar, and Babagana M. Tela, "Design and Testing of an Optimized Anaerobic Digestion System" *Sustainable Energy*, vol. 5, no. 1 (2017): 26-31. doi: 10.12691/rse-5-1-4.

1. Introduction

Anaerobic digestion is greatly influenced by several parameters such as temperature, leakages, mixing, catalyst, organic loading rate, retention time and residence time among others.

On one hand, to improve on the quality and quantity of the biogas produced by anaerobic digestion, one needs to control some of these key parameters, if not all or provide a design of the biogas digester that will incorporate the solutions to some of these parameters. On the other hand, the provision of clean, cheap yet in abundance, fuel remains the major concern of countries around the world.

The optimization and control of the biogas production process and plants is a challenging issue due to the highly unpredictable nature of wastes, particularly in developing countries where treatment options are poor if not inexistent [1]. Thus, biogas production serves the dual purpose of waste management option and renewable source of energy.

Numerous researches have been conducted on the biogas generation process and the effect of process parameters on biogas production in various parts of the world [2-17]; but very few have investigated the impact design might have on process parameters for biogas quality and quantity.

This study presents a research on the ways to enhance biogas yield and quality by focusing on the optimization of the thermal, mechanical and chemical aspects of the anaerobic digestion process; namely temperature; co-digestion by addition of poultry droppings as substrate, air tightness of the digester and promotion of mixing.

2. Design of the Optimised Anaerobic Digester System

2.1. Design of the Digester

The digester characteristics are given by equations (1, 2 and 3) [8].

$$V_d = \frac{\pi d^2 L}{4} \quad (1)$$

where:
V_d- volume of the digester
d- diameter of the digester
L- length of the digester

Volume occupied by the slurry

$$V_{os} = \frac{3.25 V_d}{4} \quad (2)$$

where:
V_{os} –volume occupied by slurry
V_d- volume of the digester

2.2. Determination of the Volume Occupied by the Gas

$$V_{og} = \frac{0.75V_d}{4} \quad (3)$$

V_{og} – volume occupied by the gas.

2.3. Determination of the Shaft Diameter to Support to Biogas Digester

As the shaft is being subjected to a bending moment only, the maximum stress (tensile or compressive) will be given by the bending moment equation [18].

$$\frac{M}{I} = \frac{\sigma_b}{y} \quad (4)$$

where:
M - bending moment
I - moment of inertia of cross-sectional area of the shaft about the axis of rotation
σ_b- bending stress
y – distance from neutral axis to the outermost fibre;

We also know that for a solid shaft, the moment of inertia,

$$I = \frac{\pi d^4}{64} \quad (5)$$

$$y = \frac{d}{2} \quad (6)$$

Substituting these equations (5) and (6) in equation (4) above yields:

$$\frac{M}{\frac{\pi d^4}{64}} = \frac{\sigma_b}{\frac{d}{2}}$$

thus

$$M = \frac{\pi \sigma_b d^3}{32} \quad (7)$$

From the equations above, the diameter of the solid shaft (d_s) could be obtained.

2.4. Determination of the Bending Stress

$$\sigma_b = \frac{\sigma_{ut}}{FS} \quad (8)$$

σ_b – bending moment
σ_{ut} – ultimate tensile stress
FS - factor of safety.

2.5. Determination of the Maximum Load or Ultimate Tensile Stress

$$\sigma_{ut} = \frac{W_u}{A} \quad (9)$$

σ_{ut} - ultimate tensile stress
W_u – ultimate load
A- final area of solid shaft

2.6. Determination of the Solid Shaft Diameter

$$A = \frac{\pi d^2}{4} \quad (10)$$

A - area of solid shaft
d - diameter of solid shaft.

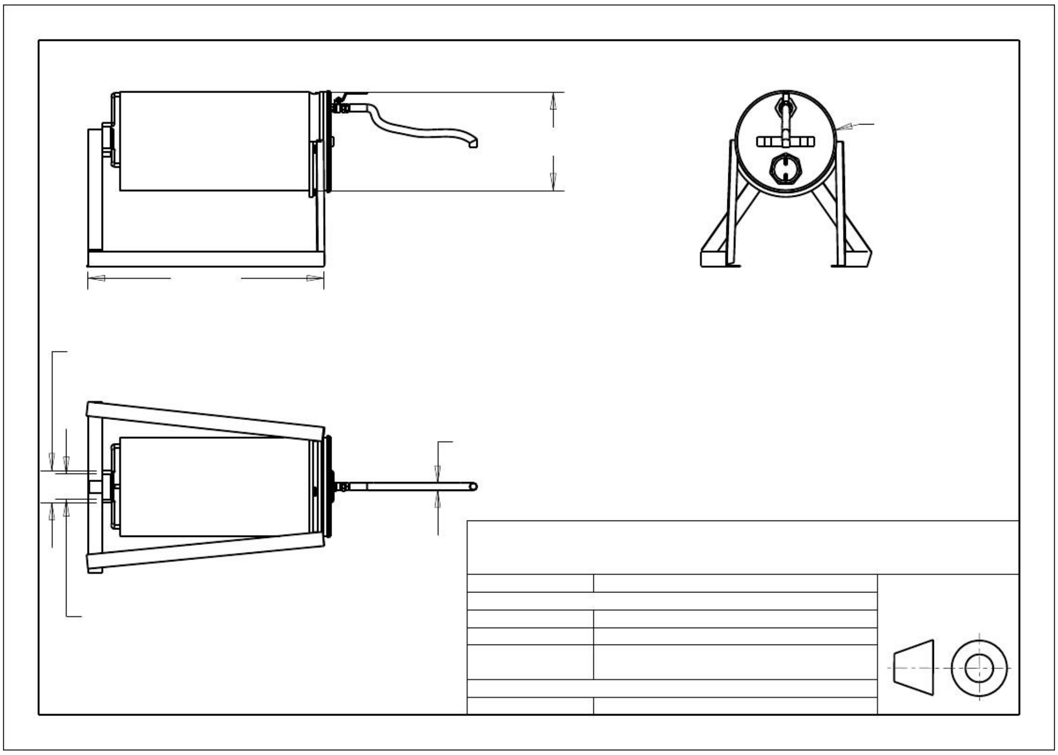

Figure 1. Orthographic views of the designed biogas digester on its mountings

3. Materials and Methods

Materials include eleven (11) batch-type biogas digesters made of a 32 litres capacity cylindrical drum each, using design details from Oumarou & Dauda [8] as shown in Figure 1. The drum is mounted on an angle iron frame. Each digester is held at the back by a ball bearing, whose supporting shaft rolls inside a pipe welded to the frame using a “T” shaped link. At the front, each digester is supported by three small size rollers positioned in a semi circular flange. The ball bearing and rollers support the whole weight (digester and load of mixture) and also provide the digester with balance and ease of rotation in order to break the scum formed inside the digester. The “T” shaped link provides a 90° swing to the horizontal, allowing the digester to be kept in the vertical position while loading.

The biogas digesters were loaded with 26.5 litres of slurry each (which represented 3/4 of the volume of the drum) and operated manually. Gas production, monitoring, pressure gauging were carried out daily to avoid bursting. A wooden shade covered with polythene plastic was designed and built to house the digesters. The polythene plastic material covering the greenhouse house like structure stops 20 cm before the ground level. The 20 cm void serves as a hot air escape route and also to prevent explosion which may occur as a result of an accumulation of leaked gases from the digesters. Flammability tests were conducted by lighting a stick of match.

A calibrated gauge using the liquid displacement method was used to quantify the amount of biogas produced before collection and storage in tyre tubes; other equipment include: a digital scale, a pressure gauge, (2) digital thermocouples, 4 mercury -in-glass thermometers, flexible hoses, thread tape, fresh cow dung, household poultry droppings, water. Cow dung- poultry droppings /water mixing ratios in the various digesters were 2:1.50 ratio by weight with step-wise addition of ground household poultry droppings as shown in Table 1. Loading were carried out monthly.

4. Results and Discussion

After three days of loading the digesters, the shape of the digesters started changing (bulging). To prevent the digesters from exploding and consequently leakage, air was released off from the gas chamber through the outlet valve. By releasing the air, the initial biogas quality may not be altered or affected by air or other gases that might have been formed within the digesters. The digesters were therefore observed and tested for leakages using cotton and foamy water sprayed over the digesters on daily basis.

The provision of the greenhouse “like “ wooden shade covered with polythene plastic material has a noticeable influence on the ambient temperature as well as the digesters body temperatures. Figure 2 shows a clear lift from the outside temperature to the digester body temperature, stressing more the impact of the structure. This eliminates the need for any other type of induced heating. Furthermore, from a least of 35.3℃ in the mesophilic range, the temperature increases to an average of 47.44℃, just approaching the thermophilic range without additional cost.

Table 1. Labelling and mixing ratio for the various biogas digesters

Digester reference	Poultry droppings Ratio (PR) (g VS/L)
Control	0
D 1	0.53
D 2	0.80
D 3	0.90
D 4 PR 1	1.00
D 5 PR 2	1.1
D 6PR 3	1.18
D 7 PR 4	1.28
D 8 PR 5	1.40
D 9 PR 6	1.50
D 10 PR 7	1.60

Plate 1. Arrangement of the biogas digesters in the greenhouse-like structure

Table 2. Average monthly temperatures in and outside the Greenhouse "like" structure

Period of test	Digester Body Temperature (DBT)	Outside Temperature (OT)	Temperature difference
November 2011	50.7	44.9	5.8
December 2011	40.6	35.5	5.1
January 2012	40.7	36.3	4.4
February 2012	41.3	35.3	6.0
March 2012	47.4	37.7	9.7
April 2012	44.4	35.6	8.8
May 2012	45.6	37.2	8.4
June 2012	49.9	43.3	6.6
July 2012	47.1	40.1	7.0
August 2012	50.3	44.9	5.4
September 2012	48.9	42.4	6.5
October 2012	53.9	45.5	8.4
November 2012	56	46.9	9.1

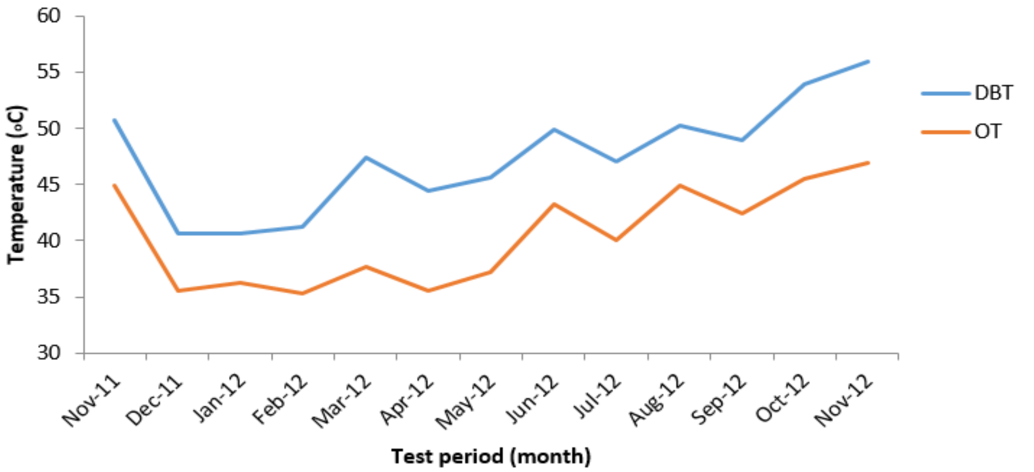

Figure 2. Period of test Vs OperatingTemperatures

Table 3. Gas production by digester with respect to hydraulic retention time (HRT)

Digesters	Hydraulic Retention Time (days)	Gas produced (Litres)
Control	23	23.9
D 1	21	18.3
D 2	24	24.5
D 3	25	25.7
D 4 PR 1	24	24.5
D 5 PR 2	Not included	Not included
D 6PR 3	Not included	Not included
D 7 PR 4	Not included	Not included
D 8 PR 5	19	27.85
D 9 PR 6	19	27.5
D 10 PR 7	14	28.1

Table 4. Gas production pattern and average hydraulic retention time of all digesters

Days	Control	D1	D2	D3	D4 PR1	D5 PR 2	D6 PR3	D7 PR 4	D8 PR 5	D9 PR 6	D10 PR 7	Remarks
1												Overall pressure increase/ Released gas, non-combustible
3												Combustible gas with air pocket
4												Fully combustible gas
5												
6												Combustible gas
7												Combustible gas
8												Combustible gas
9												Combustible gas
11												
17												Combustible gas
25												
32												

gas non combustible
combustible gas

Table 3 shows that the production of biogas in digesters 8, 9 and 10 has increased noticeably to 27.85, 27.5 and 28.1 litres respectively when the poultry dropping ratio (PR) varies between 1.40 g VS/L and 1.60 g VS/L. Also, the HRT is reduced to 14 days, that is a week faster than the digesters 1, 2, 3 and 4 with 21, 24, 25 and 24 days HRT respectively.

These results show that the use of co-substrates in anaerobic biogas digestion, coupled with a good temperature, have indeed an impact on the process efficiency and biogas production rate.

Table 4 gives more information on the impact of the gases produced and the status of the digesters during the period of study. The poultry droppings in digesters D1, D2, D3 and D4 PR 1 show very little impact on the rate of biogas production as these started producing between the 14th and 20th day while the control digester started full production around the 21st day after loading. The time by which digesters D8 PR 5, D9 PR 6 and D10 PR 7 were drastically decreasing or stopping production corresponds to the time when the first digesters start producing. It shows that at some points (i.e. less than 1g VS/L), the poultry droppings are almost inexistent because their impact could not be felt.

Digesters D8PR5, D9PR6 and D10PR7 show the highest rate of biogas production. But the overall highest volume of biogas was recorded with digester D10 with PR 7. The production could be attributed to the fact that poultry droppings have a higher biogas yield. Thus, this is a clear indication that the optimum poultry ratio in cow dung varies between 1.4 gVS/L and 1.6 gVS/L of organic loading material, under near thermophilic conditions. It is well known that these thermophilic conditions may not be always achievable without external source of heat in certain regions of the world, due to climatic conditions. To ascertain these findings, the study needs to be carried further under naturally achieved mesophilic conditions in order to achieve to double goals of low cost/ affordability and sustainable waste management. The step-wise increase in substrate addition to the cow dung has allowed for the determination of the optimum mixing and or loading ratio of cow dung / poultry droppings. These results vary slightly from those previously achieved by He *et al*. [7] who suggested a 1.5 gVS/L.d poultry dropping ratio.

Poultry droppings are not found in large quantities when one uses household poultry. There is need to conduct more research using droppings from the industrial chicken found in huge number in poultry farms or a combination of both.

This discrepancy could be caused by the fact that household poultry feed on almost everything available within the yard (i.e.: insects, grains at times feeding on daily picks from the house yard.) while industrial poultry are subjected to a controlled and consistent feeding, full of vitamins and other chemically enhanced nutrients. This brings in a change in quantity and quality of the poultry droppings, making it more heterogeneous therefore influencing directly the biogas production. Foam formation was also observed in digesters 5, 6 and 7 which later started leaking and thus failed as a result of gas discharge orifice blockage and increased pressure within the biogas digester, during the first loading. These leakages and subsequent failure could be as a result of the nutrient deficiency or the unsuitability of the substrate even though substrate of the same nature was added in the other remaining digesters. The temperature rise in the digesters could also be responsible but the most probable reason for the presence of the foam could be attributed to the non-thorough washing of the drums prior to first use because the drums originally contained perfume. Also, the pressure rise on the first day of the experiments could be as a result of intense heat and accelerated fermentation because the cow dung was kept in plastics bags for two days prior to loading. This was not intentional because it has to an extent influenced the results. The results of the initially failed digesters could not be included in the study because it may induce some interpretation errors. Moeller et al. [19] however, found a clear relationship between high nitrogen concentrations in the fermentation sludge and excessive foam formation. Apart from poultry excrements, other farm manures also contain higher amount of nitrogen in the form of ammonium, proteins and urea than what microbes can convert for their cell growth.

Mixing has been enhanced without a paddle mixer or any other device or system being in direct contact with the feed inside the digester and the temperature kept within a suitable range without sever fluctuations. To remedy to the gas discharge orifice blockage, the digesters were only turned to an angle below the orifice during mixing. Swinging was carried out by allowing the digesters to roll on the semi- circled positioned rollers on the iron frame and the digesters were raised to their vertical position often to break up the scum. The lack of mixing in the digester is known to lead to dead zones and therefore lower production of biogas. The study has also shown that this design can greatly reduce unmixed zones shown here by the long time taken by the feed producing gas. The retention time has also been affected by the improved mixing while leakages have been reduced to a minimum.

The study has shown that the design of the digesters house has the potential, of increasing the temperature inside the house by at least 4.4^{o}C, thereby influencing the biogas production. The HRT was also reduced to 14 days for digester D 10 PR 7 and an average of 21 days for the remaining digesters during the course of the study. This has to do, mostly with the combination of process parameters which were near the optimum ones: high stable temperature, promoted constant mixing, air tightness and addition of substrate.

No corrosion or any other major failure were observed on the digesters as a results of loading and off-loading during the year except on the Polythene plastic covered structure which was torn partially due to blowing wind and intense heat.

Even though biogas production technology has established itself as a technology with great potential which could exercise major influence on the energy market in rural areas, it has not made any real impact on the world energy. Serious limitations are on the availability of feedstock, poor design and microbiological failures. This research could contribute in bridging some gaps.

5. Conclusion

The study has shown that biogas yield and quality can be improved by simple designs to increase temperature, improve mixing, air tightness and addition of a substrate.

This optimized design meets the need for a sustainable waste management strategy as well as the need for improved environmental quality, showing that biogas as a renewable energy can contribute immensely towards achieving energy security across the world.

The optimum substrate ratio was found to fall between 1.4 and 1.6 g VS/L under near thermophilic conditions.

The hydraulic retention time was reduced to about 14 days.

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