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Design and Construction of a Cost Effective Small Scale Anaerobic Digester for a Nigerian Home

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Abstract: *A simple kit in the form of a truncated regular rectangular pyramid made to float on the septic tank that collects all the effluent biogas and temporarily store it in its hallow space has been designed. An average Nigerian family (two parents with four children) has been found to produce an average of 1.333kg of TS (total solid) per day. At this feeding rate, the conversion kit collects biogas at an average of 0.1076m^3/day, containing 60% Methane. Using this biogas for cooking, one may get a useful energy of about 2.5695 MJ/day which translates into 0.7137 kWh/Day that is about 260.5 kWh/year. At this rate, a small scale anaerobic digester installed in an average Nigerian home saves 46% of household energy needs.*

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I. Introduction

Burning fossil fuels to generate electricity at commercial scale is generally considered the most economical at present. Unfortunately, fossil fuel is a depleting resource and its cost increases as its availability decreases. Sometimes, they become more difficult to mine as reserves are diluted. While they still account for most of the electricity and heat produced in Nigeria, there are major problem areas that include the security of its supply and environmental factors hence the need for better alternatives.

Biogas being a cleaner and renewable form of energy could very well be a good substitute for fossil fuels whose consumption at the moment is associated with health and ecological/environmental problems and at the same time depleting at a faster rate. Several researches have been carried out on the use of biogas for cooking and possibly generating electricity worldwide, but there are still areas of improvements especially in Nigeria where not much effort have been made to popularize its use and simplification particularly on septic tanks as sources. The septic tank is a common waste structure in most Nigerian homes and its use would almost be without much additional cost. In facts, an Up-flow Septic Tank/Baffled Reactor (USBR) being a new concept for a low cost modified septic tank was constructed and tested in a small village in Egypt [1]. Others [2] have used full-scale septic tank/anaerobic filter unit with the tank's retention time varying from 22.5 to 90 h and some [3] used two-step anaerobic system to treat sewage. They tested the performance of the two up flow-hybrid septic tanks but noticed that they required high power input or high excavation depth due to the two treatment steps that existed in vertical order.

However, these had failed to offer design simplicity and ease of operation and maintenance to the poor and unskilled populace. Besides, they are not cost effective durable. In this work efforts have been made to improve on the existing shortfalls by designing a very simple but innovative floating gas collector kit that can be installed into the household septic tanks without any modification on the sewage facility.

II. Materials And Method

2.1 Truncated rectangular pyramid design

Basically, the conversion kit is a truncated rectangular base pyramid obtained by intersecting a regular rectangular pyramid with a rectangular plane parallel to the base of the pyramid (Figure1). The other four faces of the truncated pyramid, formed isosceles trapezoids; occurring in two pairs with each pair containing two congruent isosceles trapezoids facing each other. Assuming that standard septic tank section for a three-bedroom apartment have a minimum volume of 3800 liters and a black water surface area of 2.55 m^2 usually designed as a 3 m by 1.7 m and 1.6 m deep along side with the soak away section which is also having a surface area of 2.55m^2(Figure2). The floating gas collector (a rectangular truncated pyramid) is then designed to fit the 2.55 m^2 liquid surface on the tank section of the system. For convenience, the height of the truncated pyramid was chosen to be about 20% of the entire depth of the septic tank (Figure 3). Consider the top views of the truncated pyramid (Figure 1), it could be seen that the straight-line segment O_1 O_2 are perpendicular (or orthogonal) to the two parallel bases such that P_1P_3 =b, Q_1Q_3 = d, P_1P_2=a, Q_1Q_2= c.

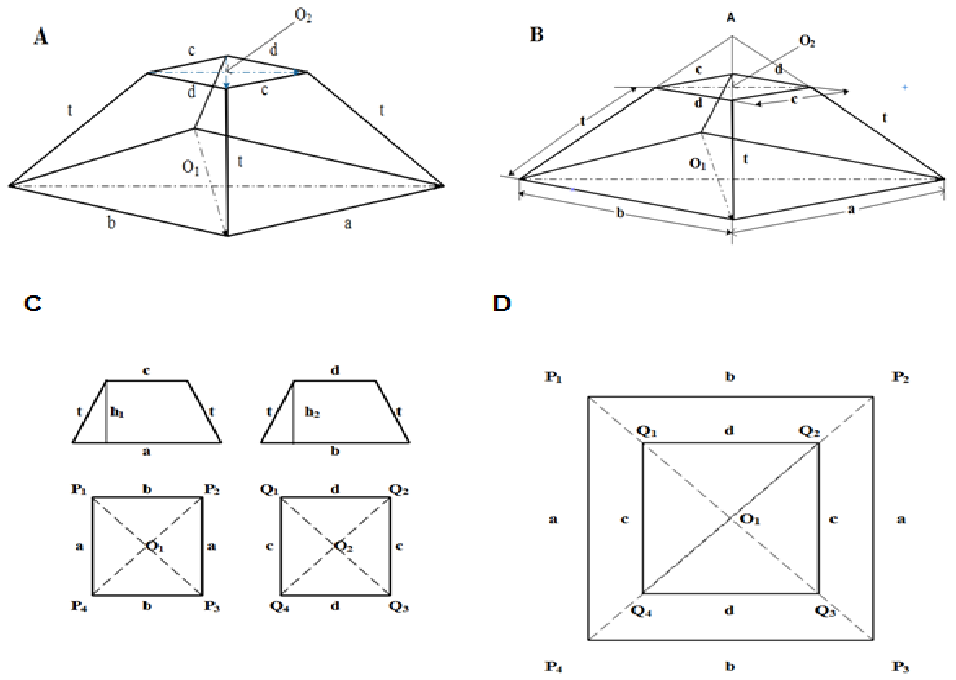

Figure 1(A, B, C & D): Truncated rectangular pyramid and sectional views

From similar triangles $O_1Q_1Q_3$ and $O_1P_1P_3$ on the faces of the truncated pyramid it is obvious that:

$$\frac{\left|\overline{O_1Q_2}\right|}{\left|\overline{O_1P_1}\right|} = \frac{\left|\overline{Q_1Q_3}\right|}{\left|\overline{P_1P_3}\right|} = \frac{d}{b} \tag{1}$$

And from the other faces $O_1Q_1Q_2$ and $O_1P_1P_2$:

$$\frac{\left|\overline{O_1Q_2}\right|}{\left|\overline{O_1P_1}\right|} = \frac{\left|\overline{Q_1Q_2}\right|}{\left|\overline{P_1P_2}\right|} = \frac{c}{a} \tag{2}$$

Therefore,

$$\frac{d}{b} = \frac{c}{a} \quad or \quad \frac{a}{b} = \frac{c}{d} \tag{3}$$

If the height of the top pyramid represented by AO_2 is $H_1$and that of the larger pyramid, AP_1 is H_2, therefore the height of the truncated pyramid$h$would be:

$$H = H_1 - H_2 \tag{4}$$

Also, if let V be the volume of the truncated pyramid, $V_1$the volume of the larger pyramid; and the $V_2$the volume of the top or smaller pyramid. Then, the volume of the truncated pyramid is:

$$V = V_1 - V_2 = \tfrac{1}{3}H_1ab - \tfrac{1}{3}H_2cd \tag{5}$$

Consider the similar triangles P_2O_2A and P_1O_1A using equation (3) we have:

$$\frac{H_1}{H_2} = \frac{\overline{P_1O_1}}{\overline{P_2O_2}} = \frac{\sqrt{a^2+b^2}}{\sqrt{c^2+d^2}} = \frac{b\sqrt{\left(\frac{a}{b}\right)^2+1}}{d\sqrt{\left(\frac{c}{d}\right)^2+1}} = \frac{b}{d} = \frac{a}{c} \tag{6}$$

From equations (4) and (6) we can write:

$$H_2 = \frac{cH}{a-c} \text{ and } H_1 = \frac{aH}{a-c} \tag{7}$$

Hence equation (5) now becomes:

$$V = \frac{1}{3}H\left(\frac{ba^2 - dc^2}{a-c}\right) \tag{8}$$

Eqn. (8) can be used to compute the volume of the truncated pyramid.

Lastly, the total surface area of the truncated pyramid is given by:

$$A = 2(\text{area of } P_1Q_1P_2Q_2) + 2(\text{area of } P_2Q_2P_4Q_4) + cd$$
$$= (a+c)h_1 + (b+d)h_2 + cd \quad (10)$$

The heights of each face (Figure 1C) is given by:

$$h_1 = \sqrt{t^2 - \left(\frac{a-c}{2}\right)^2} \quad (11)$$

and

$$h_2 = \sqrt{t^2 - \left(\frac{b-d}{2}\right)^2} \quad (12)$$

Using equations (11) and (12) in (10) gives

$$A = (a+c)\sqrt{t^2 - \left(\frac{a-c}{2}\right)^2} + (b+d)\sqrt{t^2 - \left(\frac{b-d}{2}\right)^2} + cd \quad (13)$$

But from Figure 1C t can be written as:

$$t = \sqrt{H^2 + \left(\frac{b-d}{2}\right)^2 + \left(\frac{a-c}{2}\right)^2} \quad (14)$$

Hence equation (13) becomes:

$$A = (a+c)\sqrt{H^2 - \left(\frac{b-d}{2}\right)^2} + (b+d)\sqrt{H^2 - \left(\frac{a-c}{2}\right)^2} + cd \quad (15)$$

Equation (15) gives the total surface area of material required for the truncated pyramid collector. Figure 3 gives the views of the truncated rectangular gas collector on septic the tank.

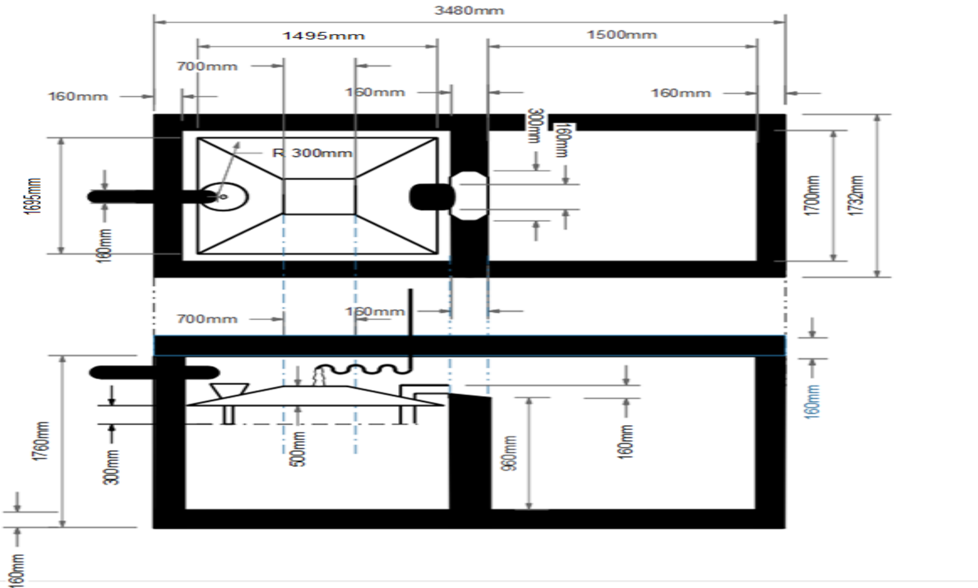

Figure 2: Top and side view dimensions of the septic tank and soak away section

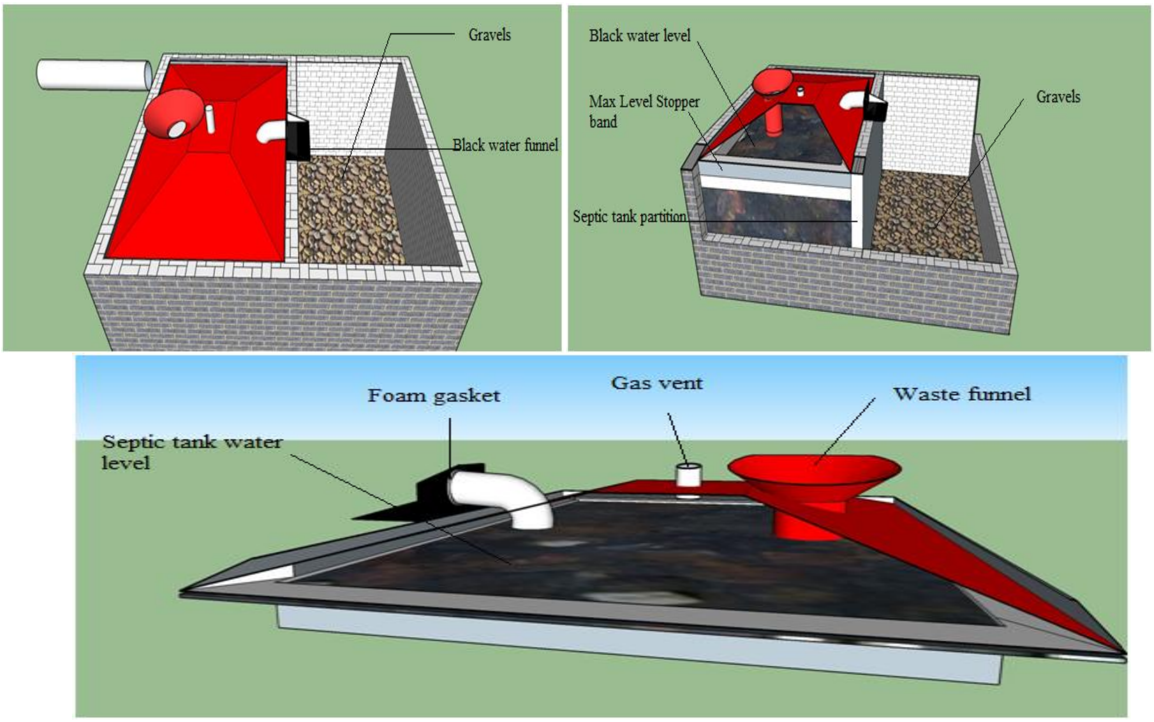

Figure 3: Truncated rectangular gas collector views on septic tank sections for a three bedroom apartment

2.2 Simplified working principle

When regular toilet waste flows through the drain pipe from the inspection chamber on to the funnel and channel into the sedimentation section of the sewage system. The funnel is such that the end of it past the edge of the gas collector and dipping into the black water (Figure 3). This is to ensure regular collection of biomass and at the same time maintaining a gas tight seal with the black water. The truncated rectangular gas collected is designed to float on the black water by some tightly fixed floating objects (Styrofoam) all around its edges and some glued through its underneath to the funnel so as to balance the thrust coming with the input waste onto its collection end. Anaerobic methanogenesis takes place in the presence of methanogenetic bacteria leading to break down of biomass and subsequent release of methane and carbon dioxide as bye products. These gases bubble out to the surface of the black water and are temporarily collected by the truncated pyramid before being vented on to the gas holder for storage. Excess water in the case of overflow is exited through the pipe attached to the gas collector into the soak-away section and drained away by gravity.

2.3 Septic tank/soak away experimental model

In order to determine the gas yield of the septic tank/soak away system an experimental model was constructed using Styrofoam (Figure 4). A family of six; 2 parents and 4 children were used in this study as a source of excreta. The father and mother are aged 45 and 38 respectively while the 4 children are aged 18, 16, 14 and 11 years.

Figure 4: An experimental septic tank digester model

2.4 Data collection and analysis

A day's yield of waste from the family was collected and digested in the digester model for over 10 days with the addition of 5 liters of water. The effluent gases were collected using an upward displacement method after which the daily gas yield, digester temperature, pH and retention times were measured and recorded (Table 1). If the production rate of Total Solid waste by a household is TS kg/day and since Dry Solid (DS) is 24.8% of Total Solid (TS) then the daily DS [4]:

$$DS = 0.248 \times TS \text{ kg/day} \quad (16)$$

Volatile Solid (VS) =86.8% of DS [4].Therefore:

$$VS = 0.868 \times DS \text{ kg/day} \quad (17)$$

Furthermore at 45% reduction rate, Volatile Solid Destroyed (VSD)[4] would be:

$$VSD = 0.45 \times VS \text{ kg/day} \quad (18)$$

Assuming all the VSD are converted into biogas. Since biogas has a density of 1.2174kg/m^3, then the biogas productionU_d per day is:

$$U_d = \frac{VSD}{1.2174} \text{m}^3/\text{day} \quad (19)$$

Hence the Specific Output Gwhich is the biogas production per unit solid waste for the reactor is:

$$\text{Specific output}, G = \frac{U_d}{TS} \quad (20)$$

The energy consumption per household in Nigeria is 570 kWh/year (1.56 kWh/day) [5] and 60% Methane-Biogas contains about 23.88MJ/m^3[6]. Therefore the useful energy produced E_u is:

$$E_u = U_d \times 23.88 \quad \text{MJ/day} \quad (21)$$

Going by the estimates given [6], biogas energy produced from human waste per day per household may meet$x$% of household energy needs.

$$x = \frac{E_u}{1.56} \times 100\% \quad (22)$$

III. Results And Discussion

3.1Experimental results and discussion

Table 1 presents the average daily quantity of wet stool sample collected from a family of six. This family was found to produce a daily average of about 1.333 kg of TS which is equivalent to about 0.331 kg of DS sample.

Table 1: Quantity of Wet Stool Produced by an Average Nigerian Family of Six

Day	Wet sample (kg)	Dry sample (kg)	% Dry matter
1	1.362	0.341	25.0
2	1.265	0.315	24.9
3	1.390	0.352	25.3
4	1.300	0.320	24.6
5	1.280	0.300	23.4
6	1.417	0.356	25.1
7	1.320	0.330	25.0
Average	1.333	0.331	24.8

This family has been found to produce an average of 1.333kg of TS (total solid) per day. At this feeding rate and using equations (16-19) the digester can theoretically generate biogas at an average of0.106 m^3/day. The biogas produced was found to contain 60% Methane. Experimentally, two separate samples, 0.220kg TS sample placed in experimental septic tank and 0.100 kg DS (= 0.4032kg TS) sample placed in reactor bottles were allowed to digest over a retention period of 10 day and daily readings of their daily biogas yield, reactor temperature and pH values are presented in Tables 2 and 3 respectively.

Table 2: Experimental septic tank reactor performance for 0.220kg TS sample digestion

Retention Time (day)	Daily yield ($\times 10^{-4}$ m^3)	Cumulative yield ($\times 10^{-4}$ m^3)	Temperature (°C)	pH
1	0	0	38	6.0
2	7	7	39	6.1
3	8	15	39	6.0
4	36	51	40	6.2
5	35	86	43	6.1
6	42	128	43	6.3
7	21	149	40	6.3
8	14	163	38	6.6
9	7	170	37	7.0
10	4	174	38	7.0

Table 3: Average value performance of reactor bottles for 0.100 g DS sample digestion

Retention Time (day)	Daily yield ($\times 10^{-3}$ m^3)	Cumulative yield ($\times 10^{-3}$m^3)	Temperature (ºC)	pH
1	0.5	0.5	37.8	6.15
2	1.5	2.0	38.8	6.10
3	2.5	4.5	39.0	6.10
4	4.5	9.0	40.3	6.25
5	6.5	15.5	42.5	6.10
6	7.3	22.8	42.8	6.33
7	5.3	28.1	40.0	6.30
8	2.8	30.9	38.0	6.65
9	1.5	32.4	37.3	7.06
10	0.8	33.2	37.3	7.06

It could be seen from Table 2 that about 0.0174 m^3 of biogas was cumulatively collected over the 10 day retention period for the 0.220 kg of TS digested. This implies that for a family of six with 1.333 kg of TS, 0.1054 m^3 of biogas can be produced daily. In Table 3, the digestion of the 100 g of DS (0.4032kg of TS) has cumulatively produced 0.033 m^3 of biogas. Therefore the digestion of 1.333 g TS would produce an equivalent of 0.1098 m^3. These quantities of biogas produced from experiment are in much agreement with the theoretical quantity of 0.106 m^3. Using the average of the twoU_d = 0.1076 m^3 of biogas for cooking, one gets a useful energy $E_u$of about 2.5695 MJ. Since 1 kWh is equal to 3.6 MJ, it implies that in kWh E_u is equivalent to 0.7137 kWh/day translating (using equation 22) to about 46% savings on energy consumption per household in Nigeria. This energy can be used for cooking or other purposes.

3.2 Cost Analysis

The cost of converting a septic tank system is a function of its dimensions (Figure 1). For a septic tank of rectangular surface of 1.5 by 1.7 m, the floating kit dimensions required would be a ≅ 1.495 m, b ≅ 1.695 m, c = 0.7 m, d = 0.8 m and h =0.6 m translating to about 3.99 m^{2}area of Aluminum sheet for its construction. The a and b dimensions are approximated so as to allow for free floating of the kit within the septic tank. Table 4 gives the detailed list of materials and quantity required alongside their prices.

Table 4: Cost Analysis

Material	Unit cost	Quantity	Cost
Aluminum Sheet (A)	₦ 3,600	3.99 m^2	₦14,364
Funnel	₦ 500	1	₦ 500
4” PVC Pipe	₦ 2,000	1	₦ 2,000
0.5" PVC Pipe	₦ 600	1	₦ 600
3 mm Flat bar	₦ 1,800	1	₦ 1,800
Labour	₦ 3,000	1	₦ 3,000
		Grand Total	₦20,464

To construct a floating kit on a septic tank of 1.5 m by 1.7 m as described and whose surface area is 2.55 m^2, one may need about **₦20,464** which is not too expensive for a system that may continue to produce biogas at least for a long.

IV. Conclusion

Biogas as a renewable source of energy can be harnessed from human waste. This has been done by converting a household septic tank using a simple conversion kit to trap the effluent biogas and be put to economic use. About 46% of our daily household energy needs can be met with existing septic tank for a family of six. However, more family members mean more energy for use. It is not expensive to build and may not require maintenance or running cost as it is fitted perfectly into our daily routine activities yet yielding a great economic benefits.

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