Re-engineering Domestic Septic Tanks into Biogas Tanks

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Technical Note

Re-engineering Domestic Septic Tanks into Biogas Tanks

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Abstract
This study is to design a novel septic tank, named Anaerobic Upflow Domestic Septic Tank (AUDST) to recover biogas as energy and treat domestic sewage. The green technology proposes alternate options to existing Domestic Septic Tanks (DST), encourages anaerobically pre-treatment to reduce bacteria, pollutants, Total Suspended Solids (TSS), Chemical oxygen demand (COD) and Biological oxygen demand (BOD) before the effluent is discharged or is removed by cesspit trucks. Studies have shown that DST in homes partially treat or just store sewage. Again, these DST have to be emptied from time to time because it lack features that will sustain anaerobic activity and usually the sludge is disposed of directly into the sea, water bodies and even into open places such as "Lavender Hills" without any treatment or disinfection. These practices cause severe public health and environmental problems. To tackle the challenge at household level, DST are redesigned to treat domestic sewage with less management, low operating cost, low secondary discharge of pollutants. The proposed new design concept is operated through three (3) units: such as desilting, anaerobic digestion and facultative filtration units. The anaerobic digestion stage is made up of baffle and anaerobic filter for accommodating sludge and providing a more intimate contact between anaerobic biomass and sewage which improves treatment performance. The anaerobic unit is fitted with locally woven baskets prefilled with packing materials. The aim is to strengthen the biological treatment process at this stage. The Facultative Filtration unit of the model is also packed with filtering media such as gravels (3-6mm in diameter) that is low in cost, and has a high durability to produce effluent with lower pollutants and suspended solids content to meet Ghana's Environmental Protection Agency (EPA) standards for the discharge of domestic effluents.

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1. INTRODUCTION

There have been several concerns from experts in the field of biogas especially in Ghana and to a great extent throughout the world about the possibility of redesigning domestic septic tanks (DST) into biogas producing system. Septic tank with anaerobic and aerobic processes that will encourage pre-treatment of sewage at household level and provide an alternate options to existing DST is inevitably going to be introduced because of high level pollution of the environment with untreated human waste in recent times. Also, studies have shown that Domestic septic tanks (DST) in homes produce effluent that is rich in organic matter and bacteria. Sludge from 75 septage samples from Accra residents in Ghana were characterised by an average Helminthes (parasitic) eggs of 4,000 no/l and Chemical oxygen demand (COD) concentration of 6,400 mg/l, which indicates that domestic septic tanks only partially treat sewage [7]. The DST in homes lack features that will induce and sustain anaerobic digestion of sewage. As a result, the DST get full quickly and have to be emptied from time to time. Also, a survey by the Ghana Environmental Protection Agency (EPA) in 2001 [5] revealed that less than 25% of the 46 industrial and municipal sewage treatment plants (conventional plants) available in Ghana were functional. Another, inventory conducted in 2006 indicated that only about 10 of the treatment plants are operational [8]. This sharp fall in the number of sewage treatment facilities has led to recent environmental problems and sewage management that we face as country. Consequently, sludge from DST is disposed of directly into the sea and water bodies through some of these overloaded facilities untreated.

The disposal site nicknamed "Lavender Hill" continues to be a major problem to most residents living in and around Korle-Gonno in the Ablekuma South Constituency. Residents are not spared from houseflies that constantly storm their houses. In fact, "Lavender Hill" has become a major source of public concern in recent weeks as cesspit trucks from Accra Metropolis, Ga South Municipality, Kasoa in the Central Region, Madina in the La Nkwatanang Municipality, and even Nsawam travel a long distance to dislodge untreated sewage into the sea [1]. Although the Accra Metropolitan Assembly has indicated it is going to decommission a broken down liquid waste disposal site popularly known as Lavender Garden or Hill, it still continues to receive hundreds of cesspit tankers everyday which discharge their contents directly into the sea near Accra's Light House at James Town (Edmund, 2013) as shown in figure 1 below.

Figure 1. Discharge of untreated sewage at Lavender Hill in Accra trickling into the sea.
Source: Asante, 2013.

Everyday, tonnes of untreated human waste and household sewage are being discharged directly into the sea and water bodies polluting the environment putting human and marine lives at risk. In fact, the reduction in the numbers of treatment plants can be attributed to the fact that the conventional methods are electricity (energy) dependent and also when the mechanical parts become faulty, the part has to be imported making it too expensive to maintain. Previous experience has shown in other countries that decentralization of septic tanks that treat sewage by anaerobic processes at household level requires less management (less sludge disposal), low operating cost and low secondary discharge of pollutants and energy is also recovered in the form of biogas. This project seeks to re-engineer domestic septic tanks into sewage treating and biogas generating tanks. The new proposed model adopts household digesters technology and equips it with a desilting, anaerobic filter and facultative filtration or contact aeration. The re-engineering which considers the EPA Discharge Guidelines of treated domestic sewage, results in comparatively lower pollutants such as SS ($\leqslant$ 50 mg/l), COD and NH3-N. The new design needs no energy to treat sewage but rather biogas can be recovered as energy. Meanwhile for the conventional plants, 0.20-0.26 kWh of electricity is needed to treat 1 m3 of sewage [9]. Domestic septic tanks treating and generating biogas can yield a whole range of benefits for users, the society and the environment in general. The main benefits are:

- Sewage treatment is decentralized at household level.
- Reduction of pathogens, worm eggs and flies for a better hygienic conditions
- Production of energy (heat, light, electricity etc.).
- Protection of natural resources such as forests, soil, water and air.

Another positive advantage that this project presents is the removal of additional cost and barrier faced by households in acquiring a new biogas plant. It is also envisaged that this new design will really jump start a sustainable home retrofitting in the country on a large scale.

DST partially treat or just store sewage and produce effluent rich in organic matter and bacteria as indicated by studies. For this reason, this project looks at continuing septic tank design and performance researches that were carried out in the past to better treat domestic sewage and generate biogas which can supply energy for domestic use. This project is relevant simply because every household is required to install or have a septic tank and will address the challenge faced with limited number sewage treatment plant that is available to the country causing dislodge of sludge from DST into lagoons or full treatment facilities pending decommission. The novel design is suitable at places where there is no centralised wastewater treatment plant and cities that do not have municipal sewage treatment system. Again, the huge one time capital investment required by conventional central treatment plant is decentralized at household level. Finally, the financial challenges faced in obtaining a new biogas system will be eliminated by simple installation of one of these novel design to perform the task of a conventional septic tank and generate biogas in addition.

The main objective of this project is to design a novel septic tank, named Anaerobic Upflow Domestic Septic

Tank (AUDST) to meet sanitation requirements and energy demands of households and institutions. The specific objectives of the paper are as follows:

1. propose alternate model options to existing domestic septic tanks

2. b) design an anaerobic digestion and filtration units for the proposed design

This paper seeks to provide domestic septic tank models that generate biogas and treat sewage. The aspects look into were hydraulic digester design in a historic context, anaerobic treatment process, packing and filtration media, design concepts, engineering design, detail engineering and isometric drawings for illustration purposes. Field construction and other subsequent activities such as wetland design for the treatment of effluent are beyond the scope of the current study.

2. BIOGAS TECHNOLOGY

Ghana began exploring the technology in the late 1960s but it was not until the middle 1980s did biogas technology receive the needed attention from government. Most plants, however, collapsed shortly after construction due to immature technologies and poor technology dissemination strategies. In order to revive the technology, a cooperative agreement between Ghana and China led to the construction of a 10 m3 plant at the Bank of Ghana. The Ministry of Energy demonstrated the Appolonia Household Biogas project which was producing gas for direct cooking in twenty seven (27) homes. The biogas was also used to generate 12.5 kW of electricity for the community supplied through a mini-gird. Others included a 1,000 m3 digester capacity plant utilizing human waste located at Kaase a suburb of Kumasi and that at Nkawkaw Catholic Hospital [4].

China is one of the countries that used biogas early in the world. By the end of the 19th century, agricultural waste covered in pits were found to produce biogas through fermentation process. In 1920, Mr. Luo Guorui built a biogas digester called “Chinese Guorui Natural Gas Store” (CGNGS) in figure 4, which was the first hydraulic digester in China [6] and opened China’s first biogas technical development company in Shantou City in 1929. Guorui’s design is square in shape and can be adopted to form one compartment of domestic septic tank in this project along ABR and AF systems because of their ability to treat wastewater and generate biogas effectively.

Since 1980s, biogas technology has been developed very fast in China rural areas and the designs have change drastically into the fix-dome biogas hydraulic digester. The reason being that curved shell supports more load than a flat slab. Again, curved structural components are more rigid and the stresses are smaller in them.

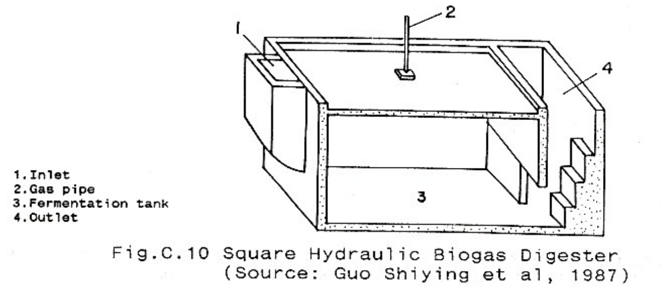

Figure 2. First Hydraulic Digester built in 1920
Source: BIOMA, 2011

Many anaerobic modified septic tank systems conceptualized, constructed and tested in an attempt to addressing the weakness associated with DST in different countries. Some noticeable ones amongst others are the:

Upflow Septic Tank/Baffled Reactor (USBR) The USBR is a new concept for a low-cost modified septic tank. It was constructed and tested in a small village in Egypt. In fact, a one year of continuous operation and monitoring of the USBR system was found to have very satisfactory removal results of COD, BOD and TSS. Again, it was observed that the USBR system was not affected by the imposed shock loads at the peak flow and organic periods but the results showed that the system was influenced by the drop in the temperature [10].

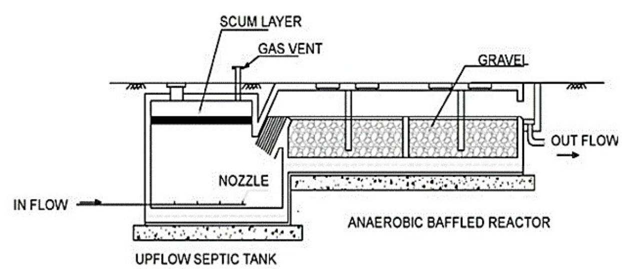

Figure 3. Modified septic tank system.

Panswad and Komolmethee used full-scale septic tank/anaerobic filter unit with the tank’s retention time varying from 22.5 to 90 h. They recommended a rather high retention period of not less than 48 h if the Thai effluent standards are to be met.

Elmitwalli et al. used two-step anaerobic system to treat sewage. They tested the performance of the two upflow-hybrid septic tanks which require high power input or high excavation depth due to that the two treatment steps exist in a vertical order.

Mendoza et al studied in a lab-scale the design and performance of a novel Gradual Concentric Chambers (GCC) reactor, integrating anaerobic and aerobic processes, treating low (165mg COD/L) and medium strength (550mg COD/L) domestic wastewaters. Although the GCC reactor had reasonable performance, its operation is considered rather complicated due to using of anaerobic effluent recycling technique and aeration pump. Based on thorough review of previous researches a new design concepts under this study was developed to serve as alternate options to domestic septic tanks being deployed in Sub-Sahara Africa. In Ghana, septic tank (figure 4 refers) is water tight storage tank in which sewage is retained sufficiently long to permit sedimentation [2] and lacks effective anaerobic treatment.

Figure 4. Typical Three-Compartment Septic tank in Ghana

2.1 Septic Tank Design

The criteria for tank design are dependent on volume for settlement, volume for digestion of sludge and storage Volume.

Settlement Volume (Vs)

$$Vs(litres) = Td \times Q \times n \quad (1)$$

Where, Td = Retention time in days
Q = Flow in litres/cap/day
n = Number of users

Digestion Volume (Vd)

$$Vd(litres) = 0.5 \times Td \times Q \times n \quad (2)$$

Where, Td = Retention time in days,
Q = Flow in litres/cap/day
n = Number of users

Storage Volume (Vst)

$$Vst = 0.25 \times AP \times Q \times n \quad (3)$$

Where, AP = accumulation period in days,
Q = Flow in litres/cap/day
n = Number of users

The effective volume of the septic tank (V)

The sum of settlement volume, volume for digestion of sludge and storage Volume is equivalent to the effective volume of the septic tank.

$$V = Vs + Vd + Vst \quad (4)$$

Organic matters in domestic sewage mainly consist of carbohydrates, protein or lipid. Their corresponding theoretic methane yields are 0.37, 0.49 and 1.04 liter/g respectively. Therefore theoretic methane yield of certain organic matter can be calculated as follows:

$$Qwg = 0.37A + 0.49B + 1.04C \quad (5)$$

Where, Qwg= theoretical methane production from 1 gram of organic matter (l/g);
A= carbohydrates content in 1 gram organic matter of domestic sewage (g/g);
B= protein content in 1 gram organic matter of domestic sewage (g/g);
C= lipid content in 1 gram organic matter of domestic sewage (g/g) (BIOMA, 2011);

Generally the flow rate is calculated based on the water consumption of residents surveyed. Firstly take the daily average water consumption as domestic sewage discharging rate per capita, then it is multiplied by n (the number people to be served by the designed system in the future) and the simultaneity coefficient k1, which is estimated as follows:

$n \leqslant 50 \quad k1 = 1$
$200 > n > 50 \quad k1 = 0.95$
$500 > n \geq 200 \quad k1 = 0.90$

Flow rate of excreta in domestic sewage for water-flush toilet can be estimated as 30 liter/capita/day, if there is no data available. Clearly by this review, it was realised that in recent year septic tanks designs are being improved to enhance removal efficiency of unsettleable and dissolved solids which is a major drawback of the conventional septic tanks. The challenge is taken up by this project for better sewage treatment.

3. DESIGN CONCEPTS

Two types of design possibilities of the Anaerobic Upflow Domestic Septic Tank (AUDST) are considered under this research. The first possibility is to design a rectangular septic tank that decontaminates wastewater through a filtration tank and recovers biogas. This design will be made up of an anaerobic baffled reactors (ABR) and Chinese Guorui Natural Gas Store (CGNGS). The ABR and CGNGS functions were adopted to propose AUDST Design with the aim to introduce facilities that will induce and sustain anaerobic activities as well as baffle flow for effective treatment of wastewater. The CGNGS activities will remove pathogens that might escape, recover biogas and produce effluent that meets EPA discharge standards. The design concepts are in two (2) main steps:

- **Step 1** – *Re-engineering of Hydraulic Digester into AUDST Design*
- **Step 2** – *Add Packing and filtering media to strengthen anaerobic activities as well as decontamination of sewage.*

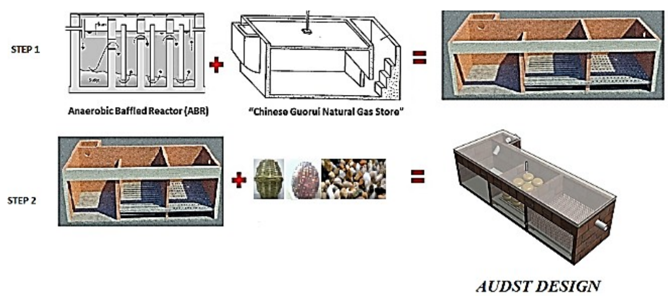

Figure 5. Design Concepts

The anaerobic unit aims at destroying pathogens. Again, the packing material used will be indigenously made baskets (figure 6 refers) intended to strengthen the biological treatment process. The last but not the least, facultative filtration unit of the model is also packed with filtering media such as uncoated and untreated gravels, 3-6mm in diameter (see figure 8), like that found in aquarium with high durability to produce effluent with lower suspended solids content to meet Ghana's Environmental Protection Agency (EPA) standards for the discharge of domestic effluents.

Figure 6. Indigenously woven basket to be used a packing material

Other available packing materials that can be used under this project is shown in figure 7 below

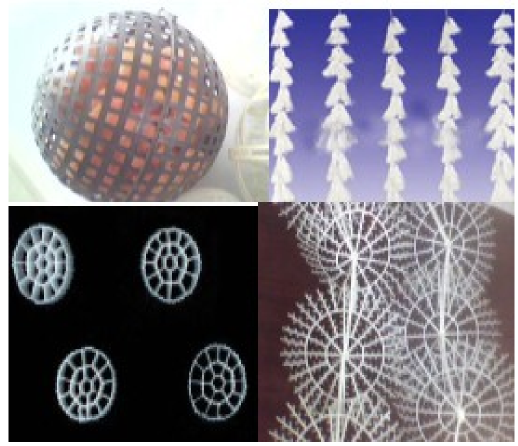

Figure 7. Plastic packing materials for strengthening anaerobic activities

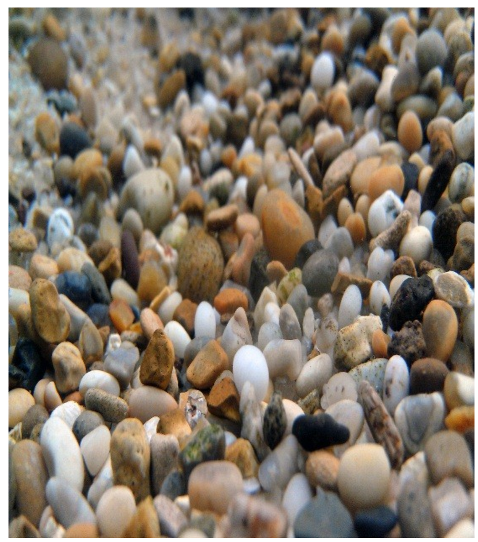

Figure 8. Gravel (3-6mm in diameter) filter materials in the Filter unit

4. PRELIMINARY DESIGN

The flow diagram of proposed designs can be drawn schematically as shown in Figure 9 below. Sewage from flashed toilet with other wastewater is settled in the settlement zone provided by the desilting unit to capture the sludge (blackwater). The liquid sewage (greywater) is then baffled in an upflow mode into the anaerobic unit for an anaerobic digestion and biogas production through a series of packing media made up of locally woven basket. This configuration provides a more intimate contact to improve sewage treatment performance and biogas generation before a downflow baffling into the filtration unit made up of gravel and followed by a subsequent discharge.

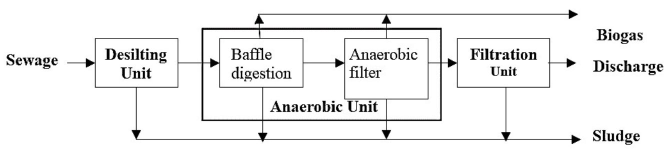

Figure 9. Flow diagram for sewage treatment from the combined discharge system

5. ENGINEERING DESIGN

5.1 AUDST Design

The design is a modified rectangular septic tank that decontaminates wastewater through a filtration tank and recovers biogas.

5.1.1 Design Parameters and Detail Design Calculation

The project considers 3 compartments (as in the case of a conventional septic tank), mainly settlement (desilting) unit for accommodating sewage, anaerobic digestion (baffle digestion and anaerobic filter) unit for accommodating sludge and facultative filtration unit to produce effluent with lower secondary discharge pollutants and suspended solids content.

The criteria for biogas filtration tank design are dependent on the settlement unit volume, the anaerobic filter unit volume and facultative filter unit volume.

Assumptions made include the followings:

1. The proposed biogas tank is design for a family of eight (8) people made up of father, mother and 6 children, then the number of users, n, is 8. This is needed to determine the sewage discharge rate per day, biogas generated, settlement volume and anaerobic unit.

2. Modification coefficient resulting from increase in the number of users are as follows: If the number of people n is less than or equal to $50 (n \leq 50)$, then k=1; if $200 > n > 50$ k=0.95; $500 > n \geqslant 200$ k=0.90 (BIOMA, 2011).

3. Average feed load per person per day 1.3 kg, and for the purpose of this design it is assumed that it is the same for all the family members.

4. d) Considering household of eight (8) people who use 100 litres/day each and a flush fresh sludge per person per day to be six (6) litres, the total flow rate (Q_{sewage}) of sewage-as well as the volume of fresh sludge (Q_f) can be obtained for the design.

5. Sewage hydraulic retention time (HRT), also known as detention time considered for the design is the average period that a given quantity of input remains in the digester to be acted upon by the methanogens for biogas generation is taken to be fifty (50) days.

Lastly, sludge emptying period (SEP) is considered to be two (2) years but maximum SEP taken as five (5) years.

5.2 Biogas Gas Production

The potential gas production (PGP) from eight (8) people using equation 20 and Table 6 falls in the range of 0.16 - 0.224 m3 per day

Lower PGP $= 8 \times 0.020 = 0.160 m^3$
Upper PGP $= 8 \times 0.028 = 0.224 m^3$

5.3 Calculation of the Volume for Design Biogas System, V_{BT}

Adopting equation 19, the volume of the design,

$$V_{BT} = (V_s) + (V_b) + (V_f)$$

Where, Vs = Settlement unit volume V_b = Baffle and anaerobic digestion volume (Anaerobic unit) V_f = Facultative filter unit volume

$$Vs = n \times k \times Q_{sewage} \times HRT$$

For 8 people, k = 1, HRT = 50 days, and Q_{sewage} = 100 liters/capita/day

$$V_s = 8 \times 1 \times 0.1 = 0.8 m^3$$

For a digestion time, $T_d t$ = 50 days and
Q_f = 6 liter/capita/day = 0.006 m^3/capita/day

$$V_b = 1/2 \times k \times n \times Tdt \times Q_{sewage}$$
$$= 1/2 \times 1 \times 8 \times 50 \times 0.006$$
$$Vb = 1.2 m^3$$

AP = accumulation period (days) = (desludging frequency (days) - digestion time (days)) [2]. For digestion time of 50 days and for the tank to be desuldged once every 5 years (1825 days), the accumulation Period (AP) is completed as:

$$V_f = 1/4 \times k \times n \times SEP$$
$$V_f = 1/4 \times (1825 - 50) \times 0.001 \times 8$$
$$V_f = 3.55 m^3$$

Now, the effective volume of the AUDST, V_{BT} becomes

$$V_{BT} = V_s + V_b + V_f = 0.8 + 1.2 + 3.55 V_{BT} = 5.55 m^3 \approx 6 m^3$$

5.4 Constructional Brick Qualification

The dimensions of the AUDST are as follows:
Length = 2.880 m,
Breath = 1.207 m and the
Height = 1.726 m.

Using a brick of$240mm \times 115mm \times 53mm$ and weighing 3.5 kg implies that the length requires about 842 bricks (approximately 1000 bricks) to construct the 6 m^3 biogas tank.

Figure 10. Gravel (3-6mm in diameter) filter materials in the Filter unit

The proposed design is operated through three (3) units namely the desilting, anaerobic digestion and filtration units as shown in figure 10 below. The proposed design is started through inoculation with anaerobic bacteria, e.g., by adding cow dung or by allowing Septic Tank sludge to build up to initiate the process. This configuration of the proposed design provides a more intimate contact between methanogens, methane producing bacteria, and wastewater to be treated. In addition, the anaerobic unit is fitted with packing material (indigenous baskets) to serve as surface for the growth of methanogens. Due to the setup, anaerobic digestion is strengthened and sustained in the anaerobic unit. Again, wastewater from the anaerobic unit downflow into the filtration unit of the model. This unit is also packed with filtering media such as gravels (3 – 6 mm in diameter) to produce effluent that meet EPA standards and can be discharged into wetland. Biogas is generated in both the sedimentation and anaerobic unit. Both units are sealed and provides an anaerobic environment for the complete digestion of both settled and baffled wastewater.

5.5 Engineering Drawing of the proposed AUDST

Based on calculation results, the detail engineering and isometric drawing of proposed design was drawn with Autodesk Inventor 3D CAD having 3D mechanical design tool as shown in figure 10 to figure 12 below. The dimensions of the design were arrived at after the volume of the proposed AUDST design was calculated. The 3 dimensional views of the isometric drawings was also presented to help appreciate the design and assist in further construction and test work.

Figure 11. Gravel (3-6mm in diameter) filter materials in the Filter unit

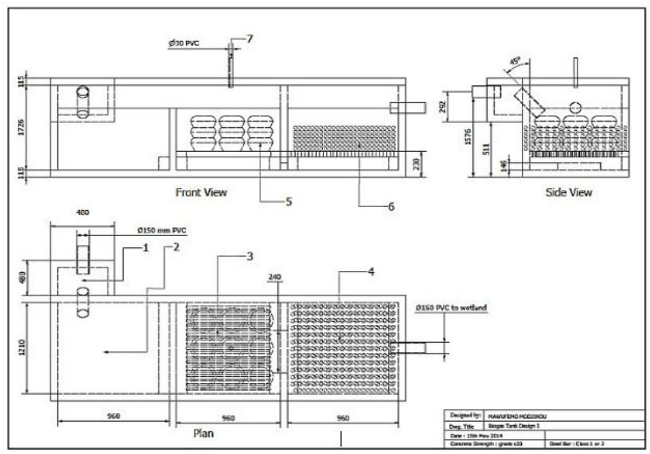

Figure 12. Detailed drawing of the proposed Anaerobic Upflow Domestic Septic Tank (1-Inlet, 2-Settlement unit, 3-Anaerobic unit, 4-Filter unit, 5-Indigenous Basket Packet material, 6-Gravel, 7-Biogas Guide)

6. COST BENEFIT ANALYSIS OF AUDST

6.1 Economic Analysis

The economic analysis of the proposed designs were carried out to enable prospective system owner to get a complete understanding of the cost involved and the technical viability of the systems.

6.2 Levelised Cost of Service of AUDST

The levelised cost of service (Figure 13 and Figure 14 refer) provided by the proposed AUDST over 5 years reveals that one time annual cost of the service provided is worth GHC850. Again, households that deploys the proposed design (AUDST) will start making saving in the second year after installation since the biogas systems start production.

BIOGAS TANK		REFERENCE INVESTMENT COSTS		
		unit cost	unit	Total cost (GHC)
AUDST (construction only)	6m^3	400	GHC/m^3	2,400
Biogas appliances (burner and pipes)				1,000
Annual Operational cost (Slurry removal and maintenance)	1 unit	350	GHC /unit	350
TOTAL DESIGN I INVESTMENT				3,750

Figure 13. Cost of constructing proposed AUDST

Period	CAPEX Initial Cost	OPEX Maintenance Cost	OPEX Recurrent Cost (Slurry Removal)	Total annual cost	Annual service units
year 1	GHC 2,400			GHC 2,400	1
year 2	GHC 0		GHC 100	GHC 100	1
year 3	GHC 0	GHC 250	GHC 120	GHC 370	1
year 4	GHC 0		GHC 144	GHC 144	1
year 5	GHC 0	GHC 300	GHC 173	GHC 473	1
			NPV of Cost =	GHC 2,543	
				NPV of Service =	2.99
	Discount Rate	20%	Levelised cost of service =		GHC 850
	Assumption:	58 m^3 of Biogas is an annual unit of service			

Figure 14. Levelised cost of service for Designs I Cost in GHC as at May, 2014

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Evidently, domestic septic tank can be redesigned to treat sewage and recover biogas as energy. Alternate models have been designed and proposed for adoption against the existing domestic septic tanks for treating domestic sewage for both energy recovery and meeting the environmental requirements for such exuding effluent.

7.2 Recommendations

Financial analysis of the alternative models proposed in this work can be undertaken towards feasibility studies for such systems. It is therefore that a prototypes be built for pilot studies and evaluation.

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