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Research Article

Design of Biomass Plant for Domestic use at Charia Community in Ghana

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Abstract: This research work seeks to mitigate the act of deforestation and save the natural vegetation by designing a biomass plant whose feedstock is cow dung for use by the Charia community of the Upper West Region of Ghana. Firewood has been the primary fuel for domestic purposes at Charia over the years. There has been a shift from the practice where dead (naturally dried) firewood was harvested as fuel. Increase demand for firewood has led to cutting down live trees, drying them and using them as firewood. Others burn these trees for charcoal. In this research, cow dung was collected from four kraals and its mass measured to establish the amount of cow dung expected daily. An average of 1428 kg of cow dung was realized per day. This amounts to a total volume of 57.12 m^3 of biogas. This volume of biogas can serve a total of 952 families which is assumed to be made up of four individuals. It was further realized that, 100% of the community's population can rely on the 57.12 m^3 of biogas as per the daily mass of 1428 kg of cow dung with a reserve of 14.73%. A total of 319.59 kg of firewood is also going to be saved.

Keywords: Acetogenesis, acidogenesis, biogas, charia community, cow dung, hydrolysis, methanogenesis

INTRODUCTION

The effect on the environment by rampant felling of trees cannot be overlooked. Households contribute to deforestation by the use of charcoal and firewood, both from trees. This act coupled with the rise in demand for fuel is gradually depleting the vegetation which adversely affects the climate. Smoke emitted as a result of burning firewood in addition to eye tract irritation can be poisonous to those exposed to it. The main polluting gas from burning firewood is Carbon Monoxide (CO). The concentration of CO becomes fatal when exposed to a person in a closed environment. Inhaling CO also can result in asphyxiation, a situation where CO combines with hemoglobin in the blood preventing absorption of oxygen. Exposure to smoke also puts people at an increased risk of contracting Acute Lower Respiratory Infections (ALRIs). There are, however, a number of factors that determine whether exposure to smoke result in health problems: the concentrations of the air pollutants, the length of exposure, age, individual susceptibility and whether or not there is pre-existing lung or heart disease.

Scattered cow dung in the community is a nuisance. It gives off bad odor and it is not a desirable sight. It can be a courier of infectious disease. The hunt for firewood comes with hazards. Attack from wild animals, cuts, falls and severe body pains are hazards related to fetching firewood. A solution to these problems can be found in using the cow dung in energy generation.

The effluent from anaerobic digestion is rich in nitrogen which is essential for plant growth. Nitrogen held in the original cow dung is lost to the air in the form of ammonia gas or dissolved in surface runoffs in the form of nitrates. In anaerobic decomposition, nitrogen is converted to ammonium ions. These ions affix to soil particles readily making nitrogen available to plants when used as fertilizer.

Biomass is any organic matter that is renewable over time. It is a stored energy in plants. The word "biomass" is originally used in the field of ecology referring to amount of animal and plant including their resource and waste arising from them, which have been accumulated in a certain amount. This excludes fossil fuels. Biomass encompasses a wide variety including agricultural crops, timber, marine plants, waste from livestock, fisheries and other organic industrial waste (Anonymous, 2008). Biomass energy therefore means converting the afore mentioned products and using them as a source of energy, such as fuel for the purposes of driving machinery, providing heat, etc. Biomass energy brings numerous benefits. It contributes as the world's fourth largest energy source up to 14% of the world's primary energy demand (Anonymous, 2008). Its environmental benefits include

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the reduction in air pollutants by being part of a closed-loop carbon cycle. This reduces carbon dioxide by 90% compared with fossil fuels (Anonymous, 2006). Sulfur dioxide and other pollutants are substantially reduced. Other environmental benefits are reduction in water pollution, increase in soil quality and improved wildlife habitat.

Harnessing energy from biomass is done in different ways as the forms of biomass differ. The various forms need processing since the raw biomass typically has a low energy density. The conversion is unique to each form. Wood and other products as bark and saw dust can be burned directly for heat and power. Energy crops are cultivated for their oil for conversion into biodiesel or starch for fermentation to bio-ethanol. Agricultural residue such as animal dung is converted to gas through either thermo-chemical, chemical or biochemical means. Food waste among other biomass forms are likewise converted to some other form for efficient energy use. The availability of the form of biomass product however influences its use in a particular location. In this work a plant is designed to use cow dung as primary feedstock in generating gas for domestic use. This will limit or eradicate the use of firewood thereby saving the natural vegetation and helping in reforestation. Also scattered cow dung in the community will be taken care of and will no more pose a threat as a courier of infectious disease.

MATERIALS AND METHODS

Location of charia: Charia community forms part of the Wa Municipality of the Upper West Region of Ghana. It is about 12 km away from Wa, the capital town of the Upper West Region. It is located at an elevation of 298 meters above sea level with geometric coordinates of 10^{0}6’0’’ N and 2^{0}34’0” W in Degrees Minutes Seconds. It has a land area of approximately 3.28 square kilometers (3.28 km^2). Its population amounts to about 3,319. Figure 1 (Anonymous, 2015) is a satellite image of Charia.

Environment and weather: The climate of the Wa Municipality is characterized by long, windy and hot dry season followed by the short and stormy wet season. The dry season occurs between November and April. The north eastern trade winds from the Sahara desert precipitatesthe coldharmattan winds between

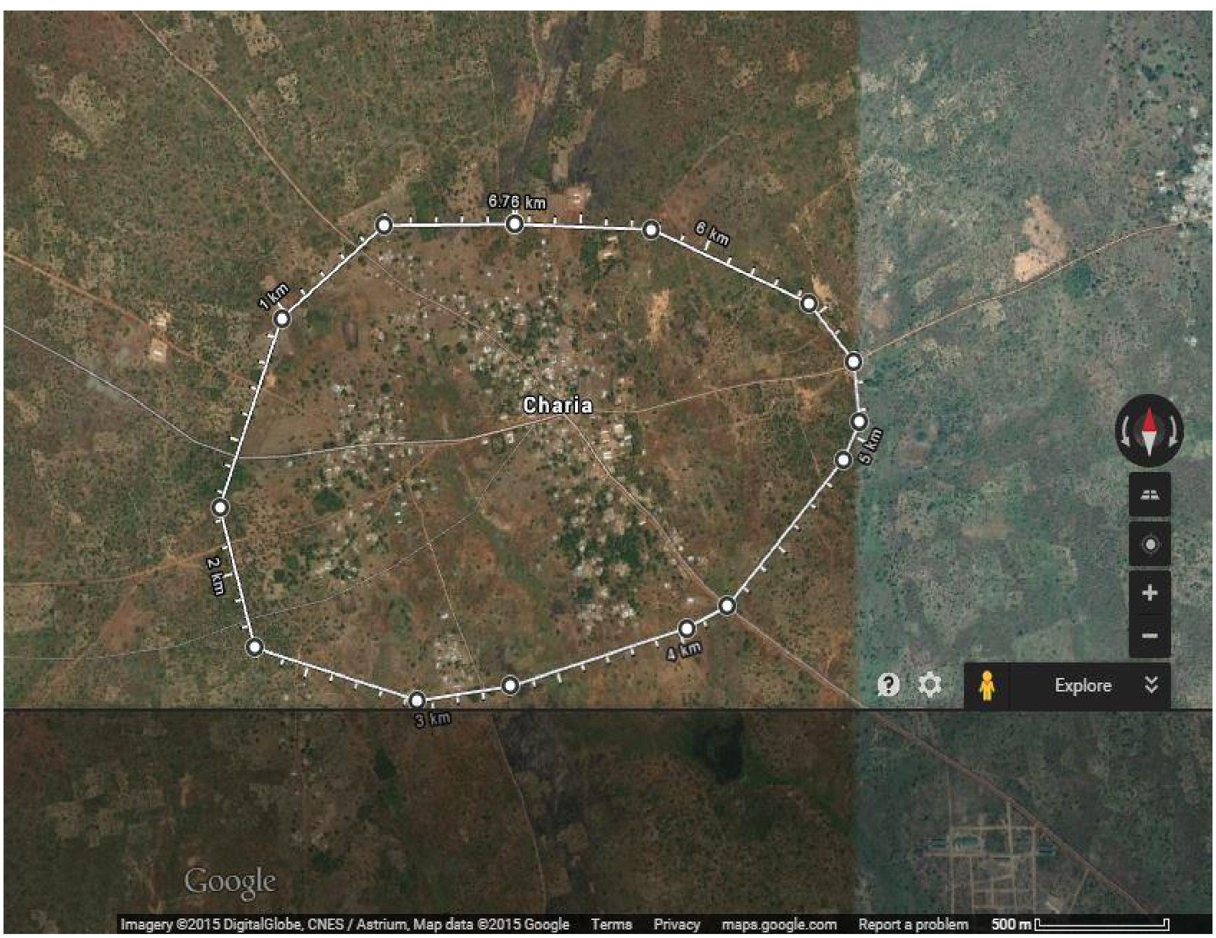

Fig. 1: Satellite image of Charia (Source: Anonymous (2015))

Table 1: Production figures of livestock, Wa municipal

Livestock	Year 2007	2008	2009	2013
Cattle	6,696	7,100	13,781	9,876
Goats	5,154	15,455	14,136	87,685
Sheep	3,303	9,568	12,552	84,315
Pigs	859	3,418	1,931	8,876

(Source: Anonymous (2013))

Table 2: Production figures of food crops inWa municipal in metric Ton

Crop	Year 2007	2008	2009	2010
Maize	36,040	40,112	44,543	8,554
Millet	23,950	27,503	31,395	8,316
Rice	93,602	10,243	11,186	616
Sorghum	18,264	20,743	23,454	9,528
Yam	154,614	164,965	176,007	109,177
Cowpea	5,572	6,432	7,387	4,296
Groundnut	57,182	63,643	70,673	20,622
Soya bean	13,636	15,304	17,123	6,440

(Source: Anonymous (2013))

November and February which brings with it coughs, cold and other respiratory diseases and skin diseases. The hot season records high temperatures with a peak of between 40 and 45°C in March and April causing dehydration and incidence of cerebral meningitis. The effect of climate change is becoming more manifest of late due to human activities in terms of bush burning, felling of trees, poor farming practices and poor infrastructural practices. The wet season lasts between April and October. The annual mean rainfall volume of between 840 mm and 1400 mm is sparsely and poorly distributed over the months. The rainfall pattern is erratic and punctuated by spells of long droughts and heavy downpours and floods. This affects humidity levels, soil moisture levels, crop growth and general agricultural productivity (Anonymous, 2013).

Economy and agriculture: Charia is an agricultural community. The natives practise both crop farming and livestock farming. The crops cultivated include yam, maize, sorghum, groundnut, soybeans, bambara beans, cowpea among others. The livestock at Charia include cattle, pig, goat, sheep and poultry. The production figures of livestock and food crops in the municipality are shown in Table 1 and 2. The crop and livestock production is both on a domestic and a commercial scale. Cattle among the other livestock reared, is owned by various sect of families. Fulani herdsmen are the caretakers of these cattle. The others are reared substantially close to the residence of the respective owners. Most farmers transport their produce to Wa on "Wadaa" meaning, Wa market day which recur every five days to trade. Economic trees at Charia include sheanut, dawadawa, mango, baobab and teak.

LITERATURE REVIEW

Cow dung: Cow dung is the waste product of cattle (cow). It is the undigested residue of plant matter which has passed through the cow's gut. The resultant fecal matter is rich in minerals. Color ranges from greenish to blackish. It often darkens soon after exposure to air. Usually, it is combined with soiled bedding and urine. Dung from cows is used for various applications. Primarily, it is used as manure for crops. It is recycled into the soil by species such as earth worms and dung beetles. It is also used to line the walls of rustic houses as cheap thermal insulator. It is used as an ingredient in the manufacture of adobe mud brick housing. Cow dung has found application as feedstock for the production of combustible gas rich in methane. This gas is used in electricity generation, domestic cooking and heating (Anonymous, 2014a). Cow dung may be collected at water points, kraals and cattle posts. The distances to these vary, hence the costs. Within walking distance, 10-50 kg may be collected e.g., in a wheel barrow; but further away donkey carts and vehicles may be used, which take on more cow dung quantities e.g., 250-450 kg per load (Anonymous, 2010).

Gas yield from cow dung: One kilogram of methane gas is more or less equal in energy content to 1 kg of petrol, LPG, kerosene or diesel (Firodia, 2004). It could be noted that 1kg cow dung produces 0.04 m^3 gas, which can feed a family of 4-6 (at 3 meals per day) for about 4 days (Anonymous, 2010). It is a common knowledge that 1 kg of cattle dung delivers 0.04 m^3 of biogas, 1 kg of human feces generates about 0.05 m^3 of biogas, and 1 kg of chicken droppings generates about 0.07 m^3 of biogas. Gas consumption for cooking per person and per meal is between 0.15 and 0.3 m^3 biogas. Approximately 0.03-0.04 m^3 biogas is required to boil one liter of water, 0.12-0.14 m^3 for 0.5 kg rice and 0.16-0.19 m^3 for 0.5 kg vegetables. Tests in Nepal and Tanzania have shown that the consumption rate of a household biogas stove is about 0.3-0.4 m^3/h. However, this depends on the stove design and the methane content of the biogas.

Cow dung to biogas conversion: Obtaining methane gas from cow dung is simple. It consists of an airtight tank filled with raw organic waste like cow dung. The anaerobic decay of this matter generates biogas. An agitator quickens the process. The gas generated has about 68% methane and 31% carbon dioxide with trace gasses. It is passed through lime water to remove the carbon dioxide and over iron fillings to remove hydrogen sulfide (H_2S). It then becomes richer with methane (Firodia, 2004). It has the advantages of producing energy, yielding high quality fertilizer and also preventing transmission of disease (Koeberle, 1995).

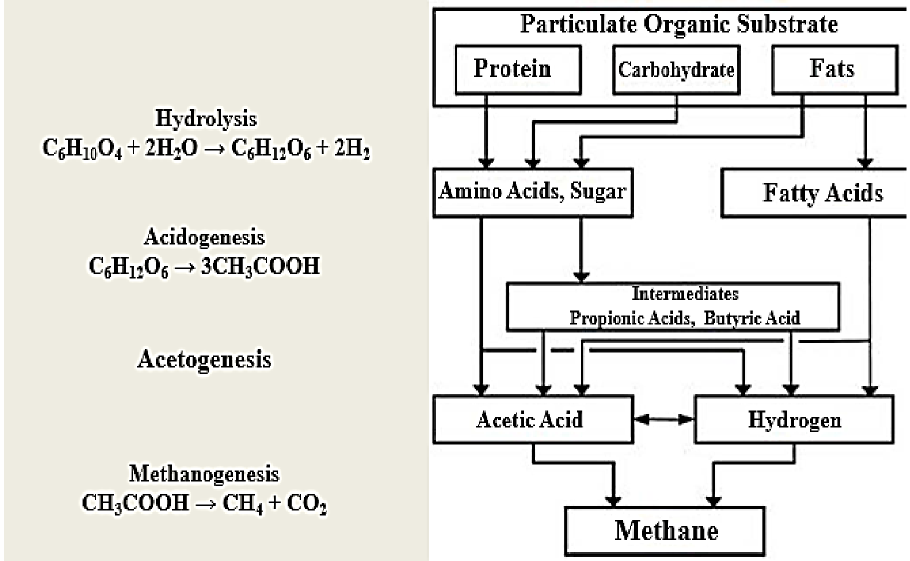

Fig. 2: Degradation steps of anaerobic digestion process (Source: Verma (2002))

Anaerobic digestion process: Anaerobic digestion refers to digestion carried out by microorganisms in an oxygen free environment. The decomposition occurs in four stages. They are Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis

Hydrolysis: During hydrolysis, bacteria transform the particulate organic substrate i.e., proteins, carbohydrates and fats into liquefied monomers and polymers to amino acids, monosaccharide and fatty acids respectively. Equation (1) shows an example of a hydrolysis reaction where organic waste is broken down into simple sugar, in this case, glucose:

$$C_6H_{10}O_4+2H_2O \rightarrow C_6H_{10}O_6+2H_2 \quad (1)$$

Acidogenesis: Acidogenic bacteria, in the second stage, transform the products of the first reaction into short chain volatile acids, alcohols, hydrogen and carbon dioxide. The principal acidogenesis stage products are prop ionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH) among others. From these products, the hydrogen, carbon dioxide and acetic acid will skip the third stage, acetogenesis, and be utilized directly by the methanogenic bacteria in the final stage. Equations (2), (3) and(4) represent three typical acidogenesis reactions where glucose is converted to ethanol, propionate and acetic acid, respectively.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH+2CO_2 \quad (2)$$

$$C_6H_{12}O_6+2H_2 \leftrightarrow 2CH_3CH_2COOH+2H_2O \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

Acetogenesis: In acetogenesis, the rest of the acidogenesis products, i.e. the prop ionic acid, butyric acid and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the hydrogen partial pressure is low enough to thermodynamically allow the conversion of all the acids. Such lowering of the partial pressure is carried out by hydrogen scavenging bacteria. Equation (5) represents the conversion of propionate to acetate, only achievable at low hydrogen pressure. Glucose in Eq. (6) and ethanol in Eq. (7) among others are also converted to acetate during the third stage of anaerobic fermentation.

$$CH_3CH_2COO^-+3H_2O \leftrightarrow CH_3COO^-+H^++HCO_3^-+3H_2 \quad (5)$$

$$C_6H_{12}O_6+2H_2O \leftrightarrow 2CH_3COOH+2CO_2+4H_2 \quad (6)$$

$$CH_3CH_2OH+2H_2O \leftrightarrow CH_3COO^-+2H_2+H^+ \quad (7)$$

Methanogenesis: The fourth and final stage is called methanogenesis. During this stage, microorganisms convert the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide. The bacteria responsible for this conversion are called methanogens and are strict anaerobes. Waste stabilization is accomplished when methane gas and carbon dioxide are produced. The degradation steps are shown in Fig. 2.

$$CO_2+4H_2 \rightarrow CH_4+2H_2O \quad (8)$$

$$2C_2H_5OH+CO_2 \rightarrow CH_4+2CH_3COOH \quad (9)$$

$$CH_3COOH \rightarrow CH_4+CO_2 \quad (10)$$

RESULTS AND DISCUSSION

Description of proposed design: The result of the research has yielded the proposed plant shown in Fig. 3 for gas generation. It comprises an inlet tank with a stirrer, an anaerobic bio-digester, and an effluent pit. Pipes and valves are used to link these components.

Components of the proposed design: The main components of the proposed design are:

- Inlet Tank Assembly
- Inlet Pipe
- Gas Holder
- Hand Valve
- Gas Storage Unit
- Hand Valves
- Water Trap
- Bio-digester
- Outlet Pipe
- Hand Valve
- Effluent Pit

Theory of operation: Equal amount of water and cow dung are fed into the hopper of the inlet tank. The valve to the tank is then closed. Manually, the stirrer is turned to ensure a preferably homogenous mixture of water and cow dung (slurry). The inlet valve to the digester is now opened to allow flow of slurry into the digester. In charging the digester for the first time, the gas flow valve isopened and the gas holder depressed to its lowest limit. This allows the escape of any accumulated air in the digester. All valves and openingsare closed afterwards to ensure an oxygen-free environment for the breakdown of the slurry to produce the gas needed. The gas generated is channeled through a pipe on the gas holder to the consumer. Upon the next charging of the digester, the effluent valve is opened to discharge the digested slurry into the effluent pit through the outlet pipe.

Materials for various components:
Inlet tank assembly: The inlet tank (Fig. 4), temporarily stores the water and cow dung to be mixed by a manually operated stirrer. For excellent machining properties, low cost and high strength, steel of 0.25% carbon content is used. The inlet tank support structure is under the combined load of the hopper, valve, the tank and the stirrer. It should be able to support the compressive load emanating from these components. Cast iron is to be used for the support.

Digester: The digester is supported by a foundation. Part of the digester is below ground whiles a portion is above ground. The digester foundation bears the load of the digester wall and the gas holder. The O-ring on top of the digester wall ensures an air-tight seal between the gas holder and the digester. For a better load bearing capacity, the foundation is made of concrete. The wall is made of clay bricks. Mortar is used to bind the bricks together. Mortar is also used improve on the impermeability of the inner wall of the digester. The digester is shown in Fig. 5.

Gas holder: The gas holder (Fig. 6) provides a cover for the bio-digester. It expands to a set limit when gas pressure builds up in the bio-digester. It is resistance to corrosion, good resistance to H_2S reaction, high tensile strength, excellent impact resistance and light weight.

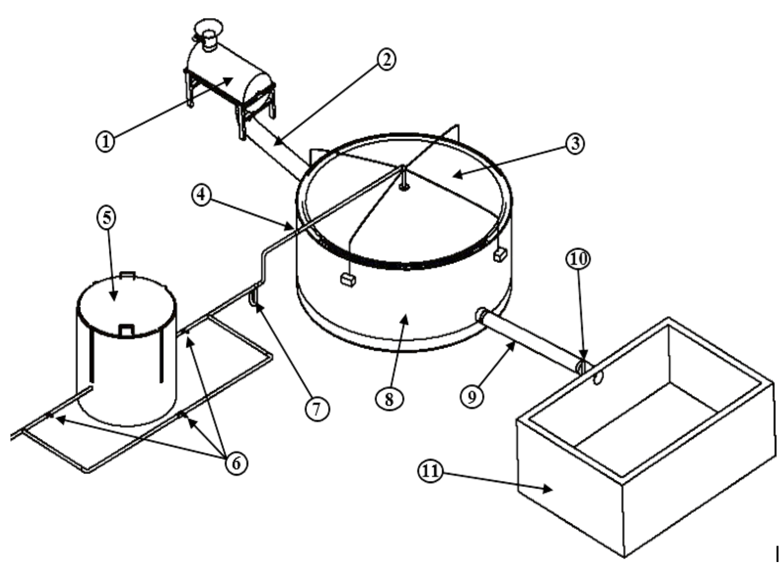

Fig. 3: Picture of proposed biomass plant

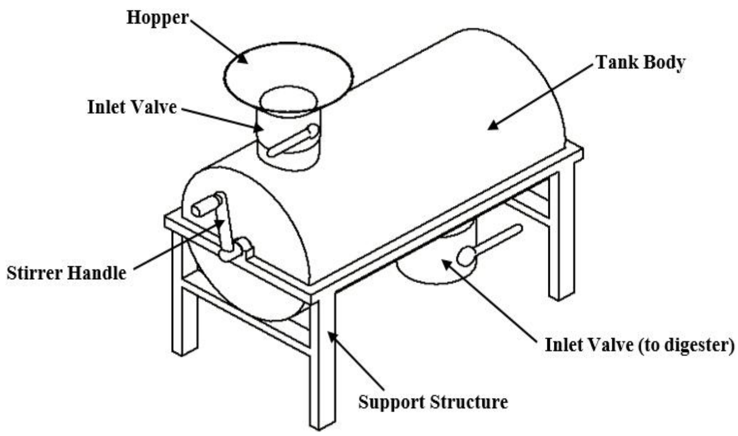

Fig. 4: Inlet tank assembly

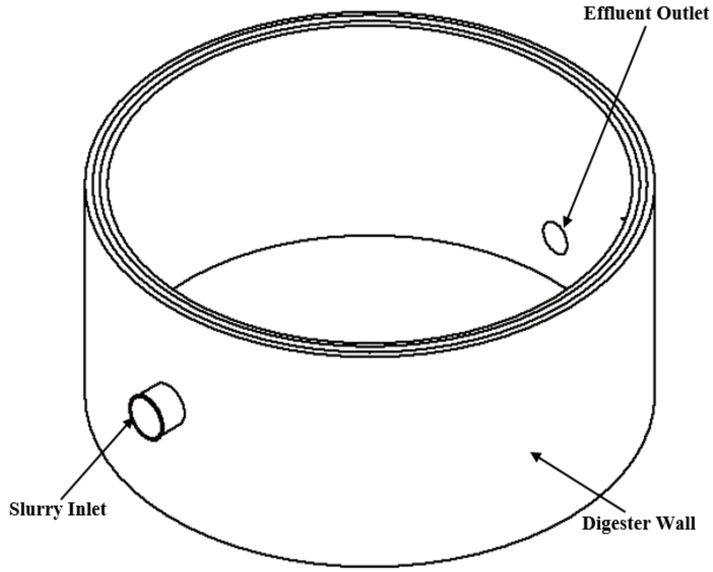

Fig. 5: Bio-digester

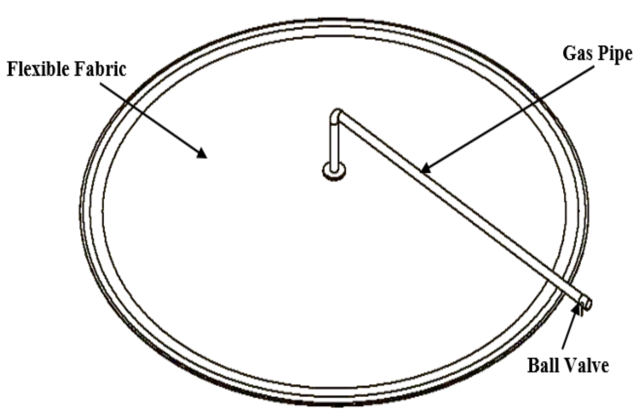

Fig. 6: Gas holder

High temperatures speed up biogas generation. Flexible fabric of Linear Low Density Polyethylene (LLDPE) is therefore selected for the gas holder.

Effluent pit: The effluent pit shown in Fig. 7 shares similar properties as the bio-digester, hence, is made of clay bricks.

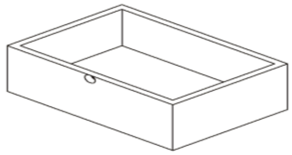

Fig. 7: Effluent pit

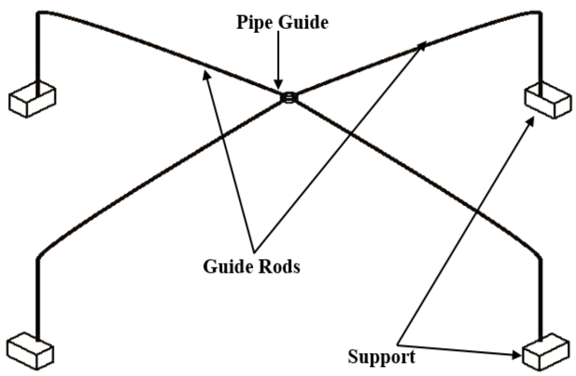

Fig. 8: Guide

Pipes: The inlet and outlet pipes both transport slurry into and out of the bio-digester respectively. They are buried in the ground. They are corrosive resistant and are made of galvanized iron.

Guide: The guide serves as an upper limit to the gas holder when it inflates. It is built on concrete capable of supporting an upward gas pressure force in gas holder. The guide is made steel rods and is shown in Fig. 8.

Water trap: The water trap is installed at preferably the lowestpoint in the gas pipeline connection. It will

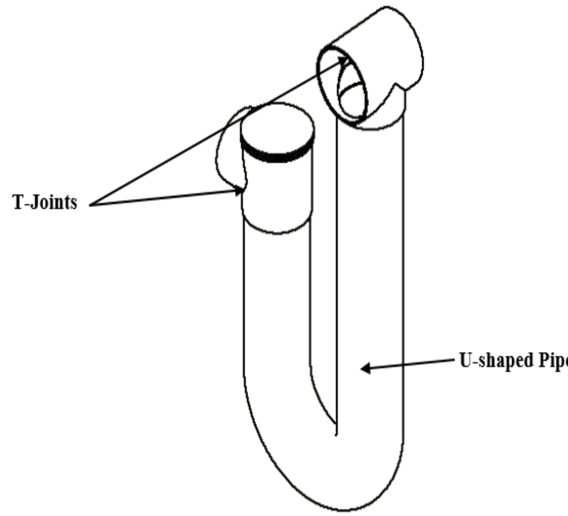

Fig. 9: Water trap

trap any moisture and relieve the system of excess pressure should the need arise. It will be of the same material as the gas pipe (PVC). It is shown in Fig. 9.

Gas storage unit: The gas storage unit (Fig. 10) is a gas bag with reinforcement. It has a lid with four locks. When turned clockwise the locks slip through the groove on the reinforcement. The weight of the lid isexerted on the gas bag to increase the gas pressure to the consumer.

The gas bag is resistance to corrosion, good resistance to H_2S reaction, high tensile strength,excellent impact resistance and light weight. Flexible fabric of linear low density polyethylene (LLDPE) is selected for the gas bag.

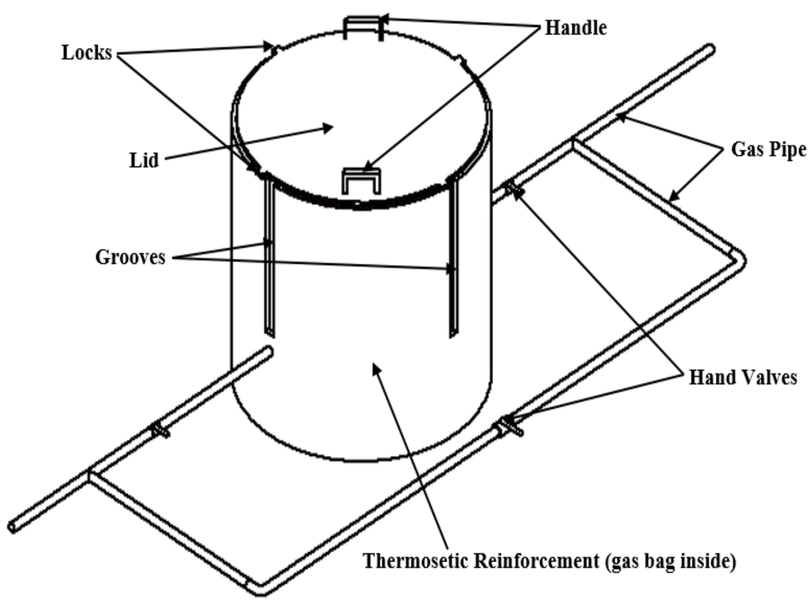

Fig. 10: Gas storage unit

Table 3: Data on amount of dung from kraals at Charia

SN of Kraal	No. of Cows	Mass of Dung (kg)
1	94	177
2	47	79
3	55	95
4	76	136

Fig. 11: Measurement of mass of cow dung using a hanging scale

Feedstock Estimation: Fresh cow dung was collected from four different kraals out of a total of seven identified at Charia. The dung was collected into sacks and marked. It was then transported to Wa and weighed to determine the mass of dung obtained from each kraal as shown in Fig. 11. The cows were kept in the kraals between the hours of 7 pm to 6 am i.e., 11 hours. A hanging scale rated at 320 kg was used in checking the mass of the dung. Table 3 shows the results of this exercise. The figures however are approximate.

From above, the averages of the number of cows per kraal and dung per kraal can be deduced:

Average No. of cows per kraal

$= \frac{94+47+55+76}{4} = 68$ cows/kraal

Average Dung per kraal

$= \frac{177+79+95+136}{4} = 121.75$ kg/kraal

Average dung per cow

$= \frac{\text{Average Dung Per Kraal}}{\text{Average No. of Cows Per Kraal}}$

$= \frac{121.75}{68}$

$= 1.79$ kg (11)

The amount of dung per cow per day i.e., 24 h will be taken as 3 kg.
It follows that:

Mass of dung per kraal/day = 68 × 3 = 204 kg

Expected biogas yield and plant size: For efficient utilization of cow dung in the digestion process, the slurry will be allowed to span 25 days in retention and then discharged for a fresh charge. The actual hydraulic retention time will be computed. The actual mass per charging the digester is therefore the 25 days accumulation of the daily mass.

Actual mass of dung per kraal/25 days = 204 × 25
= 5100 kg

It has been established that, for every 1 kg of cow dung, biogas equivalent of 0.04 m^3 is generated through anaerobic digestion (Anonymous, 2014b).

Hence, an approximate volume of biogas expected from each kraal can be computed:

Volume of biogas per kraal = (Mass of Dung per Kraal)×(Per kg Biogas Equivalent) = 5100×0.04
Volume of biogas per kraal = 204 m^3

The size chosen for the digester construction i.e., digester volume, V_d is 204 m^3.

Average time the slurry remains in the digester for treatment i.e., Hydraulic Retention Time (HRT) is given by the relation:

$$\text{HRT} = \frac{\text{Digester Volume}, V_d\ (m^3)}{\text{Daily feed rate},\ F_r\ (m^3/\text{charge})} \quad (12)$$

For F_r, it is taken that, one part of water is to one part of fresh dung (Rohjy *et al*., 2013).

Assuming that, 1 kg of dung is equal to 0.001 m^3,
Fr = (5100+5100) × 0.001
= 10.2 m^3/charge
HRT $= \frac{204}{10.2} = 20$ days

This implies that beyond 20 days, there will be no effective biogas generation. The digester however will be fed at a 25 day interval with a slurry volume of 10.2 m^3.

Average gas production per day
$= \frac{\text{Volume of biogas per kraal}}{25\ days}$
$= \frac{204}{25}$
= 8.16m^3/day
The Expected Gas from Seven Kraals = Volume of biogas per kraal×No. of Kraals
= 8.16×7
= 57.12m^3/day

The findings below result in the further computations.

- Consumption rate for household burners = 0.3 m^3/h (Eawag *et al*., 2014)
- 1 $m^3$of biogas is equivalent to 5.56 kg of firewood (Zhu, 2006)
  Biogas Usage Hours
  $= \frac{\text{The Expected Gas from Seven Kraals}}{\text{Consumption Rate For Household Burners}}$
  $= \frac{57.12}{0.3}$
  = 190.4 h (13)

Savings in Firewood = (The Expected Gas from Seven Kraals) × (5.56 kg of Firewood)
= 57.12 × 5.56
= 317.59 kg/day

The figures presented above, thus the effective biogas usage hours, 190.4 and the savings in firewood, 317.59 kg are dependent on the daily mass of (204 × 7) kg of cow dung from the seven kraals in the community. A volume of 0.06 m^3 of biogas, can feed a family of 4-6 (at 3 meals per day) for about 4 days (Anonymous, 2010).

Expected Number of Families to Be Served
$= \frac{\text{The Expected Gas from Seven Kraals}}{\text{Family Consumption Rate}}$
$= \frac{57.12}{0.06}$
= 952 families
Burning time for each family
$= \frac{\text{Expected Number of Families to Be Served}}{\text{Biogas Usage Hours}}$
$= \frac{952}{190.4}$
= 5 h/family/day

Taking 4 people per each family:

Total Number of People to be Served = 952×4
= 3,808 people will be served with biogas

It follows that, the percentage of the population to get biogas supply is i.e., 3,319.

% of population to be supplied
$= \frac{3808}{\text{Population of Charia}} \times 100$
$= \frac{3808}{3319} \times 100$
% of population to be supplied = 114.73%

CONCLUSION

Averagely, a total of 1428 kg of cow dung is expected from the seven kraals in the community per day. A total of 57.12 m^3 of biogas is expected to be generated from the daily mass of cow dung available i.e., 1428 kg. This volume of biogas can serve a total 952 families i.e., 3,808 people (1 family = 4 people) which implies the total population of the community can rely on biogas with 14.73% reserve. Savings in firewood is 317.59 kg per daily dung of 1428 kg.

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