Review, Design and artisanal fabrication of anaerobic bio-digester for biodegradable waste

Fabien Kenmogne[1], André Abanda[2], Madouma Madouma Arnold[3], Willy Arnold Donda[1,4], Ulrich Nota Yemetio [1,4] ,Emmanuel Yamb[1]*

[1]Department of Civil Engineering, Advanced Teacher Training College of the Technical Education, University of Douala, Cameroon.
[2]Department of Civil Engineering, National Advanced Polytechnical School of Douala, University of Douala, Cameroon.
[3]Ecole normale supérieure de l'enseignement technique(ENSET) de Libreville, Université Omar Bongo, Gabon
[4]Laboratory of mechanics, Advanced Teacher Training College of the Technical Education, University of Douala, Cameroon

**Corresponding Author: email: kenfabien@yahoo.fr*

The purpose of this research work is to design and fabricate a bio-digester with HDPE (high density polyethylene) geomembrane material which will be effective in recycling biodegradable waste and unisonly produces biogas and organic liquid fertilizer. At the first time, a tubular trapezoidal bio-digester was designed using computer-aided design (CAD). After that, a 300 litters prototype bio-digester was manufactured with a tarpaulin. After running air and water tightness of the system, we fed it with quantified biodegradable waste and observed for a period of 60 days. Several tests were then conducted on the bio-digester to ensure that the system could support the load to which it would be subjected under normal functioning condition. These tests included shear test, peel test, and air tightness of the system. Results obtained from the prototype and the HDPE geomembrane bio-digester shows that, this design allows the recycling of biodegradable waste from any facility. The biogas obtained was proven to be rich in methane (52-73%) content and the organic liquid fertilizer was also rich in N-P-K fulfilling the basic requirement for plant healthy growth. Economically, the HDPE geomembrane bio-digester could produce 1,250L of biogas daily at an approximate pressure 1.8 bars which can be approximated to 5 hours minimum burning with a burner of 200L/h (ie a gas burner of about 1 kW of power).

Keywords: Geomembrane, Biodegradable waste, Methane, biogas, fertilizer, Hydraulic retention time, biodigester.

1-Introduction

Waste disposal is the main issue nowadays as it contributes to climate change. In sub-Saharan context, unplanned urbanization with an increasing population will lead in the future to huge amount of waste. For instance, many towns in Africa are facing drawbacks of poor waste management with a tremendous increase of the population. Among these drawbacks, we have high exposure to malaria, water bone diseases, pest's multiplications and more greenhouse gas (GHG) emissions leading to climate change. Hence, there is an urgent need to think about solutions aiming to manage waste efficiently with less environmental impact [1].

Energy production from waste is actually the appropriate solution for sub-Saharan countries where its vast population is being faced with the challenge of supplying the energy demand ranging from the industries to citizens; this is because of the vital role that energy has to offer towards the development of the nation. The importance of energy in national development cannot be over emphasized, energy is the hub around which the development and industrialization of any nation revolve [1]. Several studies have shown that by incorporating renewable energy resources into the overall energy mix or unit of nations, any of these negative environmental impacts of energy use could be avoided or minimized. The cost for domestic, commercial and industrial uses in Central Africa has risen astronomically in the past few years following the liberalization and reform of the oil industry and the energy sector as a whole. The cost of energy is now a very significant factor which determines the price paid end users of commodities [2]. Particularly in Cameroon, almost 64.1% of the population relies on biomass mostly wood and charcoal [3]. Biodegradable waste entails biomass wastes (agricultural crop wastes, forest residues, animal manure, and organic waste) and Municipal solid wastes. The first resources mostly found in rural areas form a potential solution for an alternative source of energy through anaerobic digestion technology. This technology was introduced into developing countries as a low - cost alternative source of energy to partially alleviate the problem of acute energy shortage for households, and it provides excellent fertilizer, there by increases crop production [3]. Thus, to solve the problem of biogas technology dissemination and waste management issues in Cameroonian context, many contributions are expected, including the development of an alternative anaerobic digester constructed using a different material and design.

Anaerobic digestion of biodegradable waste for biogas production has become a subject widely studied and adopted technology worldwide for its output which is biogas and organic liquid fertilizer which helps in solving pressing development issues like food security, clean energy capacity, climate change mitigation and adaptation, economic improvement [4]. Biogas production is an anaerobic digestion process whereby bacteria existing in oxygen-free environments decompose organic matter such as animal manure [4]. Anaerobic digesters are designed and managed to accomplish this decomposition. As a result of this digestion, organic material is stabilized and gaseous by products, primarily methane (CH_4) and carbon dioxide (CO_2) are released. Ranges of temperature of operation in anaerobic digestion are either psychrophilic (<20°), mesophilic (20-45°C) or thermophilic (45-60°C).

All countries in the central east-west band of Africa suffer major health and sanitation problems. Many of these countries have the potential to improve their sanitation through the use of domestic biogas bio-digesters, and improvements in the technology may further increase the potential for the use of biogas digesters [5]. Small scale biogas plants are increasingly adopted in sub-Saharan Africa (SSA) rural communities such as Tanzania, Kenya, Rwanda, Burkina Faso, Mali, Uganda, Cameroon [6] in the framework of pilot projects. Cameroon intends to fully meet its commitment to reduce the carbon footprint of its development by 32% by 2035 compared with 2010. Cameroon's development policy, which seeks to achieve the status of emerging country by this same date, will certainly require climate change adaptation. At the international level, these mitigation measures will require technology transfers, maybe through a multilateral special fund. At the national level, the measures will also require us to harmonize our sector policies and scale up the efforts we have been making for several years now (reforestation as part of desertification control, designing a clean development mechanism, sustainable forest management and biodiversity conservation). We must size up the real stakes of COP21 which are nothing short of ensuring the survival of mankind [6].

This study has as general objective to design and fabricate a bio-digester with HDPE geomembrane material which will be effective in recycling biodegradable waste and unisonly produces biogas and organic liquid fertilizer. Specific objectives are put in place in order to aid up the attainment of the principal objective, which include:

- The proving that alternative energy can be generated from biodegradable wastes and used for several applications;
- The design and fabrication of a biogas system to compensate the energy supply in our scullery;
- To help improve agricultural production as the by-product of the biogas being produced serves as a perfect organic fertilizer;
- To inculcate a means of making use of the organic waste that lies around our premises hence adopting an environmental sanitation technique;
- The providing of researchers raw materials (data) for further scientific discoveries.

This research work is structured into two parts. The first part entitled Scientific research being divided into 3 main sections namely:

The Section 2 is concerned with the literature review, which shall contain the review on biogas production, fertilizer, and geomembrane material. Then the section 3 is focused on the material and methods related to the fabrication aspect. Section 5 shall regroup the results and discussions.

The second part is related to Know-How Transfer.

Finally, we shall end up our work by a general conclusion and perspectives.

2: Literature review

2.1. Biodegradation

Biodegradable waste are materials that can be broken down into basic molecules (e.g. carbon dioxide, water) by organic processes carried out by bacteria, fungi, and other microorganisms. This leads to biodegradation process which is the digestion of organic substances under the action of microbes and the influence of enzymes that catalyze the degradation process at the suitable operational conditions. Two (02) types of degradation is under practice which include aerobic digestion in which microbes degrade the substrate in the presence of oxygen and anaerobic digestion in which organic substrates are degraded in the absence of oxygen.

2.1.1. Anaerobic Digestion

Anaerobic digestion is defined as fermentation of organic wastes in the absence of free oxygen ([7-8]). In Anaerobic digestion (AD), gas resulting from direct organic material conversion is called biogas, a mixture of methane, carbon-dioxide with traces of other gases like hydrogen sulphide. Biogas production started Since 17th century, with the discovery of biogas as a flammable gas by the Belgian chemist Van Helmont from the decomposition (decaying) of organic matter. The first world's digester for biogas production was constructed in Bombay (India) in 1859 [9]. Systems built are mostly on a small scale aiming to provide energy and organic fertilizer to family farms. Table 1 shows examples of calorific value of different fuel sources as compared to biogas as well as the approximate mass of that fuel corresponding to 1 m^3 of biogas.

Fuel Source	**Approximate Calorific Value**	**Equivalent to 1 m³ Biogas (approx. 6 kWh/m³)**
Biogas	6 – 6.5 kWh/m³	
Diesel, Kerosene	12 kWh/kg	0.50 kg
Wood	4.5 kWh/kg	1.30 kg
Cow dung	5 kWh/kg dry matter	1.20 kg
Plant residues	4.5 kWh/kg dry matter	1.30 kg
Hard coal	8.5 kWh/kg	0.70 kg
Propane	25 kWh/m³	0.24 m³
Natural gas	10.6 kWh/m³	0.60 m³
Liquefied petroleum gas	26.1 kWh/m³	0.20 m³

Table 1: Calorific value of different fuels ([8])

Below is the biogas equivalent to different fuels ([8]):

- 1 kg firewood => 0.2 Nm³ biogas
- 1 kg dried cow dung => 0.1 Nm³ biogas
- 1 kg charcoal => 0.5 Nm³ biogas
- 1 Littre kerosene => 2.0 Nm³ biogas

Bacteria play the role of catalyzer of biomass conversion in anaerobic environment. Energy contained in the gas produced represents 20 to 40% of the lower heating value of the feedstock ([8]). Commercially proven technology mainly used for treating high moisture content organic wastes (80 to 90% and solid content of less than 25%), the yield can be directly used in spark ignition gas engine, gas turbines or upgraded to natural gas quality by CO_2 removal. The conversion efficiency is about 21%. ([9]).

2.1.2 Anaerobic digestion process description

Anaerobic digestion happens in four steps described as followed:

- **Hydrolysis**: This step consists in conversion of complex molecules (large protein macromolecules, fats, cellulose and starch) into simple sugars, long-chain fatty acids and amino acids. For instance, polymers after hydrolysis become monomers and oligomers. Hydrolysis catalyzers are enzymes excreted from bacteria. Feedstock complexity influences hydrolysis efficiency. Carbohydrates conversion is faster than raw cellulosic waste ([10]). The main reactions and bacteria occurring in hydrolysis are:

$$lipids \xrightarrow{lipase} fatty\ acids, glycerol,$$

$$Polysaccharide \xrightarrow{cellulas, cellobiase, xylanase, amylase,} monosaccharide\ ,$$

$$Proteins \xrightarrow{protease} amino\ acids\ .$$

The hydrolysis reaction equation is expressed by

$$C_6H_{10}O_4 + 2H_2O \overset{k_1}{\rightarrow} C_6H_{12}O_6 + 2H_2 \quad (1)$$

- Acidogenesis or fermentation. Hydrolysis products are converted into volatile fatty acids (VFAs ; mainly lactic propionic, butyric and valeric acid), acetates, alcohols, ammonia, carbon dioxide and hydrogen sulphide. The following equations summarize acido-genesis reaction.

$$C_6H_{12}O_6 \overset{k_2}{\rightarrow} 2CH_3CH_2OH + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \overset{k_3}{\rightarrow} 2CH_3CH_2COOH + 2H_2O \quad (3)$$

$$C_6H_{12}O_6 \overset{k_4}{\rightarrow} 3CH_3COOH \quad (4)$$

- **Acetogenesis**. Equations 4 and 5 describe this 3rd step of anaerobic digestion and the yields are:

$$CH_3CH_2COOH + 2H_2O \overset{k_5}{\rightarrow} CH_3COOH + CO_2 + 3H_2 \quad (5)$$

$$C_6H_{12}O_6 + 2H_2O \overset{k_6}{\rightarrow} 2CH_3COOH + 2CO_2 + 4H_2 \quad (6)$$

$$CH_3CH_2OH + H_2O \overset{k_7}{\rightarrow} CH_3COOH + H_2 \quad (7)$$

- **Methanogenesis**: Catalysers contributing to the production of methane, Carbone dioxide and water are according to ([7]) and ([10]) acetrophic, hydrogenotrophic and methylotrophic bacteria. Equations 8 and 9 are:

$$acetic\ acid \xrightarrow{methabogenic\ bacteria} methane + carbon\ dioxide \quad (8)$$

$$hydrogen + carbon\ dioxide \xrightarrow{methabogenic\ bacteria} methane + water \quad (9)$$

Equations 10 to 14 describe methanogenesis in details with other side reactions as well (equations 15 and 16). Detailed methanogenesis reactions***:***

$$2CH_3CH_2OH + CO_2 \overset{k_8}{\rightarrow} 2CH_3COOH + CH_4 \quad (10)$$

$$CH_3COOH \overset{k_9}{\rightarrow} CH_4 + CO_2 \quad (11)$$

$$CO_2 + 4H_2 \overset{k_{10}}{\longrightarrow} CH_4 + 2H_2O \quad (12)$$

Side reactions

$$CH_3COOH + SO_4^{2-} + 2H^+ \overset{k_{11}}{\longrightarrow} 2H_2O + 2CO_2 + H_2S \quad (13)$$

$$CH_3COOH + 2NO^- + 2H_2O + 2H^+ \overset{k_{12}}{\longrightarrow} 2HCO_3^- + 2NH_4^+ \quad (14)$$

The following equation is the simplification of the entire process:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \quad (15)$$

The theoretical calculations are made based on the primary methanogenic route which is the acetotrophic methanogenic reaction expressed by equation (11). ([7]).

During anaerobic digestion, the four separate stages occur simultaneously in such a way that the first reaction must perform before the second one proceeds and so on. ([10]). At the end of digestion, digestate containing hydrogen sulphide and ammonia need to go through ageing in an aerobic composting. The aim is to break ammonia into nitrates and reduce any odor before used as fertilizer.

The interactions between different species of bacteria are very tight, and the elements produced by some species can be used by other species as sublayers or growth factors.

Figure 1 shows the simplified process of anaerobic digestion.

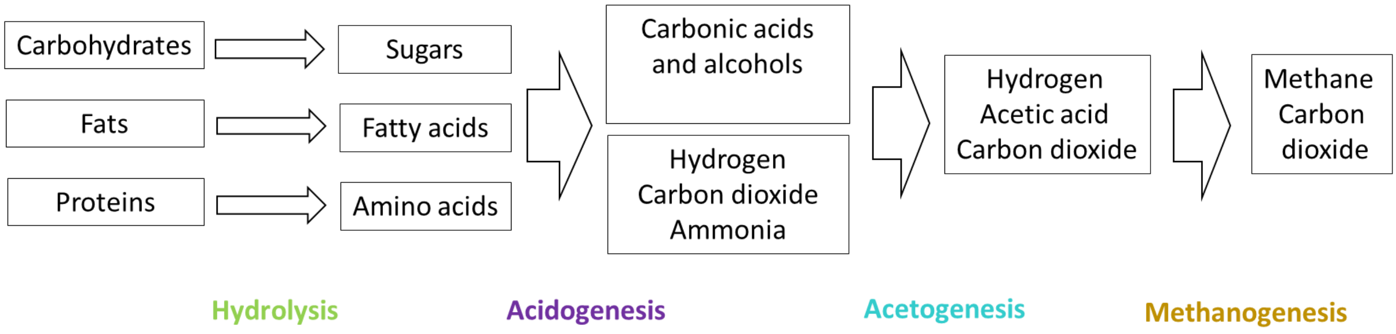

Figure 1: The simplified process of anaerobic digestion [39].

2.1.2.1 Bacteria

Efficient digestion is linked to presence of suitable bacteria colonies. Identified feedstocks with optimal bacteria content are animal manure, slaughterhouse wastes and sewage. Then, reactors may be supplied with these materials. Table 2 shows bacteria groups involved in anaerobic digestion.

Stage	Reaction	Bacteria
2	Hydrolysing and fermenting	*Bacteroides, Clostridium, Butyrivibrie*
2	Hydrolyzing and fermenting	*Eubacterium, Bifodobacterium, Lactobactillus*
2	Acetogenic	*Desulfovibrio, Syntrophobacter wolinii*
3	Acetogenic	*Syntrophomonas*
3	Methanogenesis	*Methanobacterium formicium, M. ruminantium*
4	Methanogenesis	*M. bryantii, Methanobrevibacter*
4	Methanogenesis	*Methanobrevibacter arboriphilus*
4	Methanogenesis	*Methanospirilum hungatei, Methanosarcina barkeri*

Table 2: Bacteria involved in anaerobic digestion ([7])

Weiland (2010) identifies other facultative anaerobes taking part in anaerobic digestion like Streptococci and Enterobacteriaceae. Most of the bacteria involved in anaerobic digestion are strictly anaerobes. ([10]).

2.1.2.2 Factors affecting biogas production

Any biomass cannot be used for anaerobic digestion. Ones suitable for this process are chosen according to important factors: total solids content, percentage volatile solids, carbon to nitrogen ratio (C/N), biodegradability of feedstock. Gas yield is function of the hydraulic and solids retention times, pH, temperature of fermentation, loading rate, inhibitory effects of substrate compounds and intermediate products (ammonia, VFAs, hydrogen sulphide), toxicity of any feed or reaction products, degree of mixing/agitation and the presence of any pathogens ([7]). The most important ones affecting biogas yield are volatile solids, organic composition and bioavailability. Their respective description will be done below.

- ***Solid content and dilution***: Solid content in reactor must be between 10% and 25%. Solid dilution is made in such a way that slurry obtained allows gas flow upward.

- ***C/N***: Optimal carbon to nitrogen ratio is 20:30. Too high ratio implies rapid consumption of nitrogen by methanogens for protein formation and insufficient nitrogen remaining for reaction with leftover carbon. Too low ratio leads to liberation and accumulation of nitrogen as ammonia. Therefore, pH is increased and this has a toxic effect on methanogenic bacteria. Mixing materials is a solution for maintaining an optimal C/N as each material has its own C/N.

- ***PH:*** The PH value must be within the range between 6 and 7. At a pH less than 6, methanogenic bacteria cannot survive ([11]). During the first steps of the digestion, there is a decrease followed by an increase as the reaction progresses. Methane production is stabilized when the pH is typically 7.2 to 8.2. In the case of digester operating in batch mode, pH is adjusted by adding lime.

- **Temperature**: Digestion types are identified according to temperature. There are mesophylic, thermophylic and psychrophyilic digestion. Large scale anaerobic digestion is mostly mesophilic. Thermophylic digestion is more advantageous than mesophylic and psychrophylic ones. It has a faster digestion rate therefore small digester. However, it is not easy to control, investment costs are higher, extra energy inputs is required to maintain temperature

- **Organic loading rate:** This is a measure of the biological conversion capacity of the system. It determines the tolerable amount of volatile solids by a system. Quick overloading causes inadequate mixing, increased VFA content and lower pH, which are system failure proof.

- **Retention time:** This is the duration of contact in the digester of organic material (substrate) and microorganisms (solids) needed to achieve the desired degradation. Lower retention time than the one required increases reactor efficiency. Therefore, reactor volumes will be reduced. In some cases, retention time is from 40 to 100 days ([11]).

- **Toxicity:** mineral ions particularly heavy metals and detergents hinder normal bacterial growth. Minerals (sodium, potassium, calcium, magnesium, ammonia and sulphur) quantity must be low in order to stimulate bacterial growth. Heavy metals when low are essential for bacterial growth in very small amount but toxic when their amount is high. Therefore, digestates in that case are not proper to use as fertilizers. However, when the toxicity rate is high, dilution is a solution to reduce the toxicity level.

- **Mixing/Agitation:** Process is stable when fluid homogeneity is maintained. Mixing/agitation is applied during digestion for incoming material and bacteria combination, scum formation hindrance, strong gradient temperature avoidance within the digester. Mixing should not be either rapid to avoid pronounced temperature gradients or too slow to avoid short-circuiting**.**

- **Pathogens**: Anaerobic digestion feedstock must be free from pathogens to protect workers against infections. Pretreatment at 70°C for 1 hour is a solution to destroy certain pathogenic bacteria and viruses in MSW.

Operational Parameter	Formula	Description	Unit
Hydraulic Retention Time (HRT)	HRT = V/Q	HRT: Hydraulic retention time V: Reactor volume Q: Flow rate	days m^3 m^3 / day
Organic Loading Rate (OLR)	$OLR = Q \times S/V$	OLR: Organic loading rate Q: Substrate flow rate S: Substrate concentration in the inflow V: Reactor volume	kg substrate (VS)/ m^3 reactor and day m^3 / day kg VS/m^3 m^3
Gas Production Rate (GPR)	$GPR = Q_{biogas}/V$	GPR: Gas production rate Q_{biogas}: Biogas flow rate V: Reactor volume	m^3 biogas / m^3 reactor and day m^3 / day m^3
Specific Gas Production (SGP)	$\frac{Q_{biogas}}{Q \times S}$ or GRP/OLR	SPG: Specific gas production Q_{biogas}: Biogas flow rate Q: Inlet flow rate S: Substrate concentration in the inflow	m^3 biogas / kg VS fed material m^3 / day m^3 / day kg VS/m^3

Table 3: Main parameters for evaluation and composition of different AD system performances [9]

2.1.3. Biodigester

A bio-digester could be described as a structure, usually referred to as the biogas plant in which different chemical and microbiological reactions occur. In <other word, it is called bioreactor or anaerobic reactor of which primary function is to provide within it an anaerobic condition. It is a chamber that should be air and water tight. Diverse materials could be used in fabricating the digester chamber in different sizes and patterns. It is important to note that the investment cost for a biogas plant consists mainly of the cost of the constructing the digester chamber [12].

2.1.3.1 Types of biodigester

Many digesters exist. There are: single or multi-stage digesters, low-rate digestion (floating dome, fixed dome, balloon digester), large scale, low-rate digesters (covered lagoon, plug flow, fixed film, suspended media, anaerobic sequencing batch reactor), high rate anaerobic digesters (anaerobic continuously stirred reactor, anaerobic contact reactor) second generation high-rate digesters (up flow anaerobic filter, down flow stationery fixed film, up flow anaerobic sludge blanket, fluidized bed/expanded bed), third generation high rate digesters. The following section discuss about the selected anaerobic digesters in developing countries.

❖ Total solid content (wet/dry systems)

Rate of TS content of the substrate fed into an AD system allow considering a digester system wet or dry. A digester fed with a substrate with TS content less or equal to 16% is qualified wet while bioreactors filled with substrate with a TS content of 22 and 40% are respectively semi-dry and dry [25]. Compared to wet anaerobic digestion systems, dry systems are better since they require a smaller reactor volume, lower energy requirements, and minimal material handling efforts [13]. Operating temperature (mesophilic/thermophilic)

Anaerobic digestion systems based on temperature are categorized into three categories: psychrophilic (below 20°C), mesophilic (30-40°C) and thermophilic (45-60°C) systems. Thermophilic digestions systems facilitate faster reaction rates, faster gas production and hygienisation of the digestate compared to psychrophilic and mesophilic digestions. However, thermophilic digestions are expensive due to additional cost for energy input to heat digesters. A location with a specific climate should use a digester which temperature of operation close to the temperature in the region. Hence, in developing countries with a tropical climate, digesters operate in the range of mesophilic temperature.

❖ Feeding mode

Digester geometry with others components evolve without ceasing. This evolution observed is due to the search for efficiency improvement, simplification of operation and maintenance, suitability of operation under different temperature regimes. Thus, digesters are classified into three feeding modes which are: batch, semi-continuous and continuous modes [13].

➢ ***Batch fed digesters***

In batch fed digesters, the reactors are periodically filled and discharged [14].

The feedstocks used here are fruits, vegetables, straw, animal dung, human excreta and municipal organic waste. Temperature of operation of batch digesters is in thermophilic range of temperature. Dry anaerobic digestion principle uses batch feeding mode for in batch fed digesters the total solid concentration is high (greater than 15% TS). Advantages of batch fed digesters are high biogas production due to high retention time (30 to 180 days) [15], less space occupied therefore applicable in urban areas where space is an issue, very cheap and affordable for households [16]. Nevertheless, reduced size of digesters limit the quantity of biogas produced and stored. Besides, operation and maintenance of batch digesters is laborious, dangerous at the end. Regular closure and opening after each batch sequence require gastight sealing of inlet/outlet which may result in biogas losses and the risk of explosion as residual methane in the reactor mixes with air when emptying. [16]. Design of such digester is illustrated by the following figure 2.

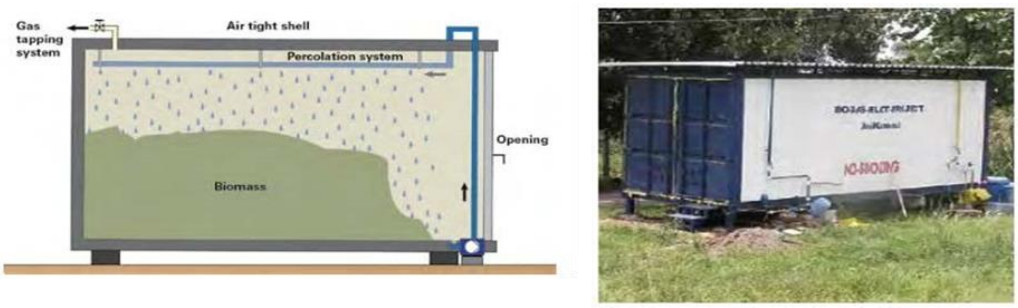

Figure 2: (left): Garage - type dry digestion plant. (Right): Dry digestion pilot plant at KNUST, Kumasi, Ghana ([16])

➢ ***Semi-continuous fed digesters***

In this category, the feeding mode is characterized by daily loading of the digester through an inlet and automatic discharge through the outlet of the slurry tank. One or more feedstock can be used in such digester which operates within mesophilic range of temperatures and at total solid of influent less than 10% of TS hence suites for wet anaerobic digestion. Compared to batch digester, semi-continuous fed digesters' retention time is low (10 to 60 days) as well as biogas production caused by lower process efficiency. Although the design of such digester is expensive for household, operation and maintenance is less laborious, require more space than batch type, this configuration is mostly found in developing countries. There are fixed dome, floating drums and tubular digesters operating on this feeding mode.

➢ **Fixed dome** digester

Fixed dome digester is a Chinese design. Also called "hydraulic" digesters they are mainly used in China ([34]) and now spread in sub-Saharan African countries for biogas production. This digester is fed through the inlet pipe. The bottom level of the expansion chamber is the limit to be reached by the feedstock. The storage part, upper part of the digester plays the role of biogas accumulator. Gas pressure is created because of the difference level between slurry inside the digester and the expansion chamber. After gas release, slurry is immediately sent to the digester. The geographical location, the availability of substrate per day, climatic condition and the number of households influence digester design [16].

Fixed dome digesters are mostly constructed underground. In China for instance, digester size range is from 6 to 10 m3 ([16]). In India the range is from 1 to 150 m^3 ([17]) and in Nepal ([18]), the range is from 4 to 20 m^3. In Nigeria, digester size of a household of 9 is about 6 m^3 ([18]). Community biogas digesters for 10 to 20 homes are better solution than individual ones especially in the case of clustered households as in Nigeria [19]. Fixed dome is found modified from the original fixed dome model in many countries. In india, janta (figure 3a) and Deenbandhu (figure 3b) models are example of fixed dome modification. Deenbandhu model is a modification of janta model designed in 1978 to reduce the price without affecting digester efficiency. Other fixed dome digesters are Chinese, Nepali GGC2047, Vietnamese designs and French types digesters which consist to surround the fixed dome by a steel drum containing biomass to avoid temperature losses [20]. Deenbandhu model is claimed to be the cheapest digester among others types of fixed dome. Gas storage of the fixed dome can also be covered by a plastic bag with a wood roof on top to protect the fragile plastic bag from solar radiation and increase the gas pressure by its weight ([20]). Generally, preferred feedstocks for fixed dome digesters are animal dung (pig, cattle, cow, etc). Also, digesters size of 4 to 10 m^3 are used by households while size greater than 10 m^3 are suited to community (schools, hospitals, prison).

➢ Floating drum digester

Firstly, developed by KVIC (Khavic & Village Commission) in India and standardized in 1962 (Charles Gunnerson et al., 1986). Biogas production with floating drum occurs at a constant pressure with variable volume ([20]). Figure 4 depicts sketch of floating drum digester. Regular paint of floating drum is necessary to avoid rust. Generally, underground floating drum consists in a cylindrical part (underground) and a moveable part above ground, the floating gasholder. Smaller household's scales are fully above ground. The materials used to construct this digester type are bricks, concrete, or quarry-stone masonry, then plastered. The moveable part, the gas-holder usually made of metal is coated annually with oil paints to protect it against corrosion. This part is the weak point of this type of digester which does not last longer and make operation and maintenance cost expensive compared to fixed dome. Well maintained metal gas holder last for 3 to 5 years in humid climates and 8 to 12 years in dry climate. Hence to improve gas holder durability, it is necessary to use fiberglass reinforced plastic or galvanized sheet metal ([21]).

- *Continuous fed digesters*

Here, load and discharge of digester occurs continuously. They operate only on one type of feedstock, reason why they are also called mono feedstock, under mesophilic range of temperatures and at a low total solid of influent (less than 10 % TS). Retention time and biogas production are lower than batch digesters. Its configuration requiring separation of gasholder from the digester makes it application inappropriate in developing countries.

- Configuration of digester design

According to fresh effluent interaction with the older content of the digester, two typologies of digesters are identified: plug flow and complete mixed digesters [10] *Plug flow or tubular digesters.*

Biogas is produced through plug flow digesters with constant volume at variable pressure. Plug flow digester size varies from 2.4 to 7.5 m^3. Figure5 shows its geometry composed of a narrow and long tank with an average length to width ratio of 5:1. Inlet and outlet pipes positioned at opposite ends are kept above ground and the remaining part is buried in the ground in an inclined position. The inlet welcomes fresh feed substrate. The outlet is an exit for digester flowing towards its position. Process temperature stability is assured by shed roof placed on top of the digester to cover it thus acting as insulator during days and night [22, 23].

The only point of interaction between the fresh influent and the older digester content is around the surface area of contact. No mixture occurs. In this digester with a tubular form (also named tubular digester), the feedstock along the digester length is at different stages of decomposition. This results from displacement of the older digester content by the incoming fresh effluent. Hence, the different steps of anaerobic digestion are separated in such a way that methanogenic step occurs towards the outlet of the digester while hydrolysis and acidogenic phases take place close to the inlet of the digester. The principle followed in this configuration is considered as a transition between wet and dry anaerobic digestion principles for the system operate at temperature within mesophilic or thermophilic ranges and higher total solid content in influent (greater than 15% TS). With a retention time ranging from 1540 days and a feeding mode either semi-continuous or continuous, the horizontal configuration of the tubular digester is the most applicable in developing countries [23].

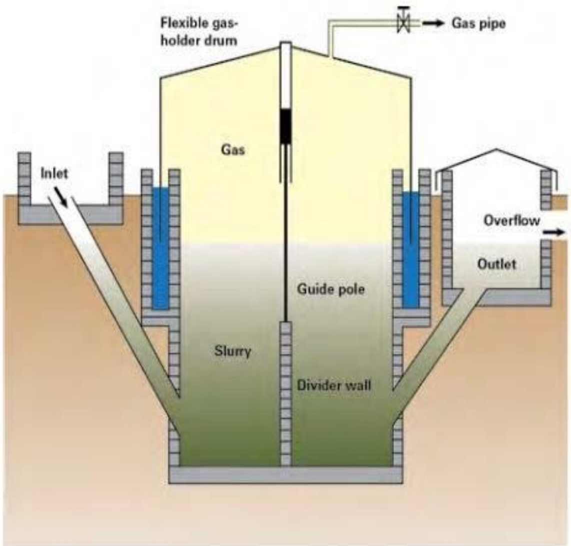

Figure 4: Floating drum digester [16].

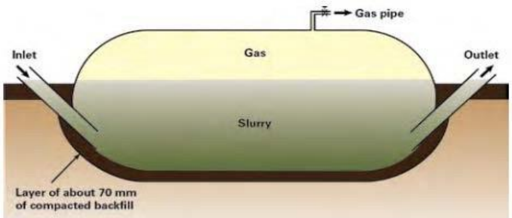

Figure 5: Scheme of plug-flow digester [17]

- ***Mixed digesters***

Fixed dome and floating drums digesters are based on this type of configuration where the incoming fresh feedstock and the older digester content are completely mixed. As plug flow digesters, the temperature of operation is within both the mesophilic and thermophilic ranges of temperatures, but the process principle here is wet anaerobic digestion principle (total solid of influent less than 10% TS). The feeding mode is semi-continuous for household's applications and continuous for industrial applications. The advantage of mixing here is complete bacteria population growth. However, the fresh influent may be lost without being completely digested when emptying digester.

- ***Leach bed digesters***

Leach bed anaerobic digestion principle is used in this configuration. The leach bed anaerobic digestion principle consists to load feedstock in the digester as a bed of solid, soak it where it is hydrolyzed. Volatile fatty acids (VFA) resulting from rapid decay of the feedstock forms are extracted into the water phase in the form of a liquor called leachate. This latter is ten recirculated or pumped into another tank where methanogenesis occurs to produce biogas. Existing variations of this kind of digesters are single or multiple staged with batch or continuous feeding mode operating on dry anaerobic digestion principle (high solid content of up to 60%TS). Some benefits of this digester design are absence of refine shredding of waste and mixing, possibility to operate at ambient, mesophilic and thermophilic conditions. The only disadvantage is negligence of development of this digester design for small scale applications in developing countries.

- Microorganism growth strategy

Suspended and fixed –film growth strategies are the main group of digester classified according to growth strategy criteria.

- ***Suspended growth strategy***

This growth strategy is the simplest growth strategy. The microorganisms are embedded within the feedstock without special accommodation for their growth. Microorganism grows with time until it reaches the optimum. Most digesters in developing countries use this growth strategy. Microorganisms are flushed out during digester discharge.

Fixed-film growth strategy

Specialized structures called biofilms serve as support for microorganism's growth. The interest in using biofilms here is to maintain the microorganism population at an optimum in order to improve the rate of biogas production. Time does not influence anymore microorganism population which does not vary* Number of stages

Single and multi-stage systems are hence specified to separate biochemical reactions that do not share the same optimal environmental conditions. Single stage is more appropriate and predominant system applied to full-scale bio-waste anaerobic digestion treatment compared to multi-stage systems. The reasons are the simplicity of the design, construction, operation and cheapness [49]. Single stage are mostly applied in small, decentralized waste management units while multi-stage digestion correspond to plants with a capacity of more than 50 000 tons/year.

2.2 Geomembrane Materials

2.2.1. Description

Geomembranes, or geosynthetics as barriers, are very low permeability coefficient polymeric sheets (typically $10^{-13}\ cm\ s^{-1}$1to $10^{-13}\ cm\ s^{-1}$) as shown in Figure 6. They are often used in current landfill liners. Geomembranes can be produced with smooth faces or textured ones and with different colors [24, 25].

Figure 6: (Left): HDPE geomembrane delivered in rolls [25]. (Right): HDPE geomembrane industry and site installation. [25]

2. 2.2. Brief history of geomembrane

Geomembranes started to be used in the 1930s, but became widespread in the 1940s. In the 1970s, geomembranes began to be specified for landfills. HDPE geomembranes started to be used first in Europe and South Africa, and then later on moved to North America. Initially, they were used in canals, and their applications then spread to Russia, Taiwan, Canada, and Europe. In the 1980s, HDPE geomembranes were famous for their high chemical resistance and for being thermally welded. The use of HDPE geomembranes in municipal landfills and the hazardous waste industry has advanced since 1985, mainly due to the high strength and low cost of the product. Nowadays, HDPE geomembranes are the most utilized component of the liner solutions in the world [24]. Although quite subjective, current geomembrane application areas can be observed in three categories: transportation, environmental, and geotechnical.

2. 2.3. Uses of Geomembrane Liners

Geomembranes are used in many situations and in different types of construction sites and structures, such as [26]: Solid waste landfills and industrial waste; Water ponds and waste liquid ponds; Waterproof liners with tunnels; Under highways; Farm ponds; Covers and subsoils of buildings; Raised or buried water tanks; Adduction and irrigation canals; Pools and artificial beaches; Vertical walls for contaminated areas.

Geomembranes are exposed to different aging mechanisms, including UV degradation, extraction degradation, thermal degradation, swelling, oxidative degradation, and biological degradation. These mechanisms can influence the material properties and even decrease their durability [27].

2. 2.4. HDPE Geomembrane Liner

High density polyethylene geomembranes are formulated with 96-97.5% polyethylene, 2-3% UV protection, generally carbon black, and 0.5-1.0% antioxidants and thermostabilizers [28]. This product exposed to aging can experience property changes due to molecular chain scission, crosslinking and bond breaking [29]. The polymer polyethylene (PE) can be defined as polyolefin which has the hydrocarbon group containing carbon and hydrogen atoms in the chemical structure. The density of polyethylene influences the physical and mechanical properties. There is a relationship between density and different PE properties, as shown in figure 7.

2.3 Good practice of HDPE geomembrane installation

In addition to excellent resin, a suitable additive package, good industrial process ability, good manufacturing quality control, satisfactory material specification for applications and good installation practice must be specified and supervised in the field by the designer. The implications of bad installation procedures can lead to a short-term service life of high-density polyethylene geomembranes. In Brazil, there is a technical standard [30] and a technical recommendation [25] concerning geomembrane installation practice. Both documents include the importance of the type of application to protect the product and good workmanship such as proper welding equipment, field seam testing, destructive seam testing, and avoiding damage and stress concentration in the product.

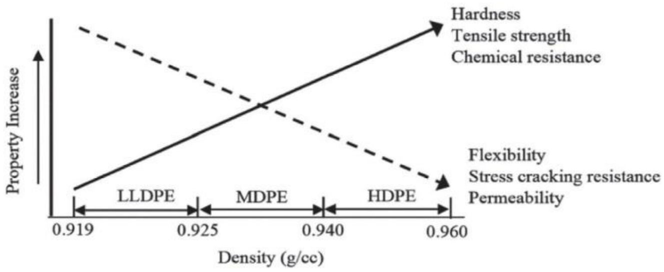

Figure 7: Material properties related to PE density

3- **Material and methods**

This section shall present the general designs, ways, the materials which includes the experimental milieu, and the methods used in fabrication of the HDPE geomembrane bio-digester. It shall also put in evidence the characteristics and quality control procedures of the said bio-digester.

3.1. Design

3.1.1 Description.

We use the tubular biogas plant design to configure the bio-digester considered here. This plant consists of a longitudinal shaped heat-sealed, weather resistance plastic balloon that served as digester and another section of it as gas storage. The gas is produced in the digester and convey through tubing to the gas storage. The inlet and outlet are attached directly to the skin of the balloon. This system does neither have any stirring device nor a pump, just from its longitudinal shape, active mixing is limited and digestate flows through the system in a plug-flow manner. To achieve a required usage pressure, sand bags are placed on the storage bag taking into consideration its material. We had used AutoCAD MEP 2016 and sketch up 2020 computer software for the designing of the model. Figure 8 shows the designed model.

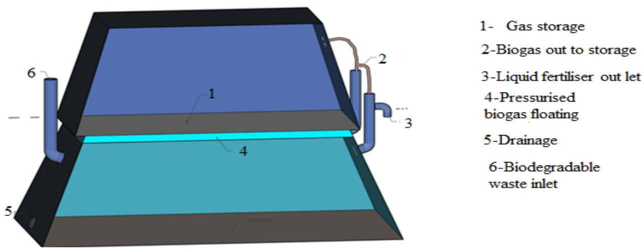

Figure 8: Biodigester model

3.1.2. Parts of the Bio-digester

The above Fig 8 shows that the bio-digester has two (02) main parts; the digester and the gas storage.

3.1.2.1. The Digester:

This is the section where anaerobic digestion process takes place. It contains the mixed water and feedstock matter. It has an inlet of Ø 100, well designed to permit waste entering into the digester and prevents biogas from escaping through it. Another part is the drain access point also in Ø 100, where the system can be drained either for maintenance or displacement purposes. Furthermore, the outlet of the system which provided access for digested liquid to flow out while prevents the escape of biogas into the air. Lastly, it’s the gas collector pipe which gives access to trapped biogas in the digester to flow to the gas storage tank.

3.1.2.2. The Gas storage:

This is the section in the system where biogas is stored prior to usage. It was constructed with a 1.5 mm HDPE geomembrane liner. It has just an inlet to gas flow which permits the gas to flow to and fro. The storage was also equipped with sand bags pockets which help to pressurize the system for adequate and required gas pressure for gas burners.

3.1.3. Design Considerations/Parameters

As each situation differs in terms of e.g. gas requirement or available feeding material, a unique bio-digester size could be calculated for each household. For larger dissemination programs, however, this would be impractical. Therefore, most such programs work with a limited number of plant sizes that are expected to cover the demand of (most) households. Although size calculations can become very complicated, for domestic application the following parameters suffice to arrive at the practical size of the bio-digester.

The table 4 summarizes the values of the main design parameters. As the aim is to develop a bio-digester size range, the hydraulic retention time is applied as a minimum and maximum value

Parameter	Explanation	Values used
Waste / water ratio	Theoretically, the waste / water ratio depends on the total solids (TS) concentration of the waste, whereby optimum fermentation results are claimed at 6 to 7% TS. The TS of waste varies considerably, for livestock in development countries TS values in the 10 to 15% (cattle) and 15 to 20% (pigs) range are reported [29]	The TS values suggest a waste / water ratio of a little under 1: 1 for cattle dung and 1: 2 for pig dung. For practical reasons. A 1 : 1 ratio has the advantage that households can easily measure the amount of required process water.
Specific gas production (SGP)	The specific gas production of dung depends on the type and quality of dung.	For cattle, typically 1 kg of dung fed to a digester produces about 40 litters of biogas per day. Values for other substrates will differ; pigs, poultry and human excreta typically have higher yields.
Minimum gas production (GP_{min})	Depending on construction costs and gas demand pattern, below a certain nominal gas production the investment becomes uninteresting for the household.	One cubic meter of biogas daily will render 2.5 to 3.5 stove hours. This could, depending on family size, suffice for e.g. breakfast and lunch preparation, and would then provide a meaningful contribution.
Hydraulic Retention Time (HRT)	The hydraulic retention time (HRT) is the period the waste/water mix fed to the installation remains in the plant. As the fermentation process works better at higher ambient temperatures, installations in warmer climates can work with a shorter HRT and vice versa. As a longer HRT requires a larger digester volume, plants become more expensive to construct.	Typical HRTs for domestic (simple) biogas plants are 40 to 60 days for warm climates and 50 to 75 days for temperate climates.
Gas storage volume	Biogas is generated more or less continuously, but consumption in households typically takes place during 3 or 4 periods during the day. The generated gas needs to be stored in the installation.	For the gas storage volume, a fixed share of the maximum amount of daily generated gas, 60% is taken

Table 4: Designed parameters. (see [31])

3.2. Materials

3.2.1. Experimental phase

To achieve our objective, we purchased the HDPE geomembrane liner online from Nigeria. While waiting for the material to arrive, we proceeded to creating a 300 litters mini size of the digester with PVC black tarpaulin of 200 microns, a similar material to geomembrane. From this mini model, we carried out experiment on how the said bio-digester of HDPE geomembrane would be fabricated and preceded to laboratory analysis of the gas produced from the digester and equally with the organic liquid fertilizer. The greatest part of this work was carried out in two main laboratories, the Civil engineering laboratory in ENSET DOUALA and the BiogasCAM international laboratory in Buea, south west region of Cameroon.

- **The Civil Engineering laboratory in ENSET**
  It disposes different apparatus/equipment for the treatment and analysis of data. In this laboratory, we fabricated the various parts of the bio-digesters and proceeded with air test to ensure the systems were air and water tight. We also determine the density of the input (slurry) to the digester.
- **The BiogasCAM International laboratory in Buea, South West region Cameroon.**
  It is located in a village in Buea called upper Bonduma, with PO box 464; LBE/2018/B/130. There at Buea, we gave samples of the digestate from the digester for quality control of NPK. The gas produced from our experimental mini digester was also tested there for prove of methane gas contain. For the organic liquid fertilizer, via BiogasCAM we had access to the Clinique Poitier Chemical laboratory located at Bessengue Douala-Cameroon, were a team of laboratory experts analyzed the organic liquid which we claimed to have fertilizer potential.

3.2.2. Materials for the fabricated bio-digesters

3.2.2.1. Descriptive list of materials

After designing and describing the bio-digester, with the aid of computer modeling, we could come out with a quantitative estimate. The table 5 describes the list of materials needed for the fabrication of a 3 m^3 HDPE geomembrane bio-digester.

Ref	Items	Description	Quantity
01	Pipes	PVC Ø 100 Pressure Pipe	1 Length
		PVC Ø 100 Flexible Gas Pipe 3/4"	1 Roll
02	HDPE Geomembrane	HDPE Geomembrane Black 1.5mm Liner	42 m^2
03	Elbows	PVC Ø 100 90° Pressure Type	2
		PVC Ø 100 45° Pressure Type	4
04	Glue	PVC Pipe Glue (Tube Type)	2
		HDPE Resin (Carton Type)	1
05	Gas	CAMPI Gas (Tin)	1
06	Plugs	PVC Ø 100	4
		PVC Ø 125	1
07	Reducers	PVC Ø 100 × Ø 63	1
		PVC Ø 125 × Ø 100	1
		Compressor Reducer Ø 20 mm × 16 mm	1
		Copper 3/8" x 1/2"	1
08	Stop Valves	Compressor Type Ø 20 mm	4
09	Tees	PVC Ø 100 Tee Pressure	1
		Compressor Tee Ø 20 mm (IMF)	3
10	Sockets	Compressor Socket Ø 20 mm	3
		Compressor Nipple Ø 20 mm	2
11	Stove	Gas Stove (One Side/Single)	1
12	Reducer	Copper Reducer 3/4" x 1/2"	2
13	Connectors	Tank Connector 1/2"	3

14	Monometer	Digital Pressure Gauge 0-10 bars	1
15	Teflon tape	50 m White tape type	1
16	Sand paper	Paper 60	1 m

Table 5: Quantitative description of estimate for biodigester

The same materials were required for the 300 litters tarpaulin prototype bio-digester except for the PVC pipe and fittings which were reduced to Ø 63 mm and instead of a geomembrane liner, a black tarpaulin of 200 microns was used.

3.2.2.2. List of Equipment used for the fabrication process

The tools and machines given in Table 6 were used for the realization of the bio-digesters.

Ref.	Equipment	Usage
01	Portable hot air gun	It provided the required heat needed for seaming of the HDPE geomembrane liner. Used for plastic welding.
02	Blow lamp	It provided fire for heating pipes. Used to create sockets in pipes.
03	Electric cutting edge	An electrical knife used for cutting geomembrane liners.
04	Hack saw	Used for cutting pipes
05	Measuring tape	Used for measurement
06	Pipe wrench	Used for tightening fittings
07	Adjustable plier	Used for gripping fittings
08	Scissors	Used for cutting light flexible materials
09	Computer	For programing and designs
10	Pressure roller	Work together with the hot air gun, Used to apply pressure on the heat affected zone.

Table 6. List of equipment and their uses

3.3. Methods

This part regroups the set of procedures which permitted the fabrication of the experimented 300 litters tarpaulin prototype digester and the 3000 litters HDPE geomembrane digester.

3.3.1. Fabrication Process/Procedure

3.3.1.1. Prototype 300 L Tarpaulin bio-digester

To come out with this system, we started out by sketching the desired plan on AutoCAD as shown in Figure 9. The next process describes the creation of the various inlets and outlets with PVC pressure fittings of diameter 63 mm. After creating the various provisions to the system, we seam them to the body of the digester using hot air gun machine. Then various parts of the digester are joined together using special heating machine and specific glues to enable the complete structure to stand upright. After seaming the storage, we coupled all the parts together and came out with what is seen in Figure 10.

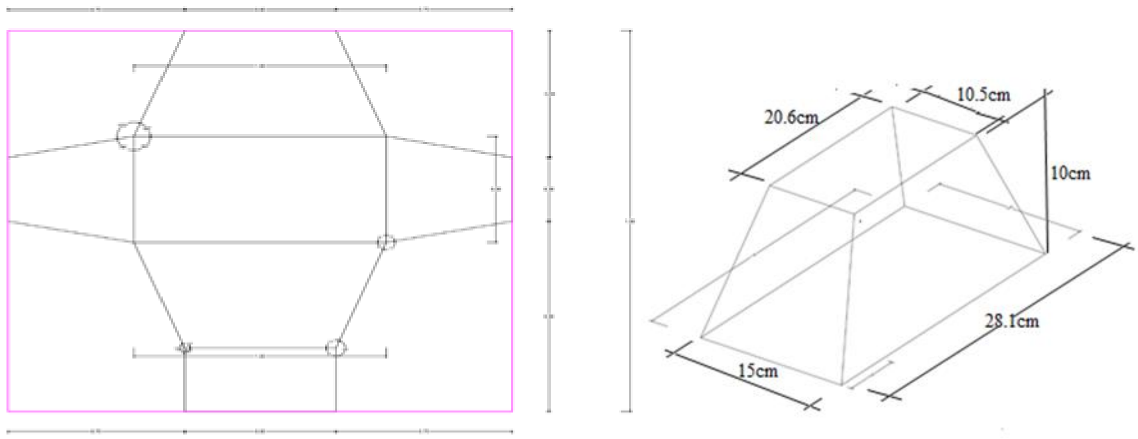

Figure 9: (Left) Geometric design of the Tarp digester , (Right): Perspective view

Fig 10: Complete 300L prototype bio-digester ready for feeding

3.3.1.2. 3000 L HDPE Geomembrane biodigester

A similar thing is done with the HDPE 1.5 mm geomembrane material, except that its parts are not like those of the Tarp digester, its part are larger and make it difficult for seaming. Nevertheless, we had sophisticated equipment to ensure leak free parts and joints. The figure 11 describes the dimensioned perspective and plain views of the HDPE digester section. Due to the nature and length of the HDPE material 3m high, we had to redesign the plain view to suit the length of the material and for quick and simple joint formation. It should be noted that the jointed areas of the member are the weaknesses of the system therefore many joins should be avoided

The next design represents the HDPE gas storage unit. From the previous calculations, the gas storage was estimated to be 60% of the digester but after installing the 300 litters Tarp biodigester, we realized that the 60% gas storage previewed theoretically was not practicable due to the rapid gas generation from the digester. After cutting the required design, we proceeded to marking the various inlet and outlets to the system.

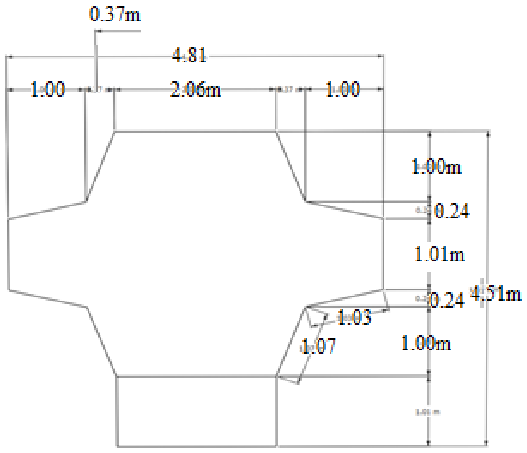

Fig 11: Plain View of the digester

3.4. Determination of the quality of the bio-digester

This section describes the type of substrate used for the formation of biogas and the liquid organic fertilizer obtained from the process. It also encompasses the various test methods used to determine the strength of the various digesters and gas reservoirs. Lastly it describes the numerical analysis of the HDPE geomembrane bio-digester.

3.4.1. Prototype 300L bio-digester.

After the construction of the 300L prototype bio-digester, we proceeded to testing it for leakages before putting biodegradable waste into it. The figure 12 shows the various testing that were done to ensure a leak free bio-digester

Fig 12: (Left) Water Tight test on Gas Storage. (Right): Mounted system after various test.

3.4.1.1. Feeding the 300 L prototype bio-digester with waste.

To feed our digester, we used the following formula:

HRT = V/Q (16)

Where: HRT is the hydraulic retention time in days, V the reactor volume in m^3, and Q the flow rate in m^3/day

We used a HRT of 60 days, V=300 L, therefore Q=5L/day, then at initial, the system requires 300 L of waste. From the laboratory, we could determine the water to waste ratio, figures 13 and 14 show the laboratory experiment. For a homogenous mixture of a kilogram of cattle waste, we had 4 litters of water, making it 1:4, with a density of 966 kg/m^3. Therefore, for our system of 300 litters, we required 75kg of cattle waste.

Fig 13: Measuring cattle waste

Fig 14: Homogenous mixture of waste and water (1:4)

3.4.1.2. Collecting data after HRT of the digester

Fig 15: (Left): Prototype bio-digester after HRT; (Right): Gas sample collection.

Fig 16: Sample of the liquid fertilizer.

After the retention time of 60 days, we collected samples of the gas produced and the organic liquid fertilizer for laboratory examination. Figure 15 (left) shows the state of the system after its hydraulic retention days. Sample of the gas was collected using a mini balloon as seen in Fig 15 (right), while Fig 16 shows the organic liquid fertilizer collected from the system for examination.

3.4.2. HDPE Geomembrane 3000 L Biodigester.

3.4.2.1. Quality of joints:

The joints were professionally designed and realized with seam from hot air gun, as shown in ***Fig 17a,*** the procedures used to realize the joints and followed by a vivid test to ensure the solidify of the system. In the first step, the membrane is welded in first pass using heat from hand weld hot air device and pressure with the hand. In the second step, the weld continues in the mid-portion of the overlap in a manner similar to that in step1. Finally in step 3, the weld is finalized by continuing application of heat and sealing edge with roller.

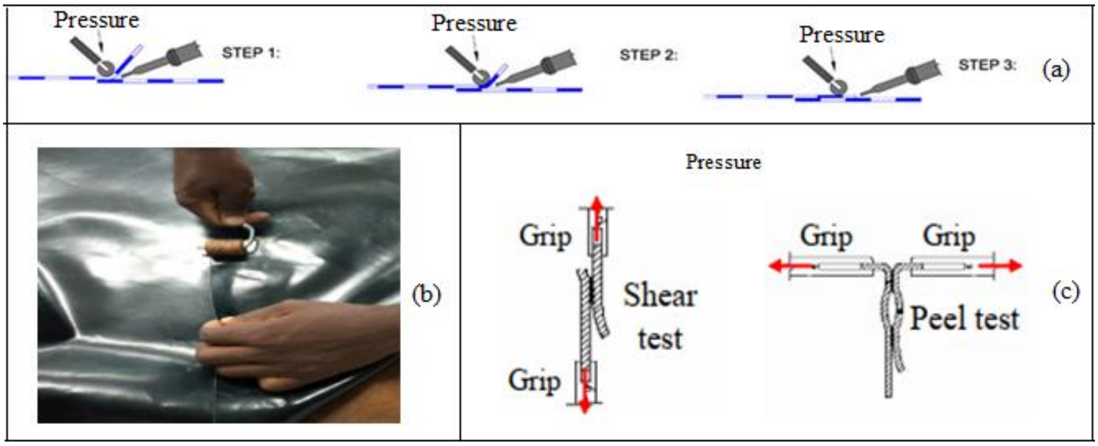

Fig 17: (a); Seam hot air welding process. (b): Jointing Process, (c) Type of test carried out

3.4.2.2. Quality of air tightness of the digester and storage unit :

The digester and storage units were equally tested for leaks despite the excellent quality of the joints. For this section of testing, we used a fridge compressor to pressurize the system and with soap test, we verified all the joints.

3.4.2.3. Numerical Analysis of the HDPE Geomembrane Bio-digester

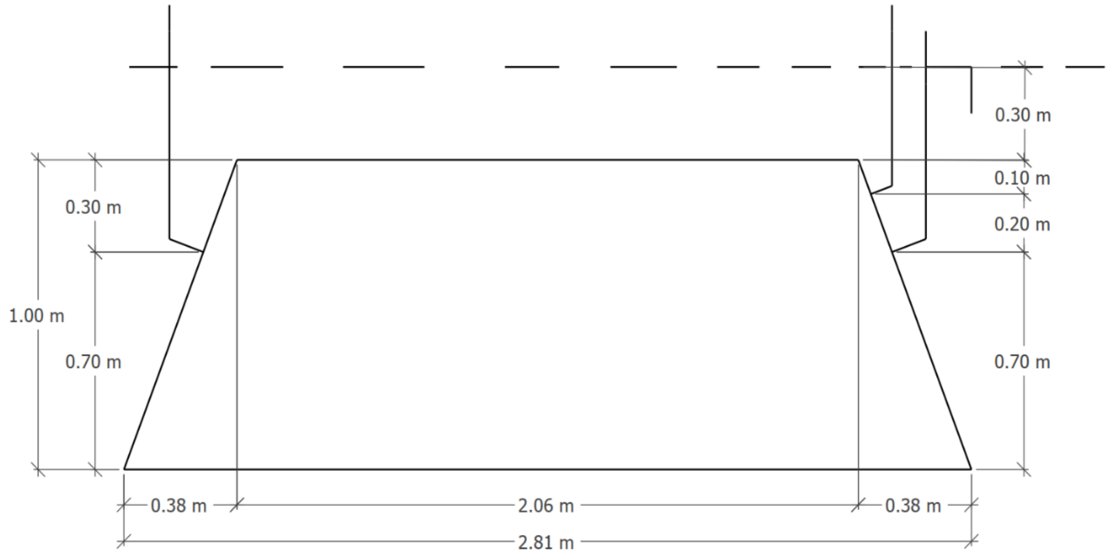

Fig 18: Digestion section

- **Component of the stress F:**

Considering the system full with waste before gas production,

the pressure $P = \frac{F}{A}$, leading to $F = \int PdA$ and

$F_x = \int_A \rho g w(z) z\, dz$ (17)

With, the constraints: w(0)=1m, w(1)=1.5m, leading to w(z)=1+0.5z leading Eq(17) to

$F_x = \int_A \rho g(1 + \frac{1}{2}z) z\, dz$. (18)

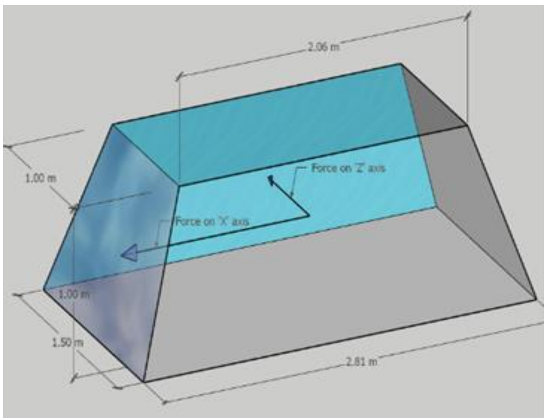

Fig19: Digestion perspective dimensioned view

For $\rho = 966\ kg/m^3$ *and* $g = 9.81\ m/s^2$, one has $F_x = \rho g\left(\frac{h^2}{2} + \frac{h^3}{6}\right) = 6317.64N \approx 6.3KN$. For the z direction, one has $F_z = \int_A \rho g w_1(z) z\, dz$ With the constraints $w_1(0) = 2.06m, w_1(1m) = 2.81m$, therefore $w_1(z) = 2.06 + 0.75z$, leading to $F_z = \rho g\left(\frac{2.06h^2}{2} + \frac{0.75h^3}{3}\right) = 121229.87N \approx 12KN$. (19)

The force acting on the y axis is neglected it since the digester is supported by the ground. The main forces causing deformation on the system are the force on the x and y directions, F_x and F_z respectively as shown in Fig 19.

- **Determination of the deformation** ε **:**

The Young modulus $= \frac{\sigma}{\varepsilon}$. Solving for circumferential stress: considering the system taking a cylindrical shape, the figure 20 shows the reaction $\sigma_z = \frac{F_z}{A}$. From the equilibrium condition, one has $\sum F_z = 0$, that is $P(2r)dz - 2\left(\frac{F}{2}\right) = 0$, leading to $F = 2Prdz$. Since $A = 2tdz$, one has

$$\sigma_z = \frac{Pr}{t} = 1593.62KPa = 1.6MPa \quad (20)$$

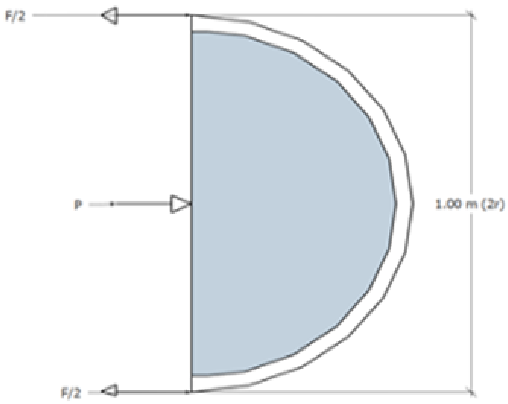

Fig 20: Hoop Stress

It is then obvious that $\varepsilon = \frac{\sigma}{E}$
where the Young modulus $E = 0.8\ GPa$ for HDPE, therefore $\varepsilon_z = 0.002$

- Longitudinal or axial stress is usually half the hoop stress: $\sigma_x = \frac{Pr}{2t} = 08MPa$ and $\varepsilon_x = 0.001$. Solving for Pressure when biogas starts producing**:** The fig 18describes the status of the digester when it starts producing gas.

- **Pressure at the bottom of the tank:**

$P_{Bottom} = PG_{out} + 0.9\rho_{waste} g$ (21)

Solving for PG_{out}:

$PG_{out} = \frac{nRT}{V_{out}} + 0.3\rho_{waste} g$ (22)

Density of biogas is $1.15\ kg/m^3, Vout = 0.17m^3, R = 8.31441, T = 29^0C + 273$, therefore

$PG_{out} = 183317.6Pa \approx 183.32KPa$ (23)

Considering density of waste to be 966 kg/m^3, the pressure at the bottom, $P_{Bottom} = 183317.6 + 966 \times 9.81 \times 0.9 = 191846.41Pa \approx 192KPa$. Note: $g = 9.81\ m/s^2$. We also assume the gas to be perfect, and that atmospheric pressure is neglected.

- Solving for security pressure level PGs: The height for the gas to attain a security level state in the digester is at 0.30m (30cm) from the top of the digester. Therefore, the pressure, $PG_s = \frac{nRT}{V_s} + 0.6\rho_{waste} g$, where $V_s = 0.58m^3$ (24)

Leading to $PG_s = 186160.54Pa \approx 186.16KPa$. This value was used to design a security valve which will prevent gas from being ejected out through the waste out let or through the waste inlet of the system.

4- Results and discussion

This is the third presents and treats results obtained from the design, fabrication of the HDPE geomembrane biodigester and the quality test evaluation of the biogas and organic liquid fertilizer obtained from the prototype bio-digester.

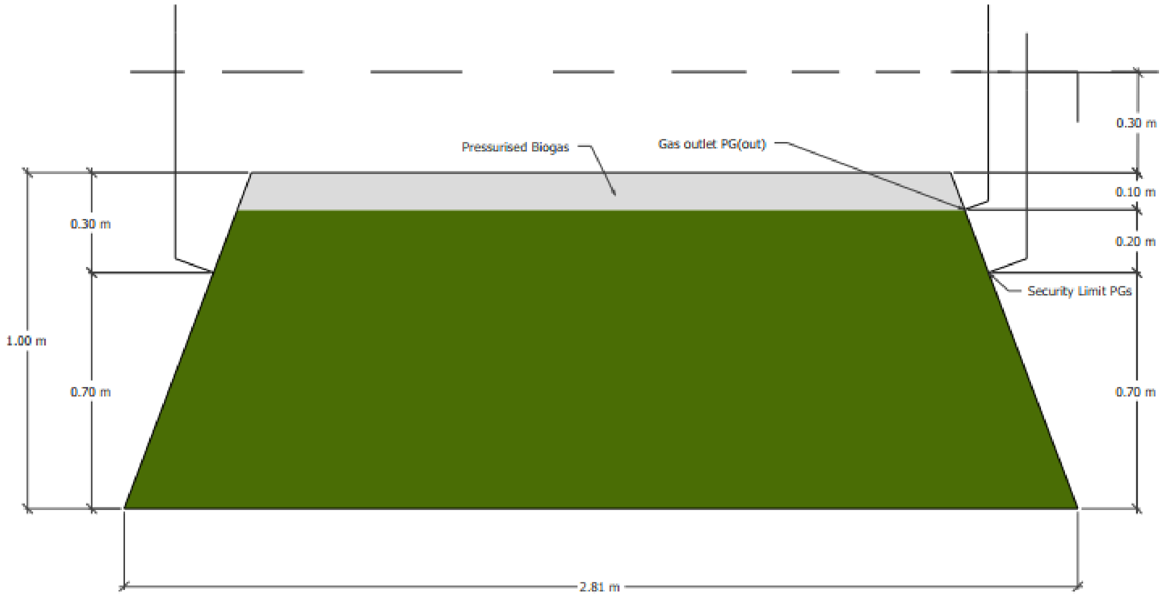

Fig 21: Digester during production stage.

4.1. Fabrication protocol

In order to fabricate a hermetical HDPE geomembrane bio-digester, we required a prototype which will aid us to investigate the form (design), jointing techniques, hydraulic retention time, gas production process and the quality of the liquid organic fertilizer.

Fig 22: Prototype (left): At day 1 after feeding, (right): After 60 days

This prototype has a digester capacity of 300 litters with a 150 litters gas storage. Both systems were tested for both water and air tightness and they were successful. It produces an average of 40 litters of biogas daily while receiving 5litters of waste (1kg of solid waste mixed with 4 litters of fresh water) daily. From the success of the prototype, we fabricated the HDPE geomembrane bio-digester.

4.2. Characteristics of the biogas obtained from the prototype:

At BiogasCAM, experts used various chemical technologies to determine the following properties of the biogas sample.

	Components	Symbol	Concentration (Vol-%)
Chemical properties	Methane	CH_4	55 – 70
	Carbon dioxide	CO_2	35 – 40
	Water	H_2O	2 (20 °C) – 7 (40 °C)
	Hydrogen sulphide	H_2S	20 – 30 ± (2 %)
	Nitrogen	N2	< 2
	Oxygen	O2	< 2
	Hydrogen	H2	< 1
	Ammonia	NH_3	< 0.05
physical			
	Colour	Colourless	
	Flame	Blue flame with little or no carbon	
	Odour	Rotten smell (like bad egg)	
	Density	1.15 kg/m^3	

Table 7: Typical composition of biogas sample from waste

Fig23: Burning test of biogas from prototype digester.

4.3. Organic Liquid Fertilizer:

Fig 24: Liquid organic fertilizer in laboratory (BiogasCAM

During laboratory analysis, two distinct samples were analyzed: the liquid digestate (LD) and another part of it which was dewatered called dry digestate (DP). All digestate samples were obtained using the composite sample technique: more than 5 subsamples (approx. 1.0 kg) were collected and mixed in order to obtain a composite sample. A subsample was analyzed according to the European methods for fertilizers. Dry weight and ashes were determined as weight residue at 105°C and 550°C, respectively. The pH was measured in the water extract (3:50 w/v) after 30 min of shaking at room temperature (RT). The electrical conductivity was determined in the filtered water extract (1:10 w/v) after 30 min of shaking at RT. Total organic C was determined by wet oxidation with potassium dichromate. Total N was measured, after wet acid mineralization, using a Kjeldahl distillation instrument [34]. The ammonium (NH_4^+) and nitrate (NO_3^-) N were determined after extraction with 1 M KCl (1:10 w/v) and steam distillation with magnesium oxide for NH_4^+ and reduction with Devarda alloy for NO_3^-). Total organic N was calculated subtracting the inorganic N to total N. Total P, S, and metals were determined by microwave wet acid digestion and by inductively coupled plasma optical emission spectroscopy. Available Cu and Zn were extracted with DTPA and determined by ICP-OES.

Table 8 shows the main characteristics of DL and DP digestates. As expected, the total solids (or dry weight) content was lower in DL than DP. Conversely, the ashes (on DW basis) were higher in DL than DP, therefore the DP had a higher content of volatile solids (or organic matter) than DL. These results are in agreement with the productive process of digestates: the DL process concentrates the soluble salts (increases the ashes and decreases the volatile solids), while the DP process concentrates the organic matter (increases the volatile solids and decreases the ashes). The pH was alkaline in all digestates and resulted highest for the DP (9.75, Table 8). Total organic C (on dry weight basis) in both digestates was ranging from 36 to 42% in the DL and DP, respectively; the total N was higher in DL (8.4% DW) than DP (2.0% DW), the C/N ratio resulting <5 for DL and >20 for DP. In DL half of total N was present as NHþ$_4$ (4.4% DW), while in DP the inorganic forms of N were negligible, and organic N was higher than 85% of total N. For all the other total macronutrients such as P, K, magnesium (Mg) and Sulphur (S), the DL showed higher content than DP.

properties	Digestates		Initial waste(Cow dong)	properties	Digestates		Initial waste(Cow dong)
	Liquid (DL)	Pellet (DP)			Liquid (DL)	Pellet (DP)	
Dry weight (% FW)	8.8	89	92.1	Total MgO (% DW)	3.6	1.4	1.1
Ash (% DW)	39	18	28.8	Total SO_3 (% DW)	3.4	1.2	1.8
pH (water)	8.77.	9.75	7.1	Total Fe (% DW)	0.25	0.29	0.46
Total Organic C (% DW)	36	42	33.9	Total Cd (mg/kg DW)	0.1	0.4	<0.1
Total N (% DW)	8.4	1.97	3.21	Total Cr (mg/kg DW)	10	16	34
NH_4^+ N (% DW)	4.4	0.04	0.44	Total Cr_{VI} (mg/kg DW)	<0.2	<0.2	<0.2

NH_4^+ N (% DW)	0.02	0.06	0.02	Total Cu (mg/kg DW)	10	59	91
Organic N (% DW)	4.0	1.87	2.75	Total Hg (mg/kg DW)	0.2	0.2	0.2
C/N ratio	4.2	22	11	Total Ni (mg/kg DW)	11	11	13
Total P_2O_5 (% DW)	4.3	2.0	2.8	Total Pb (mg/kg DW)	11	6	5
Total K_2O (% DW)	10.7	1.8	2.3	Total Mn (mg/kg DW)	360	218	402
Total Zn (mg/kg DW)	64	1.1	NA				

Table 8: Main Properties of the organic fertilizer

FW: fresh weight; DW: dry weight; cfu : colony forming unit; MPN: most probable number; NA : not analyzed.

4.4. HDPE geomembrane biodigester

After the realization of the prototype bio-digester, we proceeded to fabricate the 3000L HDPE geomembrane biodigester. During fabrication, we carried out some testes on the joints to ensure a water and air tight system. Fig 25 shows the complete fabricated bio-digester ready to be installed.

Fig 25: Successful HDPE geomembrane bio-digester ready for installation

4.4.1. Numerical analysis

From our calculations, the force acting by the side of the inlet and outlets was evaluated to be approximately to 6.3KN causing a longitudinal stress of 0.8MPa. As of the side of the system, we had a force approximately to 12KN causing a tangential stress of 1.6MPa. Comparing these values to the resistance test carried out, we observe that the system can support up to 21KN at the joints, making the bio-digester super fit for the quantity of waste that it will be receiving.

4.4.2. Pressure Evaluation in the system

The pressure at the bottom of the digester was evaluated at approximately 192 kPa equivalent to 2 bars. The gauge pressure which is the pressure required for the generated biogas to move to the storage unit was evaluated at approximately 183.32KPa. This pressure varies since the rate of gas production varies with temperature.

4.4.3. Security limit level

For the gas to attain a security level state, it means either the gas valve is closed or the gas storage is full or even a blockage in the gas network. Also, the gas in the digester must had attained a height greater than or equal to 30cm from the top downward. We evaluated the pressure to be approximately greater than 186.16 kPa for such to occur. For safety reasons, we designed a security system in function with the security limit gas pressure. The functioning principle of this security valve is the same as that of a pressure reducing valve. This valve permits fluid to pass through it only at a pressure of 186 kPa. This valve is linked to a piping network that leads to the roof top.

Note: These numerical values are mere theories and in reality may differ due to the many assumptions we took such as assuming that the gas is perfect, considering our calculations the number of moles to be of methane. Due to this factor, during installation of this system, numerical values should be taken from the pressure gauge after the system is subjected under pressure by closing the gas outlet. This practical value will be used to adjust the security valve or better still install a pressure relief valve.

4.5. Discussion

4.5.1. Environmental impact of the HDPE Geomembrane Bio-digester.

The environmental aspects of this bio-digester can be considered risky or beneficial to the environment.

- **The reduction of firewood consumption and soil erosion:** The use of this bio-digester system will play a vital role in the global struggle against global warming. It reduces CO_2 emission from burning fossil fuels in two ways: Firstly, biogas is a substitute for natural gas or coal when cooking and for fossil fuels for heating, electricity generation and lighting. Secondly, the use of effluent and digestate from the system reduces the consumption of artificial fertilizer (synthetic fertilizer) and thus avoids CO_2 emissions from fertilizer producing industries. Providing an alternative to firewood as a fuel source helps reduce deforestation and degradation of ecosystems as it sustains the capability of forests and woodlands to act as a carbon sink (Mangrove forest).
- **Reduction of greenhouse effect:** Methane is itself a greenhouse gas with a "greenhouse potential" 21 times higher than CO_2. Converting CH_4 to CO_2 (and water) through complete combustion is another way in which this bio-digester technology contributes to the mitigation of greenhouse gas emissions. This is however only valid in cases where the treated organic materials would otherwise undergo anaerobic decomposition thereby releasing methane to the atmosphere. Burning biogas also releases CO_2, but this only returns CO_2 which has been assimilated from the atmosphere by recently growing plants. There is therefore no net intake of CO_2 in the atmosphere from biogas burning as is the case when burning fossil fuels.
- **Methane escape:** As long as the bio-digester facility is operated correctly and no methane loses occur, the high greenhouse gas potential of methane production is not a problem. Burning biogas converts methane into carbon dioxide and water. Under certain conditions however, where high feeding rates are combined with low consumption or limited gas storage, biogas may escape directly through the security valve into the environment. In such cases where there is less consumption of the gas, the installation of biogas lamps together with clear operating instructions for the households will help mitigate the risk of biogas overproduction and losses. In addition, we made provision for the installation of a pressure meter which will inform households as to how much biogas is still available at the end of a day.

- **Ground water pollution:** Since the nature of material of the bio-digester is flexible, it may be exposed to vandal acts and may cause leakages which may result in slurry seeping into the subsurface. Although generally harmless, the discharge may pollute nearby water pits.

4.5.2. Economic Aspect:

The economic aspect of this bio-digester will depend on the amount of waste generate per unit and the daily fuel requirement for the unit, the table 10 describes the maximum and minimum waste requirement with the equivalent gas production with respect to the waste input.

Parameters	Units	Values
Gas storage volume	m^3	1.75
Digester volume	m^3	3.00
Min feeding	kg/day	25
Max feeding	kg/day	38
Min daily gas production	m^3/day	1.0
Max daily gas production	m^3/day	1.50
Average feeding		**31**
Average gas production	m^3/day	**1.25**

Table 10: HDPE geomembrane 3000L bio-digester production details in a warm climate

The minimum hour this HDPE geomembrane biodigester system can serve is approximately **5 hours daily**. Therefore, this proves that the system is economically feasible. Note that the minimum 5 hours of burning this will greatly depend on many factors especially the stove type.

4.5.3. Cost benefit analysis

The HDPE Geomembrane bio-digester will be cost benefit only when all it advantages related to cost are analyzed. Compared to other bio-digester systems which require so much money and time to construct, this system requires less amount of money and when all the materials required to fabrication are available, this system may take just two days to fabricate it compared for example to fixed dome type which might take two to three months before completion. Temperature control with this system is easy as compared to other methods.

- **Biogas benefit:** The total value of biogas is a function of the net amount available, the value of the fuel it replaces, and the conversion efficiency. Revenue generated therefore depends mainly on what energy source can be replaced by the biogas.
- **Benefit of organic liquid fertilizer:** In many studies on the economics of bio-digesters, the organic liquid fertilizer

value of the effluent is considered as a benefit. Accurate monetary appraisal of this value is however difficult, as the liquid fertilizer value depends on the type of storage, the climate or the practices and techniques of usage. Estimate on the financial benefits of this organic rich fertilizer used in agriculture can be obtained by assessing the costs of the substituted chemical fertilizer.

- **Benefit of proper waste treatment:** In our country Cameroon, the most common practice for the disposal of municipal solid waste is landfilling. By treating biodegradable waste in bio-digesters, a large portion of the municipal solid waste can be diverted from the landfill, thus saving space and extending the lifespan of the landfill. These cost savings can also be monetized. Furthermore, saving in transport costs to the landfill can also be estimated.

In addition to these direct benefits, indirect benefits such as less environmental pollution and improve living conditions can also be taken into account. However, as it is difficult to express these externalities in monetary terms, it still has an environmental benefit.

PART-2: KNOW-HOW TRANSFER

This study was able to explain the technics of locally fabrication of the low cost artisanal anaerobic biodigester, which can be used to decompose biodegradable waste. The anaerobic digestion of biodegradable waste can then be used for biogas and organic liquid fertilizer production in order to solve pressing development issues like food security, as well as clean energy capacity. Biogas production is an anaerobic digestion process whereby bacteria existing in oxygen-free environments decompose organic matter such as animal manure. Alternative or renewable energy, the methane CH4 can be generated from biodegradable wastes and used for the cooking of foots. Otherwise, the perfect organic liquid fertilizer produced can help improving agricultural production.

General conclusion

In the context of this research work which had as objective to design and fabricate a bio-digester with HDPE geomembrane material which will be effective in the recycling of biodegradable waste for the production of biogas and organic liquid fertilizer, the following conclusions were made: We succeeded to design a-digester and tested the design by fabricating a 300 litters prototype with a tarpaulin material. The system was fed with biodegradable waste and observed for a retention period of 60 days. From the success of the prototype, we fabricated a 3000 litters bio-digester. With sophisticated equipment, excellent joints were made and samples were examined and proven to withstand its contain. Numerically the system will produce an average of 1.25 m^3 of biogas daily and serve for a minimum period of 5 hours daily. Sample of the gas produced from the prototype including the rich organic fertilizer were examined and the gas physically was flammable with a rich blue flame while the effluent from the prototype bio-digester was a good organic fertilizer in terms of its chemical composition such as nitrogen (N),

phosphorous (P), and potassium (K), as well as the trace elements essential for plant growth, were available in the organic liquid fertilizer. The impact of the HDPE geomembrane bio-digester shows that the system could actually aid in the reduction of fuel cost in homes and actually be the solution to proper waste management in our country and if implemented around the globe, maybe the perfect mechanism in fighting against climate change.

We strongly recommend that this HDPE geomembrane bio-digester design system should be used all through the all developing countries and most especially in those rural areas that do not have municipal solid waste removal services through specialized companies such as HYSACAM in Cameroon.

References

1. Gamuchirai Mutezo, Jean Mulopo, Dumisani Chirambo, Climate Change Adaptation: Opportunities for Increased Material Recycling Facilities in African Cities, African Handbook of Climate Change Adaptation (2021) 849–874

2. Aruh B. and Baul B.S., (1986), Textbook of organic chemistry, 12th edition, McGraw Hill Tokyo, p. 28-32, 1986.

3. Mas'ud, A. A., Wirba, A. V., Firdaus, M.-S., Mas'ud, I. A., Munir, A. B., and Yunus, N. M. (2015). An assessment of renewable energy readiness in Africa: Case study of Nigeria and Cameroon. Renewable and Sustainable Energy Reviews, 51, 775–784. https://doi.org/10.1016/j.rser.2015.06.045.

4. Khan, M E., Martin, A R. (2016) Review of biogas digester technology in rural Bangladesh. Renewable & sustainable energy reviews, 62: 247-259 http://dx.doi.org/10.1016/j.rser.2016.04.044

5. Lisa M Avery et al., 2011. Agriculture, Ecosystems & Environment Volume 140, Issues 3–4, March 2011, Pages 354-360. https://doi.org/10.1016/j.agee.2011.01.019.

6. Fondufe Sakah Lydia, Jude Ndzifon Kimengsi, Akhere Solange Gwan. Strengthening Women's Participation in the Sustainable Management of the Bimbia Bonadikombo Community Forest of Cameroon: Challenges and Blueprints. International Journal of Sustainable Development Research. Vol. 2, No. 3, 2016, pp. 12-17. doi: 10.11648/j.ijsdr.20160204.11.

7. Abbasi, T., S. M. Tauseef and S. A. Abbasi, *Biogas Energy*. SpringerLink ebooks – Engineering, New York, 2012.

8. Austin, G., & Morris, G. (2011). Biogas Production in Africa. Bioenergy for Sustainable Development in Africa, 103–115. doi:10.1007/978-94-007-2181-4_10.

9. Amigun B., Sigamoney R., von Blottnitz H. Commercialization of biofuel industry in Africa: a review. Renewable and sustainable energy reviews, (2007). Doi:10.1016/j.rser.2006.10.019.

10. McKendry P. Energy production from biomass (Part 1): Overview of biomass. Bioresources Technolgies 2001; 83 (1):37 46.

11. Souza, Samuel Nelson M, Werncke Ivan, Marques Cleber Aimoni, Bariccatti Reinaldo A, Santos Reginaldo F. Electric energy micro-production in a rural property using biogas as primary source. Renewable Sustainable Energy Review 2013; 28: 385 – 91.

12. Ostrem, K., K. Milltah and N. Themelis, *Combining Anaerobic Digestion and Wasteto-Energy*.ASME, Georgia, 2004, PP. 265 – 271.

13. Li Y. B., Park S. Y., Zhu J. Y. (2011). Solid-state anaerobic digestion for methane production from organic waste. Renewable & Sustainable Energy Reviews 15 (1): 821 – 826.

14. Khalid A., Arshad M., Anjum M., Mahmood T., Dawson L. (2011). The anaerobic digestion of solid organic waste – Review. Waste Management Aug; 31 (8): 1737 – 44. 21.

15. Charles G. Gunnerson and David C. Stuckey. Integrated Resource recovery: Anaerobic Digestion.Principles and Practices for Biogas Systems. World Bank Technical Paper Number 49, 1986;

16. Vandevivere P., L. De Baere, W. Verstraete (2003). Types of anaerobic digesters for solid wastes, in Biomethanization of the Organic Fraction of Municipal Solid Wastes, J. Mata-Alvarez, Editor. IWA Publishing: Barcelona.p. 111 – 140.

17. Tomar S. S. Status of biogas plant in India. *Renewable Energy 1994, 5, 829-831.* 28.

18. Gautam R., Baral S.,Herat S. Bioags as a sustainable energy source in Nepal: Present status and future challenges. Renewable and Sustainable Energy Review. 2009, 13, 248 – 252.

19. Akinbami J. F. K., Ilori M.O., Oyebisi T. O., Akinwumi I. O., Adeoti O. Biogas energy use in Nigeria: Current status, future prospects and policy implications. *Renewable and Sustainable Energy Review*, 2001, *5*, 97-112.

20. Rajendran, K., Aslanzadeh, S., & Taherzadeh, M. J. (2012). Household Biogas Digesters—A Review. Energies, 5(8), 2911–2942. doi:10.3390/en5082911.

21. Mohammad N.Biogas plants construction technology for rural areas. *Bioresources Technology.* 1991, *35*, 283-289.

22. Nzila C., Dewulf J., Spanjers H., Tuigong D., Kiriamiti H., Van Langenhove H. (2012). Multicriteria sustainability assessment of biogas production in Kenya. Applied Energy, Volume 93, May 2012, Pages 496 – 506.

23. Ferrer I., Garfi M., Uggetti E., Ferrer-Marti L., Calderon A., Velo E. Biogas production in low-cost household digesters at the Peruvian Andes. *Biomass Bioenergy* 2011, *35,* 1668-1674.

24. Bouallagui H., Ben Cheikh R., Marouani L., Hamdi M. Mesophilic biogas production from fruit and vegetable waste in a tubular digester. *Bioresources Technologies* 2003, *86,* 85-89.

25. Roopnarain A, Adeleke R. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renew Sustain Energy Rev 2017; 67:1162–79. doi:10.1016/j.rser.2016.09.08.

26. Muh E, Amara S, Tabet F. Sustainable energy policies in Cameroon: A holistic overview. Renew Sustain Energy Rev 2017. doi:10.1016/j.rser.2017.10.049.

27. Muh, E., Tabet , F., & Amara, S. (2018). The Future of Biogas Production in Cameroon: Prospects, Challenges and Opportunities. Current Alternative Energy, 02. doi:10.2174/2405463102666180925141102.

28. Khan EU, Martin AR. Review of biogas digester technology in rural Bangladesh. Renew Sustain Energy Rev 2016;62: 247–59. doi:10.1016/j.rser.2016.04.044.

29. Okudoh V, Trois C, Workneh T, Schmidt S. The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review. Renew Sustain Energy Rev 2014;39: 1035–52. doi:10.1016/j.rser.2014.07.142.

30. Bond T, Templeton MR. History and future of domestic biogas plants in the developing world. Energy Sustain Dev 2011; 15:347–54. doi:10.1016/j.esd.2011.09.003.

31. Scarlat N, Motola V, Dallemand JF, Monforti-Ferrario F, Mofor L. Evaluation of energy potential of Municipal Solid Waste from African urban areas. Renew Sustain Energy Rev 2015;50: 1269–86. doi:10.1016/j.rser.2015.05.067.

32. A. Daisy and S. Kamaraj, “The Impact and Treatment of Night Soil in Anaerobic Digester: A Review”, Journal of Microbial & Biochemical Technology, 3:043-050. DOI: 10.4172/1948-5948.1000050.

33. Jahn, GC, LP Almazan, and J Pacia. (2005.). "Effect of nitrogen fertilizer on the intrinsic rate of increase of the rusty plum aphid, Hysteroneura setariae (Thomas) (Homoptera: Aphididae) on rice (Oryza sativa L.).". Environmental Entomology 34 (4) 938-943.

34. Preap, V., M. P. Zalucki, H. J. Nesbitt, and G. C. Jahn (2001.). "Effect of fertilizer, pesticide treatment, and plant variety on realized fecundity and survival rates of Nilaparvata lugens (Stål); Generating Outbreaks in Cambodia.". Journal of Asia Pacific Entomology 4 (1):: 75-84.

35. Rollin, A. R.; Rigo, J. M.; *Geomembranes - Identification and Performance Testing*, 1st ed., Chapman and Hall: London, 1991.

36. G.V. Rupf, P.A. Bahri, K. de Boer, M.P. McHenry, Development of an optimal biogas system design model for Sub-Saharan Africa with case studies from Kenya and Cameroon, Renewable Energy 109 (2017) 586-601. DOI: https://doi.org/10.1016/j.renene.2017.03.048.

37. Saheli, P. T.; Rowe, R. K.; Petersen, E. J.; O’Carrol, D. M.; *Geosynthetics International* (2017), doi:10.1680/jgein.16.00025

38. Perkins, S. W. In *Geosynthetics in Civil Engineering*; Sarsby, R. W., ed.; Woodhead Published Limited: Cambridge, 2007, cap. 2.

39. Meegoda JN, Li B, Patel K, Wang LB. A Review of the Processes, Parameters, and Optimization of Anaerobic Digestion. Int J Environ Res Public Health. 2018 Oct 11;15(10):2224. doi: 10.3390/ijerph15102224. PMID: 30314318; PMCID: PMC6210450.