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Research Article

Design and Construction of an Anaerobic Digester for the Ingestion of Waste from the Cocoa Industry in Nigeria

Nzubechukwu Ugochukwu Iluno[1, *], Aigbomain Akhigbe[1], Mene Namene[1], Annabel Worgu[1], Churchill Inwang[1], Paul Okpala[1, 2]

[1]Mechanical Engineering, Madonna University, Enugu, Nigeria
[2]Mechanical Engineering, Nnamdi Azikiwe University, Anambra, Nigeria

Abstract

The Anaerobic Digester designed and constructed for waste ingestion from the Nigerian cocoa industry aims to harness abundant renewable energy from crop residues like cocoa rinds and groundnuts. This study evaluates the biogas potential of these sources in contributing to the country's overall energy needs, emphasizing the imperative for environmental sustainability. Focusing on reducing fossil energy consumption, greenhouse gas emissions, and minimizing environmental impact, the project advocates for a shift towards biogas for day-to-day energy requirements, presenting direct cost savings. The utilization of fossil fuel-derived energy is known to contribute to temperature increase, greenhouse gas emissions, noise pollution, and ground-level air pollution, all of which can be mitigated through biogas utilization. This initiative involves the design and construction of a 0.24m^3 pilot plastic fossil plant for biogas generation, aiming to "green" various applications, including domestic and industrial usage as well as transportation. The digester, constructed from high-density polyethylene (HDPE) plastic, demonstrates leak-free operation, further supporting its potential for long-term sustainability. Results from a 28-day retention period show a cumulative biogas yield, with a daily assessment indicating a gas yield of 0.0496 m^3 on the 12th day. The study highlights the positive and negative influences of temperature inequality gradients ≥34°C≤38°C on biogas production. This comprehensive research contributes valuable insights for the sustainable management of waste and the utilization of biogas as a viable alternative energy source.

Keywords

Anaerobic Digester, Biogas Potential, Environmental Sustainability, Renewable Energy, Cost Savings, High-Density Polyethylene (HDPE), Greenhouse Gas Emissions, Temperature Inequality Gradients

1. Introduction

1.1. Background of the Study

Biogas is a rich combustible mixture of gases produced by micro-organisms from agricultural wastes by the decomposition of organic matters when fermented in an enclosed containment. According to Nathia-Neves et al., the process of anaerobic digestion occurs in four different stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [14]. The

[*]Corresponding author: ilunonzube24@gmail.com (Nzubechukwu Ugochukwu Iluno)

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major constituents of biogas are methane (CH_4, about 55-70% by volume), and carbon dioxide (CO_2, about 30-45%) [22]. Minimum impurities such as hydrogen sulphide (H_2S), carbon monoxide (CO) and nitrogen (N_2) are present in trace quantities.

The formation of complex organic molecules such as peptides bonding glycerol alcohol and a type of bacteria called methanogenic bacteria convert these compounds into methane. Cocoa rinds when fermented are found to possess these chemical properties and are abundant in the south western part of Nigeria. The process of anaerobic fermentation mesophologically takes place at temperature up to 35 ℃ and requires moisture content of at least 50% [9].

Biogas is primarily methane (CH_4) and carbon dioxide (CO_2) and may have small amounts of hydrogen sulfide (H_2S), moisture and siloxanes. The gases; methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with oxygen. This energy release allows biogas to be used as a fuel; it can be used in fuel cells and for any heating purpose, such as cooking. It can also be used in a gas engine to convert the energy in the gas into electricity and heat.

Biogas can be compressed after removal of Carbon dioxide, the same way as natural gas is compressed to CNG, and used to power motor vehicles. In the United Kingdom, for example, biogas is estimated to have the potential to replace around 17% of vehicle fuel. It qualifies for renewable energy subsidies in some parts of the world. Biogas can be cleaned and upgraded to natural gas standards, when it becomes bio-methane. Biogas is considered to be a renewable resource because its production-and-use cycle is continuous, and it generates no net carbon dioxide. As the organic material grows, it is converted and used. It then regrows in a continually repeating cycle.

A biogas plant is the name often given to an anaerobic digester that treats farm wastes or energy crops. It can be produced using anaerobic digesters (air-tight tanks with different configurations). These plants can be fed with energy crops such as maize silage or biodegradable wastes including sewage sludge and food waste. During the process, the micro-organisms transform biomass waste into biogas (mainly methane and carbon dioxide) and digestate. According to Kongies and Anjelidaki., it is a biotic path that is catalyzed by activities of microorganism in the absence of air [23]. Higher quantities of biogas can be produced when the wastewater is co-digested with other residuals from the dairy industry, sugar industry, or brewery industry. For example, while mixing 90% of wastewater from beer factory with 10% cow whey, the production of biogas was increased by 2.5 times compared to the biogas produced by wastewater from the brewery only.

High levels of methane are produced when manure is stored under anaerobic conditions. During storage and application of manure, nitrous oxide is also produced as a byproduct of the denitrification process. Nitrous oxide (H_2O) is 320 times more aggressive as a greenhouse gas than carbon dioxide and methane 25 times more than carbon dioxide. By converting cow manure into methane biogas via anaerobic digestion, the millions of cattle in the United States would be able to produce 100 billion kilowatt hours of electricity, enough to power millions of homes across the United States. In fact, one cow can produce enough manure in one day to generate 3 kilowatt hours of electricity; only 2.4 kilowatt hours of electricity are needed to power a single 100-watt light bulb for one day. Furthermore, by converting cattle manure into methane biogas instead of letting it decompose, global warming gases could be reduced by 99 million metric tons or 4%.

Manufacturing of biogas from intentionally planted maize has been described as being unsustainable and harmful due to very concentrated, intense and soil eroding character of these plantations.

The biogas is almost identical to the natural gas and can be used as fuel for domestic and industrial applications such as cooking, operation of automotive, and generation of electricity [13].

The gas production is a process which is dependent upon the digester temperature, retention or fermentation time, and the quality of feed stock material. It is required that a proper design analysis of the digester be done to enable the determination of the volume of gas that can be produced and at what economic rate.

1.2. Statement of Problem

It has been justified over the years through observation, studies and research that there is increase in the need of fuel for domestic and industrial application in Nigeria. Economically, observing the crude oil in Nigeria, it appears so numerous and unlimited. But this fuel appears limited after being processed. These are due to poor maintenance of her existing refinery, lack of equipment that is capable of handling treatment of biomasses and lack of machines that producing gas fuels at an economic rate and that is why the design and construction of an anaerobic digester of the ingestion of waste using biomasses are introduced to unravel every need of fuel in Nigeria.

1.3. Aim and Objectives of the Study

The aim of this study is the design and construction of the anaerobic digester for the ingestion of waste from the Cocoa Industry in Nigeria.

The specific objectives are;

1) To select the design parameters based on cost effective materials and size consideration.
2) To carry out the design analysis which involves data computation and detailed design diagram.
3) To construct and test the project.
4) To promote sustainability waste management.
5) To harness biogas production.
6) Reducing environmental impact.
7) Providing a renewable energy source for coco industry

in Nigeria.
8) Contributing to both environmental conservation and economic sustainability.

1.4. Significance of the Study

The anaerobic digester for the ingestion of biomasses is to bring about reduction of greenhouse effect, in order to provide conducive atmosphere for humanity; the study is to provide help to commercial needs in terms of maximizing the rate of fuel production and also helps in the improvement of the agricultural sector using the sludge as manure.

This project study will involve an investigation of the application of the principles of bio-engineering for the design of a digester that will practically convert waste biomass to methane for domestic and industrial applications such as cooking gas, heating, automotive, generation of electricity, etc. and also produces a sludge which serves as fertilizer and other civil engineering applications.

1.5. Scope of the Study

The project work is limited to minimal production of methane and is designed for cocoa rinds as biomass. The biomass can be used mostly as cooking gas to do a lot of things, in both domestic and industrial levels as it is very safe and eco friendly.

2. Literature Review

2.1. Waste Control and Disposal in Nigeria

Waste control and disposal has been a major problem in the Nigerian environment as they result in environmental pollution. The lack of the idea and willpower for the exploitation of renewable energy using these wastes is also of concern. The major factor affecting Nigeria economic progress is electricity. Due to this fact, some scientists and engineers have done remarkable works in the area of conversion of these wastes to alternative source of energy in the form of biogas and liquid ethanol.

Biogas is a methane based gas produced by anaerobic digestion of organic materials, industrial, and domestic wastes such as cocoa rinds, peanut shells, sugarcane sticks, corn sticks and chaffs, animal and human wastes, etc. It is a typical anaerobic ecosystem where complex organic polymeric substances are enzymaticaly broken into final end products of methane and carbon dioxide [17].

At any rate, gas production from biomass provides clean and renewable energy that is environmentally friendly, cost effective in production, protects and improves the hygiene of the citizen and offers the required alternative energy and technology [6].

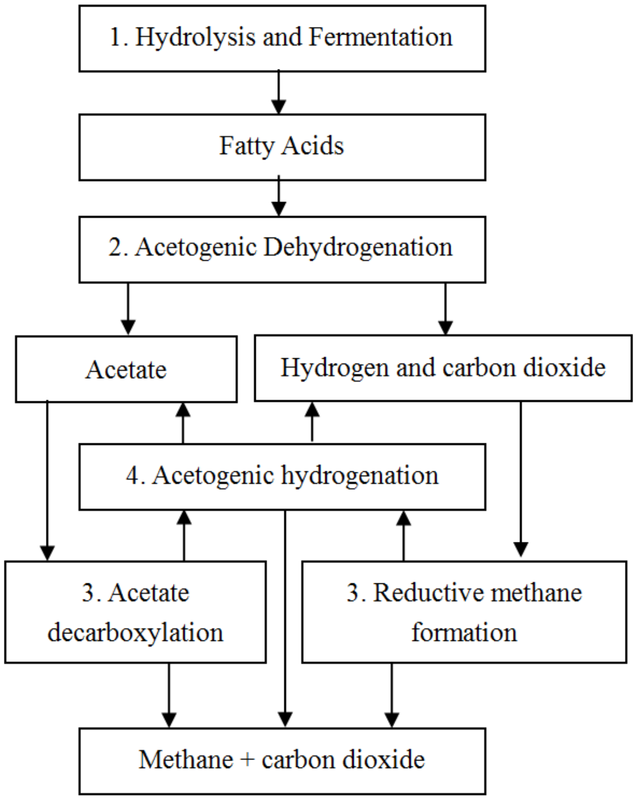

Figure 1. *Steps in anaerobic digestion involving four groups of bacterial activities. Flow chart as described by [17].*

2.2. Principles of Operation of the Digester

The basic operation of a biogas digester is anaerobic digestion. Anaerobic digestion is a natural biological process that develops organic materials and agricultural wastes to biogas in the absence of air. This can be achieved in four stage process namely:

2.2.1. Hydrolysis and Fermentation

This is the first stage of the process. Here, fermentation takes place whereby, anaerobic bacteriause enzymes to decompose high molecular organic substances such as proteins, carbohydrates, cellulose and fats into low molecular compounds. The monomers that emanate from the bacteria are fermented to volatile fatty acids (VFAs), such as acetic, butyric and propionic acids and alcohols, carbon dioxide, hydrogen, and other lactic acids.

According to Lue et al., hydrolysis can be rate determining step, although prior research has also demonstrated that methaiogenis might exist as a rate of hydrolytic to methanogenic micro-organism [18].

Their studies revealed that using insoluble cellulose in which the concentration of soluble reducing sugars was 1%, hydrolysis and fermentation of cellulose by continuous culture followed first order kinetics and the rate constant was equal to 1.18 per day.

According to Yu et al., hydrolysis rate of carbohydrates under anaerobic conditions are generally faster than that of protein [34]. Their studies also showed that 31 to 65% of carbohydrate, 20 to 45% of protein, and 14 to 24% of lipid were acidified in an up-flow reactor with an agitator and gas-liquid-solid separator. The rate of hydrolysis of cellulose, protein and lipid were in the range of 0.04 to 0.13, 0.02 to 0.03 and 0.08 to 1.7 per day respectively.

2.2.2. Acidification

During the second phase, propionibacterium consuming lactate are produced. Lactic acid forming bacteria continues the decomposition process into organic acids, carbon dioxide, hydrogen sulphide and ammonia. Acid bacteria form acetate, carbon dioxide and hydrogen during the acetogenesis phase. The methangenesis phase involves methane, carbon dioxide and alkaline water. Propionic acid may also result from metabolism of long fatty acid that contains odd numbers of carbon atoms as an end product.

The attribution of acid producing bacteria that convert fatty acid, amino acids and simple sugar into acetic acide, hydrogen, and carbon dioxide [28].

The prop ionic acid may also be formed by the following reactions:

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$$

$$3CH_3CHOHCOOH + H_2 \rightarrow 2CH_3CH_2COOH + CH_3COOH + CO_2 + 2H_2O$$

The second reaction is as a result of work done by propionibacterium consuming lactate, produced by lactic acid bacteria.

2.2.3. Acetogenesis

The fermentation of products such as butyric, prop ionic acids is converted to simpler products before being used by methanogenic bacteria. This conversion is done by acetogenic bacteria or H_2 producing bacteria. According to Hansen et al., acetogenis is the process by which these higher VFAs and other intermediate are converted into acetate, with hydrogen being produced [16].

Table 1. *Acetogenesis Equation.*

Equation and Standard Gibbs Free Energy Changes During Acetogenesis of biomass [31]	
Reaction	**ΔG° (KJ/reaction)**
Ethanol + $H_2O \rightarrow$ acetate$^-$ + $2H_2$ + H^+	+9.6
Lactate$^-$ + $2H_2O \rightarrow$ acetate$^-$ + $2H_2$ + HCO_3^- + H^+	-3.96
Butyrate$^-$ + $2H_2O \rightarrow$ acetate$^-$ + $2H_2$ + H^+	+48.1
Propionate$^-$ + $3H_2O \rightarrow$ acetate$^-$ + HCO_3^- + $3H_2$ + H^+	+76.1

According to Braun et al., another group of acetogens known as H_2^- acetogenic and homoacetogenic bacteria convert H_2 and CO_2 to acetate [7] according to the reaction below:

$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$$

2.2.4. Methanogenesis

Methanogenesis is therefore the final stage in anaerobic digestion, producing methane and carbon dioxide. Methanogens are capable of metabolising a very narrow range of substrates and they can grow on H_2 and CO_2. Methanogenic microorganism represents a group of obligate anaerobic archaea; as a testament to the acutsensitivity of methanogenic microorganism to oxygen [12].

With the regards to environment need of methanogensis, microorganisms tend to require a higher ph than previous stages of anaerobic digestion in addition to lower redox potential, the later requisite having caused significant trouble for laboratory cultivation [33].

$$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$$

Table 2. Methanogenesis Equation.

Equation and Standard Gibbs Free Energy Changes During Methanogenesis of biomass [31]	
Reaction	**ΔG° (KJ/reaction)**
$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$	-31.0
$4H_2 + HCO_3^- + H^+ \rightarrow CH_4 + 3H_2O$	-135.6
$4HCO_2^- + H^+ + H_2O \rightarrow CH_4 + 3HCO_3^-$	-130.4

In the above reaction, hydrogen transfer and utilization regulate the rate of H_2^- producing reactions by controlling the partial pressure of hydrogen. The H_2 concentration strongly affects the metabolic pathways used by the fermentative bacteria and is responsible for the type of end products formed.

2.3. History of Biogas

Anecdotal evidence indicates that biogas was used for heating bath water in Assyria during the 10th Century BC and in Persia during the 16th Century AD [24].

According to Pure Biogas Solutions, reviews of history prove that the first bio digestion plant to produce biogas from waste was built in Leper colony in Bombay, India in [25]. The second country to adopt the idea is China. In the early 19th Century, simple biogas digester had appeared in the coastal area of Southern China. In the 20th century, an eight cubic meter biogas tank was invented and built by Santou Guorui biogas lamp Company [15]. This was the first wave of biogas in China.

Further research and development on bio digestion plant continued as China looked for cheaper sources of energy. In 1953, the Chinese Guorui Biogas Company published the first lecture notes on Biogas and it was then, the first monograph on biogas in China and indeed, the world over, [10].

The second wave was also in China and was originated in Wuchang in 1958, in a campaign to exploit the multiple functions of biogas production, which simultaneously solved the problem of the disposal of domestic and agricultural wastes and thereby improvement of hygiene in that country.

China carried forward the campaign for the development of more efficient bio digestion plants and in late 1970 and early 1980, the third wave of biogas usage occurred. At this time, the Chinese government has considered biogas production a cost effective and clean usage of natural resources in generation of energy for the rural communities. Some 6 million digesters were set up in China, which became the biogas capital of the world, attracting many from the developing countries to learn from it. In one of the constructions, a community sized biogas plant was designed and aimed at maximum efficiency with several modifications over some existing plants. It was an $18m^3$ fixed dome biogas steel tank that was designed, constructed and tested, [10].

According to Syed., the digester was divided into portions which were in the ratio of 2:1. This ratio was described as desirable for optimum efficiency [29]. The process yielded methane and carbon dioxide ($CH4 + CO_2$), the carbon dioxide problem was removed by an enrichment well of potassium hydroxide (KOH).

The concept of design then, was to have basic components of the plants which included the main digester, the slurry inlet and an outlet provisions. The gas produced was stored in the dome where it was distributed through small pipes to the consumers. Pressure developed in this plant was estimated from the differences in levels of slurry in the digester. This was controlled in such a way that the methane produced must burn [19].

In 1976, farmers in Fuji were intrigued about converting plants and livestock wastes to biogas as a waste management measure, although this concept was not sustainable. Many factors exist which could explain the situation. The main reason was the renewed interest that came in 1997 after a better Chinese Modified Dome (CMD) design was established. Other reason was government funding of projects. However, by 2002, some failures were also observed [6].

In Siri Block, Karnataka, south India, 43% of the rural household use dung resources to operate biogas and 65% of them had already built their plants.

An important factor to encourage widespread adoption of biogas technology is an appropriate legal framework. For example, a comprehensive ecological tax reform law came into effect in Germany in March 1999 that raised taxes on energy sources tied to carbon emission, and exempted the renewable from taxation.

In February 2000, the German parliament passed a Renewable Energies Sources act that included payments for excess green energy generation fed back into the power grid. In the event, the meters run backwards, reducing the customer's electricity bills. These policies made green energy cost-effective, and were essential to the ultimate success of green power programmes [32].

2.4. Biogas in Nigeria

According to Akinbami et al., industrial revolution brought coal, a fossil fuel to the forefront of the global energy scene [2]. This was later overtaken by another fossil fuel, crude oil and natural gas is on the verge to take over the dominant role in the world energy supply mix. The increasing world-wide awareness and concern about the environmental impacts of fossil fuels coupled with the recent oil price shocks, and likely future price hikes, have given enormous weight to a switch to renewable energy sources. In order to contain the uncertainty usually associated with structural transformation of the economy typical of a developing country like Nigeria, a three scenario analysis has been adopted to examine the future prospect of biogas in Nigeria. Generated energy from biogas is estimated to a range of 5.0-171.0 x 10^{12}J in the period 2000-2030 under a moderate ambition of biogas technology programme. Some constraints may however hinder this realization.

These constraints include economic, technological, and socio-cultural constraints. To overcome some of these constraints, the use of biogas in rural areas is highly recommended. [5].

According to Anozie et al., in one of the developments, a batch pilot-scale biogas reactor was fabricated using a 3mm mild steel plate [3]. It was a horizontal, cylindrical digester. This package facility was easy to install and operate, consisting of several components that can be assembled and put to use much like a do-it-yourself kit. During a forty-day anaerobic digestion of four types of agricultural waste (cocoa rinds, corn stalk, mixed substrate, and poultry droppings), the biogas production from each waste was determined using the water displacement method via batch operation.

Net weight (38.49kg) of substrate mixed with water in the ration of 1:1 was used as feed. Laboratory analysis showed that the biogas produced contained 60% methane while carbon dioxide and other trace gases made up the balances of 40%. The gas produced burnt well in a Bunsen burner with a blue flame.

Cocoa rinds produced a significant yield of methane during the pilot run and a maximum reactor pressure of 1.34 bars was recorded for a period of seven days of no gas harvest when agricultural wastes were used as substrate, indicating that biogas production in a reactor is a relatively low pressure operation.

2.5. Availability of Feed Stock

According to United Nations Conference on Trade and Development (UNCTAD), based on the data from International Cocoa Organization, quarterly bulletin of cocoa statistics, cocoa is grown principally in West Africa. In order of annual production size in the region, Cote d'Ivoire, Ghana, Nigeria and Cameroon are the largest producers yielding 35%, 21%, 5% and 5% respectively of world production. This means that about 66% of world production is made within West Africa.

From the 1970s in Nigeria, oil boom and industrialization has led to a massive rural-urban migration and that has impacted on cocoa farming and production.

According to The Federation of Cocoa Commerce Ltd in 2010, Nigeria produced an average of 160,000 tonnes of cocoa between 1997 and 1998. The output has increased marginally to 175,000 tonnes in 2005, while other producing West African countries jointly produce about 2,135,000 tonnes per annum. Feed stock can be received from neighboring countries in West Africa to boost supply when the need arises. One of the factors to improve cocoa yield in Nigeria is to improve the supply and availability of fertilizers, insecticides, pesticides, etc and also to replace trees that are over 40 years old [4].

The advent of petroleum business and the search for white-collar jobs, as well as ineffective government policy on cocoa farming also affect the increase in production.

It is estimated that cocoa rinds will contribute significantly towards the achievement of Nigeria's Biogas Energy of between 5.0 - 171.0 x 10^9KJ by 2030, if cocoa plantation and yield is improved, sustained and used for the purpose of biogas generation.

Adenikinju highlights that cocoa rinds are mostly used in Nigeria as animal feed, burnt as fuel for cooking purposes, disposed indiscriminately, etc [1]. These hamper their availability for conversion to biogas energy.

According to Sambo., the Central Bank of Nigeria (CBN) 2007 figures specified that energy consumption per capita (kgeo/capita) in Nigeria has declined from 151.3 – 81.4 in 2003 to 2007 respectively, while electricity consumption per capita (kwh/capita) also decline within the same period from 174.6 to 167.6 units [27]. These decreases negate the population growth as projected by the National Bureau of Statistics (NBS) of 2.8 to 3.2 in the periods of 2003 to 2007 respectively. Biogas generation using cocoa rinds offers great contribution towards bridging these gaps.

Figure 2. *Cross Sectional area of Cocoa showing the Seeds and Rind.*

The Nigeria policy on biomass is to effectively harness non-fuel/wood biomass energy resources and integrate them with other energy resources and that the Nigerian nation shall promote the use of efficient biomass conversion technologies to boost her energy potentials [27].

According to Chevron Technology Ventures., one of the promising commercial partnership "Catch light Energy" with Weyerhaeuser Company (50 – 50 joint venture) is working to uncover the strengths of biomass so as to commercialize advance biofuels made from agricultural-based materials [8]. Chevron is focusing on both biochemical and thermo chemical conversions to achieve this target.

It is therefore important to recognize these policy statements and strive to key into the challenges as well as harness the huge potentials of biogas technology using mainly cocoa rinds which are abundant in Nigeria and hitherto not gainfully utilized as the biomass for the generation of gas energy.

3. Materials and Methods

3.1. Material Consideration

Consideration of choice of material for the digester tank is very necessary; this is to determine the effective operation and durability of the plant.

The material selection for the construction of the digester, the over head water supply tank, the slurry inlet funnel, and the waste discharge funnel will be high density polyethylene. Reviews of similar projects show that high density polyethylene does not corrode and has the ability to withstand heat generated within the digester as a result of anaerobic digestion and can also easily absorb heat from the ultraviolet rays of the sun. In order to enhance rapid heat absorbing capacity, the outer part of the digester is painted black.

The material used for the stirrer is carbon steel because of high strength, good machinability and high wear resistant property.

3.2. Components of the Biomass Digester

The biogas digester is the combination of various equipment and parts that make up the plant. Like other energy plants, various plant builders have developed biogas plants that are functioning all over the world. The use of cocoa rinds as the biomass will key into the process of plants already in operation. Attempt will not be made to reinvent the wheel but to design a pilot plant capable of processing the abundant raw materials of cocoa rinds in Nigeria. The major components of the biogas digester are therefore as follows:

1) The digester tank
2) The stock inlet hopper
3) The stirrer
4) The motor
5) The gas tank
6) Water supply tank

Other components include:

1) Linkages and outlet piping
2) The burner
3) Storage tube
4) Gauge valve
5) Non return valve
6) Analyzer
7) Compressor
8) Pressure gauge
9) Other auxiliary components

3.3. Design Consideration

In this section, the detailed analysis of various parts of the digester will be considered. This will include the properties and other variables such as temperature and pressure in the digester.

3.4. Digester Tank Design

3.4.1. Description

The tank is made of high density polyethylene and cylindrical in shape. The function of the tank is to hold the slurry i.e., the mixture of cocoa rinds and water, while the anaerobic decomposition occurs in the digester. Although the stirrer is a separate component, it is coupled on the motor and together embedded in the digester. The stirrer is used to agitate or stir the slurry in order to achieve homogeneity.

The digester is designed such that the appropriate orifices/holessizes is boredand having to cover detachable in cases of maintenance, same time good sealing component along it such are the rubber washer/ gasket and lid for proper sealing. These holes are bored on the detachable top plate to accommodate the stock inlet nozzle, the stirrer, water supply nozzle, the pressure gauge fitting and the gas discharge nozzle. For digested sludge discharge case the top plate will be detached, then the manure will be poured out as well as maintenance take place.

3.4.2. Process Condition

This process of anaerobic digesting is done at mesospheric condition which also means at environmental temperature condition. This occurrence brought about having the digester painted black to enable maximum heat absorption form the environment and radiantly, this is to help the slurry to warm up for fast fermentation result, molecule expansion for methane and carbon dioxide escape trapped and providing gas pressure in the digester tank.

3.4.3. Control Process of the Digester Tank

The use of weather tools severely played some roles in the resulting condition in the digester system, slurry i.e. the mixture. Such tools are

1) The pressure gauge
2) The PH meter

3) Infrared thermometer

3.4.4. Tank Calculations

REQUIREMENTS
h = Height of the digester tank.
v = Volume of the digester tank.
d = Diameter of the digester tank.
r = Radius of the digester tank.
P = parameter of the tank
Having;
h = 1.075m
v = 240 Liters
1000 Liters = 1m ^{3}
240 Liters = V

V = 0.240m ^{3} V = πd^2h/4 (1)

d = $\sqrt{4v/\pi h}$

d = $\sqrt{\frac{4*0.240}{\pi*1.075}}$

d = $\sqrt{0.284}$

d = 0.533m

r = d/2

r = 0.533/2

r = 0.267m P = 2πr (2)

P = 2 $*\pi*$0.267

P = 1.678m.

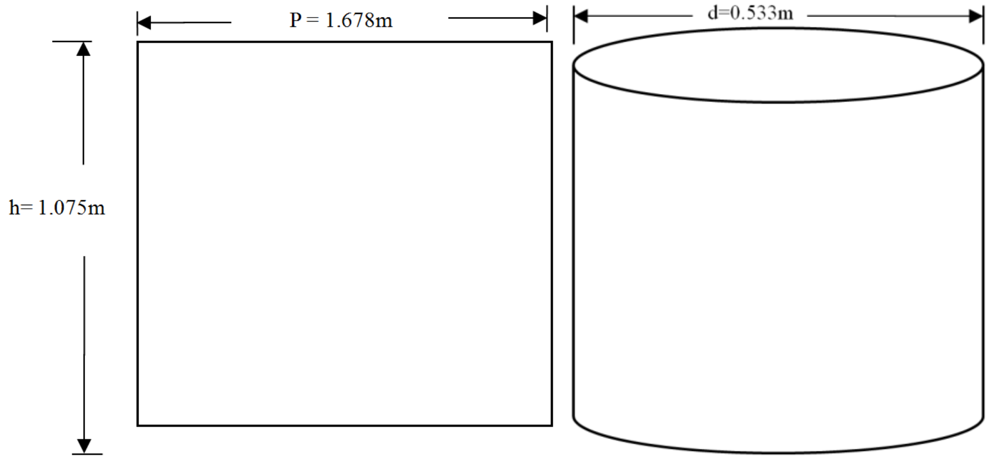

Figure 3. *Dimension of the HD Polypropylene barrel drum for the Digester Tank Used.*

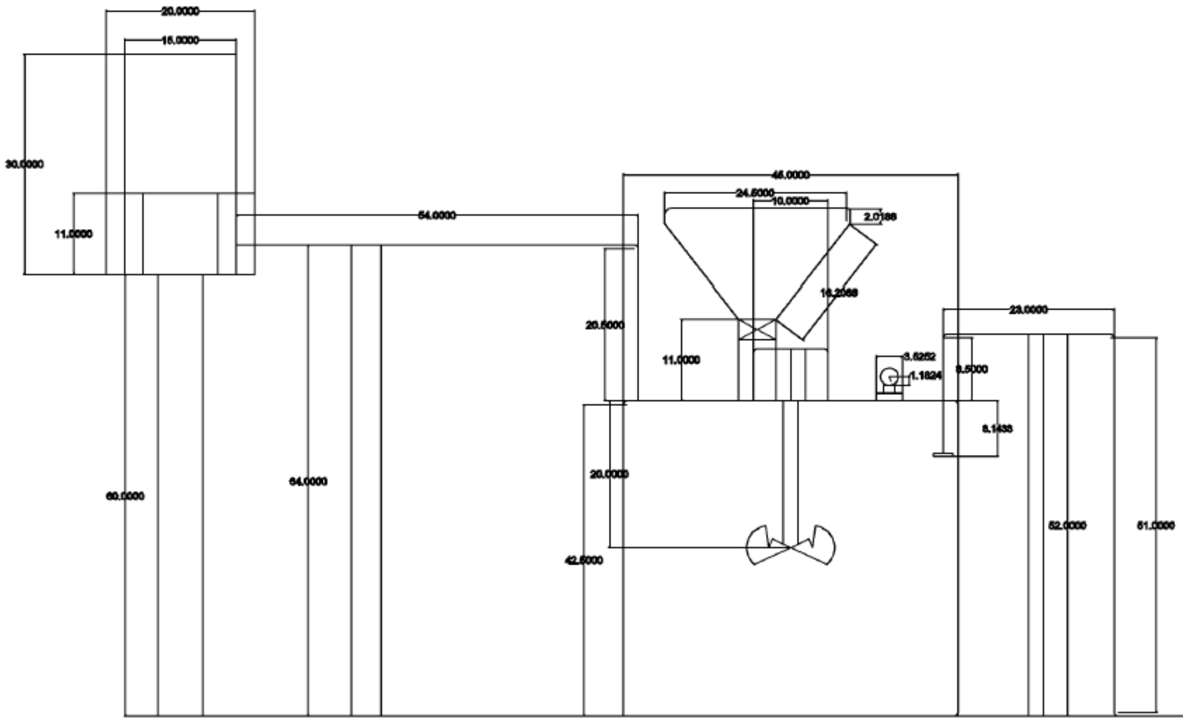

Figure 4. *Front view of the Design.*

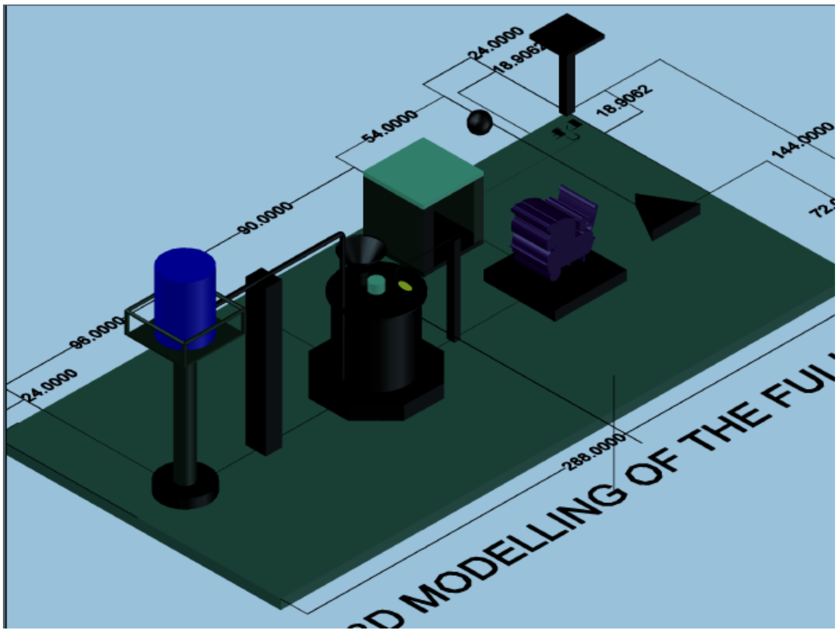

Figure 5. *3D modeling of the Design.*

3.5. Design of the Stirrer

During biogas production, the slurry is continuously stirred to yield maximum output. The other reason is to avoid hard scum being formed at the surface of the slurry thereby preventing the release of biogas.

For better agitation, the stirrer is vertically mounted at the centre of the digester tank. For the purpose of this pilot design, a hand wheel is sufficient as the prime mover connector. The stirrer is therefore comprised of the following:

1) The stirrer wheel and hub
2) Stirrer shaft
3) Stirrer paddle

The stirrer shaft and paddle are made of stainless steel and while the paddle is attached to the top side of the stirrer shaft and are of reasonable size and length so as avoid contact with the walls of the digester tank.

Now let,

F = force (N)

R = radius at which the stirrer handle turns (m)

T = shear stress (N/m^2)

P = power (W)

N = number of turns (rpm)

T = torque (Nm)

D = diameter of shaft (m)

If

N = 60rpm

F = 10NR = 0.15m

T = 50,000N/m^2

Circumference at which stirrer handle rotate

$$C = 2\pi r \quad (3)$$

$$= 2 * \pi * 0.15$$

C = 0.942m

Power required turning the stirrer / seconding

$$P = FC \quad (4)$$

$$= (10 * 0.942)/sec$$

∴Power (P) = 9.424watts

Torque transmitted by shaft,

$$T = (P * 60)/2\pi N \quad (5)$$

$$T = (9.424 * 60)/ 2 * \pi * 60 = 1.499Nm$$

$$\text{Now if } T = (\pi/16) * T * d^3 \quad (6)$$

Then substituting figures therefore,

$1.499 = (\pi/16) * 50000 * d^3$

$d = \sqrt[3]{(1.499)/ (50000\pi/16} = 0.053m$

This is the diameter of the stirrer shaft.

3.6. Temperature Consideration

Anaerobic breakdown of waste occurs at temperature lying between 0 ℃ and 69 ℃, but the action of the digester bacteria will decrease sharply below 16 ℃. Production of gas is most rapid between 29 ℃ and 41 ℃ or between 49 ℃ and 60 ℃.

This is due to the fact that two different bacteria multiply very fast in this temperature ranges. However, the higher temperature bacteria are much more sensitive to ambient influences.

Observations made, showed that temperatures between

30 ℃ and 40 ℃ have proved to be most effective for stable yield of methane. When experiments were conducted at neutral pH and temperatures range between 20 ℃ and 45 ℃, optimum production was found at 40 ℃, Biogas produced outside these temperature ranges will contain more percentage of carbon dioxide and other gases.

Eastman and Ferguson., observed that hydrolysis of cellulosic materials by enriched culture at pH 6.7 was faster than at 5.1 and 5.2 [11]. However, bacteria death rates could increase at higher temperature ranges beside the increase of energy,

Temperature and pH are therefore the two most important environmental factors that affect hydrolysis.

3.7. Pressure Consideration

During methanogenesis reaction, hydrogen is transferred and utilized. Reaction equations such as

$$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3$$

$$4HCO^-_2 + H^+ + H_2O \rightarrow CH_4 + 3HCO_3$$

…….will be produced. [31]. While hydrogen concentration strongly affects the metabolic pathway used by the fermentative bacteria and the quality of product, partial pressures are built [30].

According to Mclnerney and Bryant & Mosey.; the inhibition of some H2- producing reactions by H_2 concentration has been known as one major cause of digester failures [20, 21]. The digester therefore needs to be designed against these pressures.

To determine the required pressure, the internal pressure generated by the biogas will be compared with the maximum allowable pressure of the high density polyethylene barrel drum.

Let

R_u=Universal Gas Constant (KJ/Kmol K)

R = Gas constant of biogas (methane) (KJ/Kg K)

M = Molar mass of biogas (CH_4 +CO_2) (g/mol)

ρ =Density of Biogas (methane) (Kg/m^3)

T = Temperature in the digester tank (K)

P = Pressure generated by Biogas (N/m^2)

And if,

R_u = 8.314 (KJ/Kmol/K)

Molar mass of methane CH_4

Carbon (C) =12.0425

Oxygen (O) =6.0213

Hydrogen (H) = 1

M = 16.0425 + 38.0213 = 54.064(g/mol)

ρ = 0.717 (Kg/m^3)

Assume

$$T= (35+ 273)\ (K) = 308\ K$$

$$R=R_u / M \tag{7}$$

$$R= 8.314 / 54.064 = 0.154(K J. KgK)$$

$$P= \rho TR \tag{8}$$

$$P= 0.717 * 308 * 0.154 = 34.009\ (KN/m^2)$$

$$P = 34.009\ (KN/m^2)$$

Pg is the pressure generated by the biogas.

The next is to calculate the maximum allowable pressure of the HD Polypropylene.

Ultimate Tensile strength =400(MN/m^2)

Yield stress = 30(MN/m^2)

Let

t= Thickness of high density polypropylene barrel drum (m)

σ= Ultimate tensile strength (N/m^2)

d= Diameter of Digester tank (m)

p= Maximum allowable pressure in the digester tank (N/m^2)

F= Force exerted by gas (N)

L= Height of the digester occupied by the gas (m)

If,

σ= 300MN/m^2

t=1.5 ∗10^{-2}m

d=0.533m

L= 50% ∗1.075 = 0.538m.

Then, the maximum allowable pressure acting on the wall of the barrel will be

$$P = (\sigma * 2t)/d \tag{9}$$

$$= (300 * 10^6 * 2 \times 1.5 * 10^{-2})/0.533$$

$$= 9000000/ 0.533$$

$$P = 16.889MN/m^2 \text{ or}$$

Maximum allowable force acting on the wall of the barrel:

$$F = pdL \tag{10}$$

$$= 16.889 * 10^6 * 0.533 * 0.538$$

$$=4842988.306N$$

$$F= 4.842MN$$

The pressure generated by the biogas is smaller than the maximum allowable pressure the galvanized steel plate can withstand. It therefore means that the galvanized steel plate is safe to use for the digester.

3.8. Velocity of Travel Through the Orifice

The rate of flow (or discharge) of the biogas is the quantity of a fluid flowing per second through an orifice. The continuity equation is based on the principle of conservation of mass which states that, if no fluid is added or removed from the pipe in any length, the mass passing across different section of the pipe shall be the same.

Let, Q -Rate of production of biogas (m^3/s)

A_1 - Area of digester (m^2)

V_1 - Velocity of biogas in digester (m/s)

A_2 - Area of orifice (m)

V_2 - Velocity of Biogas through the orifice (m/s)

d - Diameter of orifice (m)

If, d = 0.025(m)

According to Rajput., Q = Area ∗ Average velocity is a constant [26]

$$Q = A_1 V_1 = A_2 V_2 \quad (11)$$

If $2m^3$ will give $1m^3$ per day of 86400 sec

$2m^3 = 1m^3/86400s$

$= 1.157 * 10^{-05}$ (m^3/s)

Therefore $0.240m^3 = 1.389 * 10^{-6}$ (m^3/s)

Therefore rate of production of biogas from this pilot scheme will be:

$$Q=1.389 * 10^{-6}(m^3/s)$$

$$\text{But } Q= A_2V_2$$

$$A_2 = (\pi d^2)/4$$

$$Q = (\pi d^2) * V_2 4$$

$$Q = (\pi * (0.025)^2) * V_2 4$$

$$V_2 = 4Q/0.025^2\pi$$

$$= (4 * 1.389 * 10^{-6})/0.025^2 * \pi$$

$$= 0.00283 m/s$$

Therefore velocity of Biogas through the orifice

$V_2 = 0.00283(m/s)$

3.9. The Gas Cylinder

The gas cylinder is a bought item and is the regular gas storage cylinder. A normal pressure gauge is installed on the cylinder to indicate the level of fluid in the gas cylinder. The cylinder has two valves (inlet and outlet). The inlet valve receives the gas from the digester while the outlet valve supplies the gas to the consumer.

3.10. The Hose Link

The hose links are also bought items. They are flexible so as to allow easy movement of the various parts. The hose links are two in number, one of the hose is used to connect the valve on the digester to the inlet valve on the gas holder while the second hose is used to connect the gas holder to the consumer.

Table 3. *Bill of quantities.*

S/N	Materials and Description	Quantity	Unit	Unit cost/Naira	TotalCost/Naira
1	Detachable Top andLid Locker. High Density Polyethylene Barrel Drum (Digester).	1	240Ltr	21,300	21,300
2	Stirring shaft with filaments and wheel.	1	SET	15,000	15,000
3	Electric Motor.	1	1 hp	25,000	25,000
4	½”Non-return dual plate for gas outlet.	1	pc	2000	2000
5	1”Ball Valve for water supply to the digester tank.	1	pc	600	600
6	Stainless air filter for gas outlet from the digester tank.	1	pc	2800	2800
7	Hopper for Stock Feeding.	1	pc	800	800
8	Pressure Gauge for the Digester Tank.	1	pc	2500	2500
9	Direct drive compressor for gas extraction from the digester tank.	set	1.5 hp (Donated by Ekwemike Trust Fund)	185,000	185,000
10	½”High Density PVC pressure pipe for linking the connections.	1	pc	3,600	3,600
11	Rubber Hose Pipe.	20	Yards	400	8000
12	Gas Cylinder.	1	3kg	9500	9500

S/N	Materials and Description	Quantity	Unit	Unit cost/Naira	TotalC-ost/Naira
13	Adhesive Gum.	1	473 ml	2,200	2,200
14	Silicon Sealant.	1	pc	2,500	2,500
15	½” Elbow Pipe Joint.	5	pcs	300	1,500
16	½” Union Pipe Joint.	5	Pcs	450	2,250
17	½” Adapter Pipe Joint.	5	pcs	300	1,500
18	Teflon Tape.	3	pcs	300	900
19	Thread Locker.	1	4ml	400	400
20	High Density Polyethylene Drum for Water Supply.	1	100Ltr	8,500	8,500
21	2” Ball Gauge Valve for Stock Feeding.	1	200m	3,000	3,000
22	½” Electrical Fitting Pipe.	7	pcs	500	3,500
23	Wire.	1 Bundle	2.5m	7,300	7,300
24	Socket Switch & Head.	3	pcs	800	2,400
25	Over Head Tank Pole.	1	4864m	15,500	15,00
26	2” Back Nut.	1	pc	1,300	1,300
27	1” Back Nut.	2	pcs	600	1,200
28	Single Phase Cooker.	1	Set	7,900	7,900
29	Gas Regulator.	1	Pack	3,000	3,000
30	Gas Storage Tube.	1	Pc	2,200	2,200
31	Gas Control Nozzle.	2	Pcs	1,200	2,400
32	½” Gas Socket.	2	Pcs	1,200	2,400
33	Black Paint.	1	500ml	1,200	1,200
34	Paint Brush.	2	Pic	200	400
35	Cement.	3	Bag	3,500	10,500
36	Fine Aggregate.	30	Pan	200	6,000
37	Coarse Aggregate.	30	Pan	300	9,000
38	Hose Clip.	10	pcs	100	1,000
39	1” Pipe Clip.	1	pc	300	300
40	½” Ball Valve.	5	pcs	500	2,500
41	Blue Gum.	1	100ml	500	500
42	Transportation	lot		18,000	18,000
43	Labour.	lot		18,000	18,000
GRAND TOTAL					421,350

4. Results and Discussion

4.1. Experimental Result and Discussion

The first two experiments were carried out using a 10 liter plastic can, with the stock being digested, about half the size of the plastic can, no specific measurements taken. We also added 50% of water above the stock level, and was kept and observed for some days. First samples were kept inside a room, another outside.

After retention of 18 days, we noticed pressure in the container, expanding uniformly, then the gas was tested with a single phase burner having the gas burnt for about 84 seconds after which the flame diminished, then we were motivated to carry out the main design project.

Coming to the main design work after construction and digestion of feedstock, the maximum period retention for gas yield was 28 days were we read $0.003m^3$at mean temperature 36.5℃, as the day pass on we read different mass volume yield as shown in Table 4. As climate changes temperature of the plant varies as well influencing the state of the system. About (21-25℃) on a rainy day and about (36-38℃) on a normal day. The highest confirmed temperature on the tank was 51℃.

From the experiment, at a temperature of 34-38℃ there is kind of steady gas production and rapid pressure in the system, but at temperature of about 23-25℃, there was no rapid pressure in the system,

We continued with our tests and got different pressures at different temperatures. The main observation was that, when the temperature around 33-35℃, there is better production of gas. At every stage we also checked the pH value at 2 days interval, the first 2^{nd} intervals we recorded base which is 7.6 and 7.8 but noticed acid of 6.7 on the 3^{rd} interval, while other intervals are recorded base.

Below, are the results recorded after 38 days of retention period for biogas yield observation and pressure in the system?

Mass of biogas =60moles

R=62.36LmmHg/k-mole

R= $0.0623m^3$mmHg/k − mole

$$V= mRT / P$$

At day 1

$$V= (60 * 0.0623 * 36.5)/46.2$$

$$V= 0.003m^3$$

At day 2

$$V= (60 * 0.0623 * 39)/38.9$$

$$V= 0.004\ m^3$$

at day 3

$$V= (60 * 0.0623 * 32)/34.6$$

$$V= 0.003\ m^3$$

At day 4

$$V= (60 * 0.0623 * 39.5)/32.4$$

$$V= 0.005\ m^3$$

Likewise other days in the table

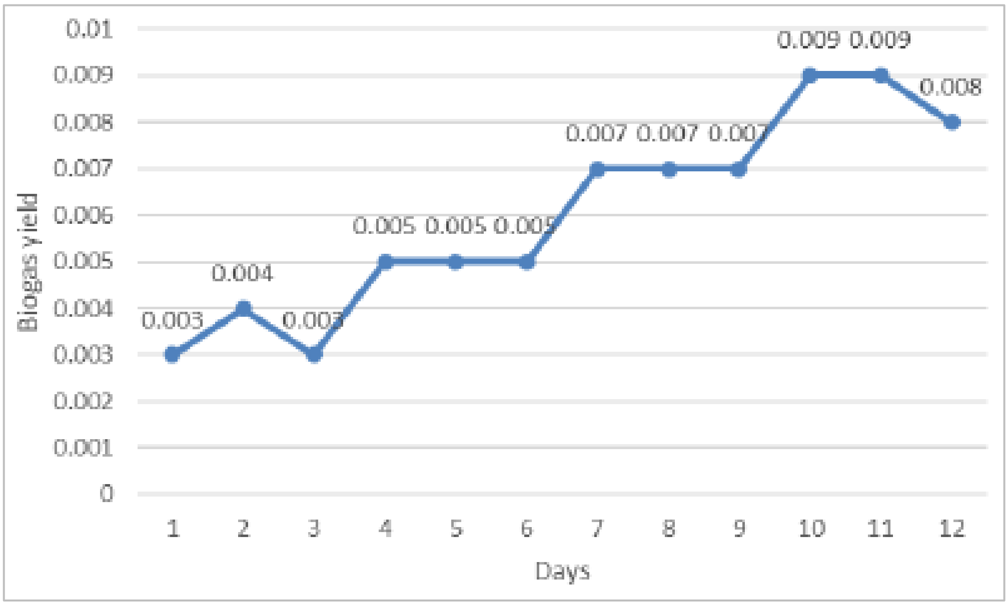

Figure 6. *Amount of Biogas yield.*

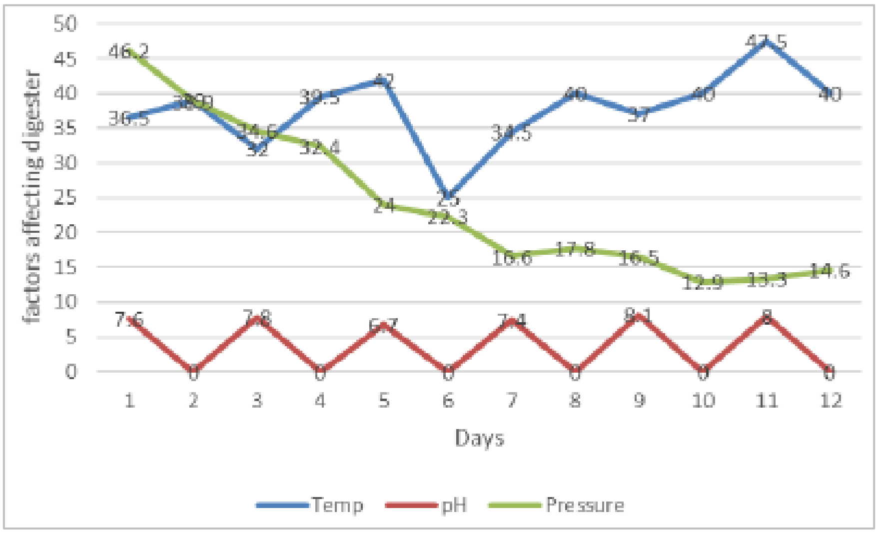

Figure 7. *Factors affecting the digesting process.*

Table 4. *Result Analysis.*

Biogas (V)/m^3	**0.003**	**0.004**	**0.003**	**0.005**	**0.0049**
TEM/ ℃	36.5	39	32	39.5	42
pH	7.6		7.8		6.7
TEM/ ℃at5pm	38	42	30	41	46
TEM// ℃ at8pm	35	36	34	38	40
Pressure/mmHg	46.2	38.9	34.6	32.4	24.0
Days/sec	1	2	3	4	5
Biogas (V)/m^3	0.005	0.007	0.007	0.007	0.009
TEM/ ℃	25	34.5	41	37	40
pH		7.4		8.1	
TEM// ℃at5pm	25	31	42	37	39
TEM// ℃ at8pm	25	38	40	37	41
Pressure/mmHg	22.3	16.6	17.8	16.5	12.9
Days/sec	6	7	8	9	10
Biogas (V)/m^3	0.009	0.008			
TEM/ ℃	47.5	40			
pH	8.0				
TEM// ℃at5pm	51	42			
TEM// ℃ at8pm	45	38			
Pressure/mmHg	13.3	14.6			
Days/sec	11	12			

4.2. Line Graphs Discussion

From the line graph displayed in Figure 6 above, it shows the gradient of biogas produced at 28 days retention period, while from Figure 7 displayed the factors affecting the digester and it influence on the biogas production. Starting from the PH, it has always being base until the 5^{th} day when we observed acid 6.7, having the pressure afterwards reduced drastically till the remaining days left. Also the biogases produced before and after the acid stage maintained the same level of production at the 4^{th}, 5th, and 6^{th} days.

4.3. Components of Biogas

The major and valued component of biogas is methane (CH_4) which typically makes up about 60%, with the balance being carbon dioxide (CO_2) and small percentages of other gases. The proportion of methane depends on the feed stock and the efficiency or the process. For cocoa rinds, a range of methane content between 40 to 70% is recorded and their chemical components are.

Table 5. Components of biogas.

Component	symbol	% content of gas
Methane	CH_4	40-70
Carbon- dioxide	CO_2	30-60
Hydrogen	H_2	1.0
Nitrogen	N_2	0.5
Carbon – monoxide	CO	0.1
Oxygen	O_2	0.1
Hydrogen-Sulphide	H_2S	0.1

4.4. Economics of Acceptability

The viability and acceptability of this plant will depend mainly on:

1) The availability of feed stock (cocoa rinds). As established in previous sections, Nigeria produces about 5% of World cocoa amounting to 175,000 tons per annum in 2005, but today in 2021 Nigeria is known as fourth largest cocoa producer covering 6.5% of global production, amounting 270000 tons in 2020/2021 and this figure is however expected to grow tremendously every year to come.
2) Socio-economic - whether the biogas energy generated conflicts with existing energy or keys into the Nations energy deficiency and Nigeria's Biogas Energy expectancy of generating full alternative of fuel to industrial and domestic application for the country and world at large.
3) The value attached to generation of renewable energy and legal incentives such as tax reimbursement and subsidies for users, will also call for total stop of rise in fuel price and negative environmental impact of global warming and exhaust emission will be eliminated.
4) The value derived from by products such as CO_2 convertible heat, fertilizers, materials for civil works etc, will as well use for development of the country.
5) Socio-political values, the scale, location, population and acceptability of the community where the digestion plant will be erected.
6) Cost of collection of feedstock and distribution of gas.
7) Synergy with truck operators to convert their trucks to bi-fuel, and downstream oil marketers for effective distribution of biogas.

5. Conclusion and Recommendation

5.1. Conclusion

In conclusion, the implementation of an anaerobic digester for cocoa industry waste in Nigeria not only addresses pressing environmental concerns through sustainable waste management but also serves as a pivotal step towards achieving a circular economy. By converting organic waste into biogas, the project not only reduces the environmental impact of waste disposal but also contributes significantly to the renewable energy sector, fostering economic sustainability. This holistic approach not only benefits the cocoa industry but sets a precedent for responsible industrial practices, emphasizing the synergy between environmental conservation and economic viability.

5.2. Recommendation

The bio gas yield can be improved by heating the digester. In Nigeria, this may not be necessary as the ambient temperature ranges between 30 to 38 ℃ in most days. Granulating the feedstock into finer sizes will help to accelerate fermentation of heavy organic molecules and therefore will improve digestion. Cocoa rinds are very rich in proteins, carbohydrates, cellulose and fats. Gas yield can be improved by also using vegetable water and continuous stirring, and can be accelerated and made more consistent by continuously feeding the digester with additional biomass daily.

The biogas product has its main constituents as methane and carbon dioxide in the percentage of 60 and 35 respectively.

Moreover, we recommend the following for future woks:

1) It will be important if stopped neutralizing the large volume of carbon dioxide generated, it should be trapped and put into profitable use such as CO_2 fire extinguishers, preservatives, inert gas, etc.
2) Collaborative Initiatives i.e. to encourage collaboration between government bodies, private enterprises, and

research institutions to support the widespread implementation of anaerobic digesters. This can be achieved through policy incentives, joint funding efforts, and knowledge-sharing platforms.

3) Capacity Building i.e. Invest in training programs to build local expertise in anaerobic digestion technology. This will empower communities to independently operate and maintain the digesters, ensuring the long-term success of the initiative and fostering job creation.
4) Public Awareness i.e. Launch awareness campaigns to educate cocoa industry stakeholders, local communities, and the general public about the benefits of anaerobic digestion. Highlighting the environmental and economic advantages will foster a positive perception and garner support for similar initiatives in other industries.
5) Monitoring and Evaluation i.e. Implement a robust monitoring and evaluation system to track the performance of the anaerobic digesters over time. This data can inform future improvements, optimize efficiency, and provide valuable insights for scaling up the project.
6) Policy Integration i.e. Advocate for the integration of anaerobic digestion practices into national waste management and renewable energy policies. This will create a good regulatory environment, encouraging widespread adoption of similar projects across various industries.
7) Knowledge Exchange i.e. Facilitate international knowledge exchange programs to allow experts from successful anaerobic digestion projects in other regions to share their experiences and best practices. This cross-cultural exchange can enhance the effectiveness of the cocoa industry waste management initiative in Nigeria.

By addressing these aspects, the implementation of anaerobic digesters for cocoa industry waste can extend beyond a local project, evolving into a comprehensive and replicable model for sustainable waste management and renewable energy production.

Finally, the next level will also be the fabrication/construction and testing of this in bigger design.

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Conflicts of Interest

The authors declare no conflict of interest.

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