DEVELOPMENT OF A BIOMASS DIGESTER FOR DOMESTIC USE

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ABSTRACT

This study presents the development of a 250-liter high-density polyethylene biogas digester integrated with a multi-stage purification system, designed for decentralized household energy applications. The system utilized 92.5 kg of fresh cattle dung mixed with 49.5 kg of water (1.87:1 ratio), maintaining a 165-liter working volume (66% capacity) under mesophilic conditions (26-32°C). A comprehensive monitoring protocol was implemented, recording temperature, pressure, and daily biogas production using calibrated pressure gauge and measuring the volume of the flexible storage chamber.

The digestion process exhibited characteristic phases of microbial adaptation, with biogas production reaching 140 liters on day 26, representing the system's peak daily output. The three-stage purification unit effectively treated the raw biogas, by using iron fillings for the removal of hydrogen sulphide, water scrubber for ammonia and silica gel for absorption of moisture, producing fuel suitable for domestic applications.

System performance was enhanced through several design innovations: (1) a reinforced gas holder capable of sustaining pressures up to 236 kPa, (2) optimized slurry mixing through periodic manual agitation, (3) addition of calcium carbide as catalyst increases methane content of the produced gas and (4) integrated safety features including pressure relief valves and a separate gas storage system from the digester. The purified biogas demonstrated consistent combustion characteristics in standard cooking tests, with a rich blue flame indicating high burning temperature.

These results validate the technical feasibility of small-scale anaerobic digestion systems using locally available materials. The study provides empirical data on operational parameters and production time lines that can inform future designs. While demonstrating successful biogas generation, the work also identifies opportunities for improvement through enhanced mixing mechanisms and temperature control. This research contributes to the growing body of knowledge on appropriate renewable energy technologies for rural communities, offering a model for sustainable waste-to-energy conversion.

Keywords: *Biogas production, anaerobic digestion, biogas purification, waste-to-energy conversion, clean cooking-fuel*

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1. INTRODUCTION:

In Nigeria, the escalating costs of cooking gas and kerosene, coupled with environmental and health concerns regarding the widespread use of fuelwood, have placed significant strain on the middle and lower classes [1]. As fuelwood remains a primary source of cooking fuel, its unsustainable consumption exacerbates deforestation and contributes to air pollution. This situation underscores the urgent need for a clean, affordable, and renewable energy source to alleviate the burden on households while mitigating environmental degradation. Therefore, the imperative to address the energy needs of the populace while promoting environmental sustainability necessitates comprehensive strategies that harness the potential of cow dung for biogas production. This entails not only the design and implementation of efficient biogas digester and storage units but also the promotion of awareness and capacity-building initiatives to facilitate widespread adoption among households, particularly in rural areas where the energy deficit is most acute.

Biogas production started in Assyria were gas produced is used to heat bathing water as far back as 10th century BC. Biomass digesters play an important role in addressing global concerns related to energy sustainability [2]. As fossil fuels face instability and energy demand continues to rise, exploring alternative energy sources becomes

very important. In this context, biogas emerges as a promising renewable energy solution that utilizes organic waste, aligning with the principles of circular economy and resource efficiency [3].

1.1 Aims and Objectives

The aim of this project is the development of a biomass digester and biogas purification system for domestic use. The objectives of the project are:

I. To design a biomass digester for production of biogas.
II. To fabricate the designed biomass digester.
III. To test the fabricated biomass digester.

2. MATERIALS AND METHOD

2.1 Description of The Biomass Digester

The biomass digester consists of three modules which are connected together for digestion, scrubbing and storage.

2.2 Bio-digester Drum:

This is a sealed compartment where slurry organic waste is converted into biogas. The bio-digester drum consist of openings for inlet and outlet of slurry organic waste, gas outlet and mixing mechanism (where necessary). It may also contain insulation to regulate the temperature of the biomass.

2.3 Biogas Scrubbing Chamber.

Biogas scrubbing chambers are designed to remove impurities and other contaminants such as carbon dioxide (CO_2), hydrogen sulphide (H_2S) and moisture from raw biogas. The biogas scrubber enriches the produced methane (CH_4) gas which can then be used efficiently as a fuel. The biogas scrubbing chamber consist of the inlet for raw biogas, outlet for purified biogas, scrubbing media (materials like carbon, iron oxide pellets and/or water), and regeneration or disposal system for used scrubbing agent [4].

2.4 Biogas Collection System.

This is usually a cylinder used to store the biogas produced during the anaerobic digestion process. The storage unit ensures that the produced biogas is readily available for use. It contains a sealing mechanism to ensure that the biogas stored do not escape. Biogas storage unit can exit in several shapes and forms such as fixed drum, balloon digester, gas bags and floating drum.

2.5 Biomass Digester Fittings and Hose:

These are crucial components used for the transportation and management of the produced biogas during anaerobic digestion. It consists of inlet and outlet pipes, pressure relief valves, check valves check valves, gas hose and slurry hose.

2.6 Design Calculations for the Bio-Digester Drum:

Volume of Digester Drum, V (m^3):
For a cylindrical drum:

$$V = \pi \times R^2 \times H \quad (2.1)$$

Where Radius of drum, R = 295mm
Height of drum, H = 950mm

$V = \pi * 295^2 * 930$
$= 2.543 \times 10^8\ mm^3$

Volume Occupied by Slurry matter, V_s (m^3):

$$V_s = \pi \times R^2 \times h \quad (2.2)$$

Where height of slurry matter in bio-digester drum, h = 620mm

$V_s = \pi \times 295^2 \times 620$
$= 1.695 \times 10^8\ mm^3$

.
Gas Collection Volume, V_g (m^3):

$$V_g = V - V_s \quad (2.3)$$

$V_g = 2.543 \times 10^8 - 1.695 \times 10^8$
$= 8.48 \times 10^7\ mm^3$

Volume of biogas storage tube

$$Vt = 2\,\pi^2\,(R_s + r_s)\,r_s^2 \quad (2.4)$$

Where R_s = inner radius of storage tube

r_s = tube radius

Total volume of biogas produced

$$V_T = V_g + V_t \quad (2.5)$$

Stresses in the wall of the bio-digester drum;

Several assumptions were made in the calculations of stress associated with the bio-digester drum. These assumptions are:

i. The wall of the drum is considered thin, that is the radius of the drum is much larger than the wall thickness.
ii. The slurry is a homogeneous fluid and can be associated with a single value for density.
iii. The gas pressure is uniform throughout the gas section.

Hydrostatic pressure exerted by slurry, Ph (Pa):

$$P_h = \rho \times g \times h \quad (2.6)$$

Total Pressure on the Drum walls, Ptotal (Pa):

$$P_{total} = P_h + P_g \quad (2.7)$$

Hoop stress, σh (Pa):

$$\sigma h = \frac{P_{total} \times R}{t} \quad (2.8)$$

Longitudinal Stress

$$\sigma l = \frac{P_{total} \times R}{2t} \quad (2.9)$$

Where t = thickness of drum.

ρ = density of slurry.

2.7 Biomass Digestion Process:

The digestion of biomass into biogas involves several chemical reactions that occur during the stages of anaerobic digestion. These reactions breakdown complex organic compounds into simpler molecules, eventually producing biogas which primarily consists of carbon dioxide (CO_2) and methane (CH_4). The stages associated with the digestion of biomass are:

2.7.1 Hydrolysis:

This is the first stage of the biomass digestion process. Complex organic polymers such as carbohydrates, proteins, and lipids present in the slurry mater are broken down into simpler monomers of simple sugar, amino acids, fatty acids and glycerol by the action of hydrolytic enzymes. This takes place in a neutral to slightly acidic solution (pH 5.5 - 6.5) [5]. It can occur under both mesophilic (20^0C - 45^0C) or thermophilic (45^0C - 60^0C).

$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6$

Proteins + $H_2O \rightarrow$ Amino Acids

Lipids + $H_2O \rightarrow$ Fatty Acids + Glycerol

2.7.2 Acidogenesis:

This is the second stage of the biomass digestion process where bacteria convert the product of hydrolysis into volatile fatty acids, alcohols, hydrogen, carbon dioxides and other byproducts in a slightly acidic solution (pH 5.0 - 6.5) and a temperature range of mesophilic (35^0C - 40^0C) or thermophilic (50^0C - 55^0C). Acidogenesis is more rapid under thermophilic conditions. The presence of nutrients like nitrogen, phosphorus and trace of other elements is essential for the growth of the acidogenic bacteria. In this process, glucose is fermented into pyruvate and then into products like acetate, butyrate, propionate, ethanol, etc.

(Glucose → Acetic acid + Carbon dioxide + Hydrogen)

$C_6H_{12}O_6 \rightarrow CH_3CH_3CH_2COOH + 2CO_2 + 2H_2$

(Glucose → Butyric acid + Carbon dioxide + Hydrogen)

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

(Glucose + Hydrogen → Propionic acid + Water)

2.7.3 Acetogenisis:

Volatile fatty acids and alcohols are converted into acetic acid (acetate), hydrogen, and carbon dioxide by acetogenic bacteria. Methanogenic bacteria use acetate and hydrogen produced in this stage for the production of methane in the methanogenesis process. A slightly acidic solution (pH 6.0 - 7.0) favours the acetogenic reaction since bacteria are reactive to lower pH values. The rate of hydrolysis increases with temperature, mesophilic (30^0C - 40^0C) or thermophilic (50^0C - 60^0C) conditions. Low hydrogen pressure (<10-4atm) is required since high hydrogen concentration can inhibit acetogenic bacteria by shifting the equilibrium of the reaction to the left.

$CH_3CH_2CH_2COOH + 2H_2O \rightarrow 2CH_3COOH + 2H_2$

(Butyric acid + Water → Acetic acid + Hydrogen)

$CH_2CH_2COOH + 2H_2O \rightarrow CH_3COOH + C0_2 + 3H_2$

(Propanoic acid + Water → Acetic acid + Carbon dioxide + Hydrogen)

$C_2H_5OH + H_2O \rightarrow CH_3COOH + 2H_2$

(Ethanol + Water → Acetic acid + Hydrogen)

2.7.4 Methanogenesis

This is the final stage of biogas production, methanogenic archaea convert acetic acid, hydrogen and carbon dioxide into methane and water. This is the most crucial step in producing methane which is the main content of the biogas. This occurs at a higher pH value (pH 6.8 - 7.5), low hydrogen concentration and thermophilic (30^0C - 60^0C).

Methanogenesis is divided into two separate reactions which are:

i. Acetolactic methanogenesis: Acetate is split into methane and carbon dioxide.

$CH_3COOH \rightarrow CH_4 + H_2O$

(Acetic acid → Methane + Carbon dioxide)

ii. Hydrogenotrophic Methanogenesis: Hydrogen and carbon dioxide are converted into methane and water.

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

2.8 Purification of Biogas

Biogas purification is an important process in the production of biogas because it enhances the quality of the biogas by removing impurities such as hydrogen sulphide (H_2S), carbon dioxide (CO_2) water vapour ammonia (NH_3) and other contaminants present in the produced biogas.

The biogas purification chamber shown in fig-1 consist of three sections for the removal of hydrogen sulphide, ammonia, moisture and other contaminant found in the produced biogas.

Fig-1: Biogas purification chamber

i. First Section; Iron Fillings (Hydrogen Sulphide Removal)

Hydrogen sulphide is corrosive, so its removal is important to prevent damage of metallic equipment mostly used in storing cooking gas, and other metallic equipment associated with cooking gas. Removal of sulphide from biogas also prevent the release of harmful sulphuric gas during combustion.

The produced biogas is passed through iron fillings in the first chamber. The reaction between hydrogen sulphide and iron (Fe) reduces the hydrogen sulphide to iron sulphide.

The residue iron sulphide is removed from the system by periodic cleaning of the purification chamber and replacement of the iron filling when degradation (iron rust) is noticed in the iron fillings.

$Fe + H2S \rightarrow FeS + H_2$

ii. Second section; Water (Ammonia and other impurities)

Water helps to scrub the produced gas by dissolving water soluble impurities like ammonia, carbon dioxides and other impurities. Bubbling the gas through water also removes excess moisture therefore reducing the overall moisture content. Removing excess moisture and ammonia reduces the risk of corrosion in biogas utilizing equipment and removes the foul smell associated with ammonia. Ammonium which is a product of this reaction can be removed from the system by regular replacement of the water in the purification chamber.

$NH_3 + H_2O \rightarrow NH_4OH$

In aqueous solution, ammonium hydroxide partly dissociated into ammonium and hydroxide ion separately.

$NH_4OH \rightarrow NH_4 + OH^-$

iii. Third section, Silica gel (Final drying and moisture control)

The desiccant in the third chamber serves as a moisture control by removing any residual moisture after the gas has been passed through the water scrubber. The biogas is passed through silica gel which have high moisture absorbing characteristics leaving the gas dry and ready to use.

2.9 Product of Anaerobic Digestion of Biomass:

The by-product of anaerobic digestion of biomass are the biogas which mostly consist of methane, carbon Dioxide, hydrogen sulphide and traces of water vapour, nitrogen oxygen and ammonia, the other by-product of anaerobic digestion is the digestate matter which normally serves as manure due to its rich protein content [6].

2.9.1 Biogas

Biogas generally contains methane (CH_4), Carbon dioxide (CO_2), Sulphur (S), Moisture (H_2O) and traces of other non-combustible gases. [7] Analysed the content of biogas produced from pig manure, the content of biogas obtained by using a laboratory bio-reactor are; residual moisture and NH_3 (6.6%), H_2S (4.2%), CO_2 (21.4%), H_2 (1.08%) CH_4 (65.22%) and N_2(1.49%).

$$\text{VOLUME}_{\text{componet}} = \left(\frac{\%\text{Component}}{100}\right) \times \text{VOLUME}_{\text{Total}}$$

Where;

$\text{VOLUME}_{\text{componet}}$ = Volume of Specific gas component(L),

%Component = percentage of that gas in the biogas,

$\text{VOLUME}_{\text{Total}}$ = Total volume of produced biogas (L).

Stoichiometric air-to-fuel ratio

For simplicity, it is assumed that biogas constitute of only methane (CH_4), Sulphur in form of hydrogen sulphide (H_2S) ammonia (NH_3) and moisture (H_2O), other constituent and impurities are neglected. CH_4 and H_2S being the only combustibles in the constituent under consideration.

For the combustibles;

Methane:

$CH_4 + 2O_2 \rightarrow 2CO_2 + 2H_2O$

2 moles of oxygen is required to burn 1 mole of methane. But XCH_4 moles of methane is present. Thus, oxygen required to burn methane present is $2XCH_4$.

Hydrogen Sulphide:

$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$

3 moles of oxygen are required to burn 2 moles of hydrogen sulphide. But XH_2S moles of hydrogen sulphide is present. Thus, oxygen required to burn hydrogen sulphide is (3/2) XH_2S.

Therefore, total oxygen required for the combustion of the biogas

Vol of $O_2 = 2X_{CH4} + \frac{3}{2}X_{H2S}$.

Since air is 21% oxygen by volume, Stoichiometric air to fuel ratio for the biogas is

$S = 0.21 \times$ Vol of O_2 by volume per volume of biogas.

2.9.2 The slurry

The slurry provides a medium in which anaerobic bacteria can thrive. These bacteria break down the organic matter in cow dung through hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately producing methane (CH_4) and carbon dioxide (CO_2). The slurry is composed of cow dung mixed with water in the ratio of 2:1 by mass.

2.10 Methodology

The digester was made of a 250-liter High Density Polyethylene (HDPE) drum with diameter 590mm and a height of 930mm. A 9-inch inlet valve was installed at the top of the drum to facilitate feeding the slurry. The slurry was prepared by mixing 92.5 kg of cow dung with 49.5 kg of water at ambient temperature of 29^0C to ensure homogeneity and foster growth of the methanogens needed for digestion of the biomass. After thorough mixing by hand, the slurry was poured into the drum until it reached a height of 620mm, leaving sufficient head-space in the drum to accommodate the biogas produced during the digestion process. Once the drum was filled with the slurry, the inlet valve was closed to create an anaerobic environment necessary for the microbial digestion of the organic matter. The anaerobic process was initiated as the bacterial present in the cow dung begin to break down the organic materials, resulting in the production of biogas primarily composed of methane and carbon dioxide. The digester was monitored at regular interval of 3 days to measure key parameters that would help evaluate the performance of the system. These parameters include the pressure measured by a pressure gauge mounted at the

top of the biodigester drum, volume measured by the change in thickness of the tube used for collecting the gas and temperature of the biogas produced measured using a thermometer connected to the top of the biodigester drum. The range of PH of the slurry was also measured.

The produced biogas was directed through a purification chamber designed to remove impurities such as hydrogen sulphide (H_2S), moisture and other contaminant thereby ensuring the produced biogas is suitable for domestic use. The purification chamber consists of three containers of height 300mm and diameter 110mm connected in series. The first container was filled with iron fillings which acted as a desulphurization agent reacting with the hydrogen sulphide present in the biogas to form iron sulphide (FeS), effectively removing the H_2S from the gas. After passing through the first container, the biogas moves into the second container which was filled with water. The water serves as a scrubber to remove water-soluble impurities and reduce the of the gas. Further purifying it before moving to the final stage. In the third container, a silica gel desiccant was used to absorb any remaining moisture, ensuring the gas is dry and free from unwanted contaminants.
After Purification, the biogas was collected in a tube with specifications 185/195-15 TR13, which was designed to safely store the biogas until it was needed for use. The tube was carefully selected for its ability to withstand pressure generated by the biogas and to provide a stable storage environment. The collection and storage of the biogas was monitored to ensure it was not overfilled. Throughout the digestion process, an ambient temperature range of 24^0C-33^0Cwas maintained as this mesophilic range was optimal for the growth of the methanogenic bacterial responsible for the production of biogas. The slurry was disposed through the 2” valve located at the bottom of the drum after the hydraulic retention time have elapsed.

3. RESULT AND DISCUSSION

The rate of production of biogas can be defined by the volume of biogas produced and the pressure in the biogas retention chamber at an interval of three days. These parameters are dependent on the ambient temperature and the pH range of the slurry within this time interval. Chart -1 shows the comparison between the ambient temperature, pressure in the biogas retention chamber, volume of gas produced and the pH range of the slurry mater.

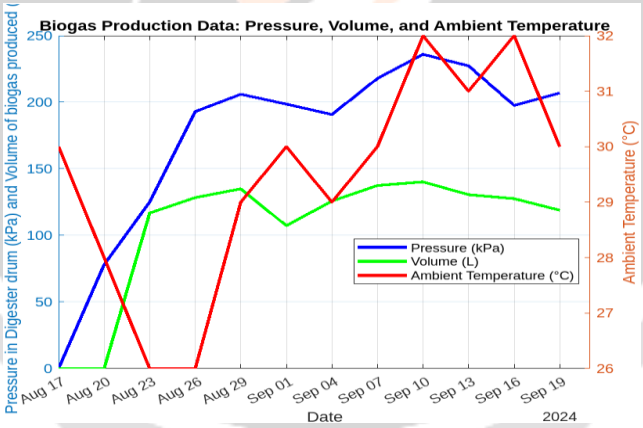

Chart -1: Biogas production parameters

The change in the characteristics of the slurry was determined by the change in the pH value of the slurry measured at each interval using a universal pH indicator paper. The pH values fluctuated slightly throughout the process but remained within the optimal range for biogas production (6.2 to 8). Chart -2 shows the relationship between variation in the pH value of the slurry and the volume of the produced biogas at an interval of three days. As more volume of biogas is produced, the value of the pH of the slurry reduces down until the maximum volume of biogas is produced and increases as the slurry becomes more acidic.

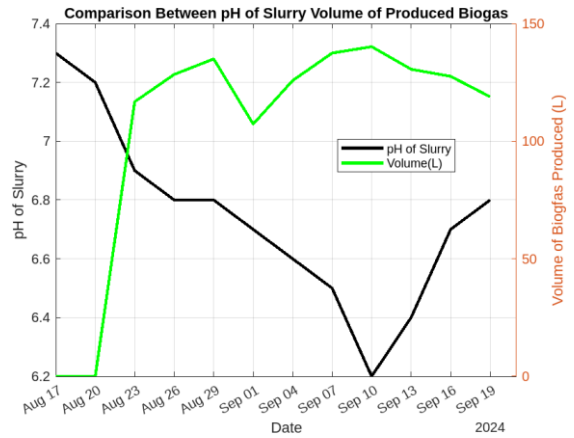

Chart -2: How pH of slurry affects the volume of biogas produced

Fig -2: Flame produced during the first 60 seconds of combustion

Fig -3: Continuous burning of produced biogas

During the first 60 seconds of combustion, yellowish tint appeared forming the entire feather of the flame this was as a result of purging out residual impurities such as hydrogen sulphide or excess carbon dioxide which was not completely removed in the purification chamber. Fig -2 shows the flame produced during the combustion of the produce biogas within the first 60 seconds. Fig -3 shows the flame produced during continuous burning of the biogas after the first 60 seconds. The flame produced during this period was bluish with no outer layers indicating complete combustion of the produced biogas.

Fig -4: Biomass Digester

4. CONCLUSION

The development of the biomass digester successfully demonstrated the potential of cow dung as a resource for biogas production. The system was able to convert organic waste into a clean and renewable energy source suitable for domestic use. The integration of a purification chamber effectively removed impurities, ensuring the quality of the biogas for use in household applications. This project provides a cost-effective solution to the rising energy demands in rural areas, offering both environmental and economic benefits by reducing dependence on conventional fuels and promoting waste management practices.

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