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Construction and Performance Evaluation of Locally Built PVC-Based Biogas Digesters

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Abstract
This study investigated the construction and performance of three locally-built biogas digesters designed to produce biogas from various organic material combinations. Conducted during the harmattan season with suboptimal temperatures (below 30°C) and lacking a stirrer mechanism, the experiment faced challenges resulting in low biogas yield within the initial 14-day retention period. A 7-day extension produced minimal biogas, emphasizing the negative impact of cooler temperatures and the need for longer retention times. To improve biogas production, the study recommends utilizing fresh organic waste for enhanced mixing, ensuring airtight digesters to prevent gas loss, and employing materials with high heat retention, wear resistance, and corrosion resistance. These improvements aim to optimize biogas digester performance, particularly in cooler climates.

Keywords: biogas, digester, Biogas Purification, Renewable Energy, Sustainable Technology

1. Introduction
Energy has always been an essential input for all aspects of life, with various sources used throughout history to meet basic needs like food and shelter (Asere et al., 1992; Abubakar, 1990). Currently, fossil fuels dominate the world's primary energy consumption. However, as non-renewable resources with rapidly depleting reserves, they cannot sustain our consumption rates. Therefore, exploring alternative renewable energy sources is crucial (Garba et al., 1995; Fotenal et al., 1983). These alternatives encompass a wide range of renewable energy sources, including biomass conversion, solar energy, wind energy, geothermal energy, small-scale hydropower generation, lower energy intensity industries, material and energy recycling, and improved cooking stoves (Filip and Nikko, 2013).

Throughout the centuries, humanity has relied on various sources of energy for smooth economic growth and development. While coal was the primary source of energy in the nineteenth century, oil took centre stage in the twentieth century. Mitigating the greenhouse effect caused by carbon dioxide emissions from energy production and industry is critical and can be achieved through emission reduction and recycling. The latter involves converting carbon dioxide into useful energy and chemicals (Sonya and Venko, 2020).

Emission reduction can take two forms: replacing fossil fuels with renewable ones (solar, wind, biomass, etc.) or improving energy efficiency in all human activities in various ways. One solution to the problem of carbon dioxide emissions is to close the carbon cycle by using renewable fuels derived from currently grown biomass and recycling the carbon dioxide emitted by current vegetation via photosynthesis. This philosophy underpins the use of biomass as an energy source (Sonya and Venko, 2020).

Fossil fuel combustion contributes significantly to environmental problems like global warming and greenhouse gas emissions. Biogas, however, offers a promising alternative to mitigate these issues (Ahmed et al., 2017). Compared to traditional cooking fuels, biogas production reduces the release of various pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and nitrous oxide (N_2O). This creates a cleaner cooking environment, especially beneficial for women who are often exposed to harmful indoor air pollution.

Biogas is produced through the anaerobic digestion of various biodegradable materials like cow dung, poultry droppings, pig manure, straw, grass, leaves, kitchen scraps, and even algae. This process, which occurs in the absence of oxygen, breaks down organic matter into a less dense gas mixture. Biomass, the source material for biogas, is considered a valuable and renewable energy resource as it can be converted into heat, power, transportation fuels, and biomaterials (Peshatwar et al., 2019).

A digester is a plant that processes biodegradable waste into biogas. It can be made using airtight tanks with different configurations. These digesters can be fed with energy crops such as corn silage or biodegradable waste such as animal waste, food scraps, or sewage water (Lise et al., 2008). The existing digested biomass, rich in microbes, supplies anaerobic bacteria to fresh biomass entering a digester. The digester tank creates an ideal environment for anaerobic microbes to "digest" the biomass, producing digested solids, liquids, and biogas. In general, anaerobic digestion is a living process that requires favorable conditions (temperature, moisture content, oxygen exclusion, and pH) as well as a consistent food supply to thrive ("Introduction to Biogas and Anaerobic Digestion," 2019). The microorganisms convert the biomass into biogas (mainly methane and carbon dioxide) and digestate (Lise et al., 2008). Most anaerobic digesters in the world are based on wet-type anaerobic digestion, in which biomass (usually animal dung) and water are mixed in equal parts to form a slurry with a total solids (TS) content of about 10-15%. While this type is appropriate for most regions, it becomes a challenge in large plants that require large amounts of water daily, often in water-scarce areas ("War on India's Toxic Pollution," 2020). The most common anaerobic digestion systems are liquid, plug-flow, and solid-state digesters ("Types of Anaerobic Digester," 2002).

Biogas is derived from the remains of plants and animals (Peshatwar, 2019). Anaerobic digestion has high potential for waste food and organic matter treatment (Chiamaka, 2018). Past experiments have shown that about 15-30 liters of methane gas can be produced from 1 kg of cow dung when properly mixed (Chiamaka, 2018). Biogas is unique among renewables due to its specific characteristics, such as:

1. Collection and monitoring of organic waste.
2. Fertilizer and slurry use in agricultural irrigation.

The efficient production and performance of methane gas depend on the proper mixing of biomass like cow dung, bagasse, rice husk, grass fodder, sugar cane residue, oat straw, and the organic fraction of kitchen wastes.

The natural breakdown of biodegradable material by microorganisms in the absence of oxygen is known as Anaerobic Digestion. Biodegradable material is placed in a digester, devoid of oxygen, to be broken down by naturally occurring microorganisms found in the material, producing biogas and digestate ("DAEDE," 2021). Methane is a flammable gas that can be used in furnaces for cooking or as fuel for engines, and it is the most important component of biogas. Biogas also contains carbon dioxide as well as trace amounts of hydrogen, hydrogen sulfide, nitrogen, and water vapor ("Dan Ciolkosz," 2019). In the absence of oxygen, anaerobic bacteria digest organic substances to produce biogas (anaerobic condition). It can be made from manure, sewage, wastewater from livestock farms and industrial plants, as well as agricultural waste. Biogas is composed of 60% to 70% methane (CH_4), 28-30% carbon dioxide (CO_2), and 2% hydrogen sulfide (H_2S), nitrogen (N_2), and steam. The property of biogas is largely determined by the amount of combustible methane present, whereas the amount of carbon dioxide does not affect the property of biogas due to its lack of combustibility. Therefore, the project focused on the generation of biogas from different blends to provide fuel for society, cushioning the effects of inadequate energy supply from conventional sources.

In the past, wood and fossil fuels have been the primary sources of energy for domestic and industrial purposes such as cooking, heating, and power generation. However, the high demand for these resources, coupled with their limited availability, has led to environmental issues like deforestation, global warming, and ozone layer depletion (Orhohoro et al., 2018). The search for alternative energy sources led to the discovery of biogas, which can be traced back to the 10th century when animal waste was used to produce methane gas. Biogas was discovered around 2,000 to 3,000 years ago in ancient China. In the 10th century, biogas was used for heating bathwater in Assyria and later in Persia in the 16th century (Muhammad et al., 2016). In the 17th century, Italian scientist Alessandro Volta discovered its flammable properties, identifying it as methane gas (CH_4) in 1821. The production of biogas by anaerobic digestion was initiated by Propoff in 1875, and the first anaerobic wastewater treatment plant was established in Germany in 1906. By 1913, an anaerobic digester with heating capabilities was built, and in the 1920s, a sewage plant in Germany fed collected biogas into the public gas supply system (Klinkner et al., 2014).

The development of simple biogas plants for rural families began in India in the 1950s, with significant growth in the 1970s due to strong governmental support. By the early 20th century, anaerobic digestion systems began to resemble modern technology (Klinkner et al., 2014). Biogas technology has been widely adopted, especially during energy crises and periods of high electricity prices, serving as an alternative energy source. Farm-based facilities are among the most common, with six to eight million family-sized, low-technology digesters providing biogas for cooking and lighting. Larger systems with better process control are used in China and India for electricity generation. Europe has a good track record of treating various farm, industrial, and municipal wastes using biogas facilities, some of which have been operational for over 20 years ("A Short History of Anaerobic Digestion," 2012).

Biogas is produced through the anaerobic (oxygen-free) breakdown of organic matter. Methane, the most important component of biogas, is a flammable gas used in furnaces, for cooking, and as engine fuel. Biogas also contains carbon dioxide, hydrogen, hydrogen sulfide, nitrogen, and water vapor ("Introduction to Biogas and Anaerobic Digestion," 2019). Anaerobic bacteria digest organic substances in the absence of oxygen to produce biogas. It can be generated from manure, sewage, wastewater from livestock farms and industrial plants, as well as agricultural waste. Biogas is composed of 60-70% methane (CH_4), 28-30% carbon dioxide (CO_2), and 2% hydrogen sulfide (H_2S), nitrogen (N_2), and steam. The properties of biogas are largely determined by the amount of combustible methane present, whereas carbon dioxide does not affect its combustibility.

The natural breakdown of biodegradable material by microorganisms in the absence of oxygen is known as anaerobic digestion (AD) ("Origin of Biogas," 2021). Biodegradable materials such as animal manure, food scraps, wastewater treatment solids, restaurant grease, and municipal and industrial wastewater can be used in this process. In a digester devoid of oxygen, naturally occurring microorganisms break down organic matter to produce biogas and digestate. The temperature of the digester is usually set based on the material being digested and the type of system used. A biogas-powered combined heat and power (CHP) unit is often used to generate both electricity and heat. Most anaerobic digestion facilities use a similar process, but some have multiple stages.

Anaerobic digesters process biodegradable waste into biogas using airtight tanks. These digesters can be fed with energy crops like corn silage or biodegradable waste such as animal waste, food scraps, or sewage water (Lise et al., 2008). The existing digested biomass, rich in microbes, supplies anaerobic bacteria to fresh biomass entering the digester. The digester tank creates an ideal environment for anaerobic microbes to "digest" the biomass, producing digested solids, liquids, and biogas. Anaerobic digestion requires favorable conditions (temperature, moisture content, oxygen exclusion, and pH) and a consistent food supply to thrive (Filip and Nikko, 2013). The microorganisms convert the biomass into biogas (mainly methane and carbon dioxide) and digestate (Lise et al., 2008). Most anaerobic digesters in the world are based on wet-type anaerobic digestion, where biomass and water are mixed to form a slurry with a total solids content of about 10-15%. While this type is suitable for most regions, it poses challenges in large plants that require large amounts of water daily, often in water-scarce areas ("War on India's Toxic Pollution," 2020). The most common anaerobic digestion systems are liquid, plug-flow, and solid-state digesters (Vandevivere, 2002).

Anaerobic digesters can be classified based on various criteria:

a. Biomass can either blend freely with the reactor liquid or be fixed to a surface (Shannon et al., 2002).
b. The organic loading rate, or the demand per unit volume of influent mass rate of chemical oxygen (Shannon et al., 2002).
c. Centralized and decentralized plants (Chiamaka, 2018).

There are different types of anaerobic plants for biogas production:

i. On-farm digesters: Crop residues and manure, as well as waste from neighbouring communities, are placed in a half-buried concrete pit with an impermeable cover on a farm or ranch. The biogas is collected under the cover before being transported to a storage tank. The digestate can be used as a soil conditioner. Operations must be monitored daily for safety and process control. The power capacity of each unit varies.
ii. Biogas plants: Large-scale biogas plants process tons of household or industrial waste (food, paper, and other residues) from multiple communities. The material is sorted to separate organic matter from solid waste, then macerated and pumped into tall steel towers. Biogas is collected and stored. These plants are often located near industrial plants that use the gas or electricity produced.
iii. Wastewater plants and sewage treatment: Household and industrial wastewater are treated at water treatment plants to remove contaminants. Cleaned water is discharged into rivers, while thickened sludge can be used to generate biogas, though at a lower yield than crop residues and manure feedstock. The sludge in continuous flow systems is treated in large vessels covered by a metal dome and constantly stirred by agitators.
iv. Micro-scale anaerobic digestion: Small-scale units are ideal for local, municipal, restaurant, or domestic use. Some units, consisting of two plastic compartments (one for fermentation and one for gas storage), are very cheap. Small digesters can be connected to a generator to produce electricity. The disadvantage of micro-scale digesters is that they require ongoing maintenance and have a lengthy start-up period. Homemade units are commonly used for heating, cooking, and lighting in regions with limited energy access. Anaerobic digesters are used in over 40 million Chinese households ("How does an anaerobic digester work," 2019).

2. Materials and Methods

2.1 Materials Selection

The design of the biogas digesters was made based on the following considerations:

1. Size of the digester
1. Mass of the feedstock or solid waste
2. The volume of water required
3. Mixture ratio
4. Temperature

The materials for the construction of the biogas digester were chosen based on their availability and properties because biogas consists of hydrogen sulphide which reacts with metals and causes it to corrode. PVC materials were chosen because they have excellent resistance against most chemical and solvent attacks.

The following materials on Table1 were used to experiment:

Table 1: Materials

S/No.	Material	Quantity
1	PVC Drum	3
2	½ inch PVC Pipe	1.35 m
3	Tyre Tube	3
4	Clips	8
5	Hose	1.83 m
6	½ inch Ball Valves or Tap	3
7	Glue (A&B Aradite)	2
8	Weighing Scale	1
9	Brass Rod	1
10	½ inch Metal Nipple	2
11	Copper Pipe	3
12	PVC adapter and reducer	3
13	Cow Dung	26.5 kg
14	Chicken Droplets	9 kg
15	Kitchen Wastes	2.6 kg

2.2 Equipment

The following equipment was used to experiment:

1. Hand gloves
2. 20 Litre bucket
3. 5 litres of water per gallon
4. Weighting scale
5. Hand saw
6. Gas welding
7. Brass rod
8. Stirrer

2.3 Design Analysis and Specification of the Digester

This section deals with the design and proper sizing of the digester with its specifications. The design calculation was based on the balloon type of digester. The size of the digester was determined by finding the volume of the digester.

$$V=\pi H\left(\frac{D}{2}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where;

V = volume of the whole digester,

D = diameter of the digester and,

H = height of the digester.

A review of the literature on balloon digesters suggests that the digester volume should be about 75% of the total plant volume while the gas chamber volume should be about 25% (IRENA, 2016).

Hence, V_d and V_g can be calculated by multiplying the total plant volume by 0.75 and 0.25 respectively.

The feedstock volume is gotten by (IRENA, 2016);

$$V_s = \frac{mass\ of\ solid\ waste\ (kg)}{mass\ of\ water\ (litre)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where 1 litre of water is used for 1 kg of solid waste and the volume of the feedstock should equal the volume of the digester, hence:

$$V_s = V_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

For ease of calculation, a standard PVC drum of 572 *mm* height and 375 *mm* diameter was used to construct the digester plants, hence:

$$V = \pi \times \frac{0.325^2}{2} \times 0.572 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

$V = 0.048\ m^3$

$V = 0.75 \times 0.048$

$V_s = 0.75 \times 0.048$

$V_d = 0.036\ m^3$

$V_g = 0.25 \times 0.048$

$V_g = 0.012\ m^3$

For ease of calculation, the mixture ratios and solid waste proportions for the three digesters were:

1. **First Digester**:
   - Mixture ratio: 1:1.5
   - Solid waste: 18 kg
   - Water: 30 litres
2. **Second Digester**:
   - Mixture ratio: 1:2
   - Solid waste: 12 kg
   - Water: 24 litres
3. **Third Digester**:
   - Mixture ratio: 1:1.6
   - Solid waste: 13.84 kg
   - Water: 22.14 litres

2.4 Fabrication of Digesters

The digesters were made from PVC drums. A gas outlet was perforated with a hot steel pipe, and the gas collection pipe was connected to the cover of the drums. No outlet for the effluent was provided as it was a batch digestion process. Each digester was filled with a specific mixture of cow dung, chicken waste, and kitchen waste, along with water in different ratios.

The proportions of waste in each digester were:

1. **First Digester**:
   - Cow dung: 64%
   - Chicken droplets: 27%
   - Kitchen waste: 9%
2. **Second Digester**:
   - Cow dung: 60%
   - Chicken droplets: 30%
   - Kitchen waste: 10%
3. **Third Digester**:
   - Cow dung: 64.5%
   - Chicken droplets: 29.7%
   - Kitchen waste: 5.8%

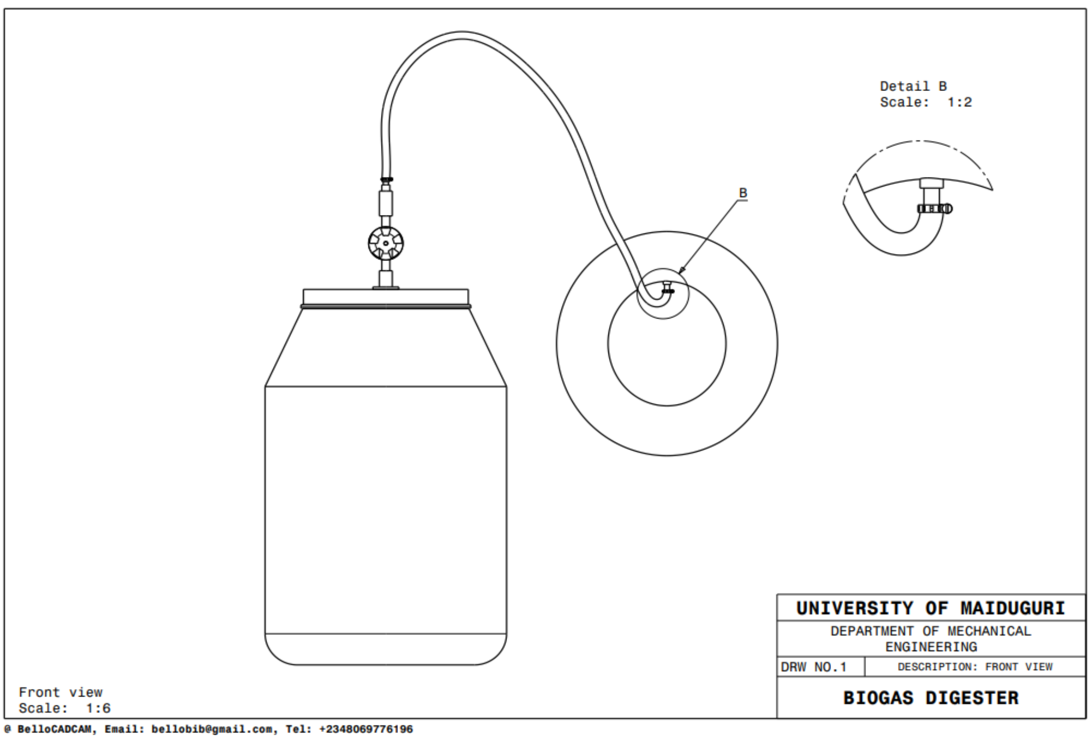

Figure 1: Front View 2D Wireframe of Digester

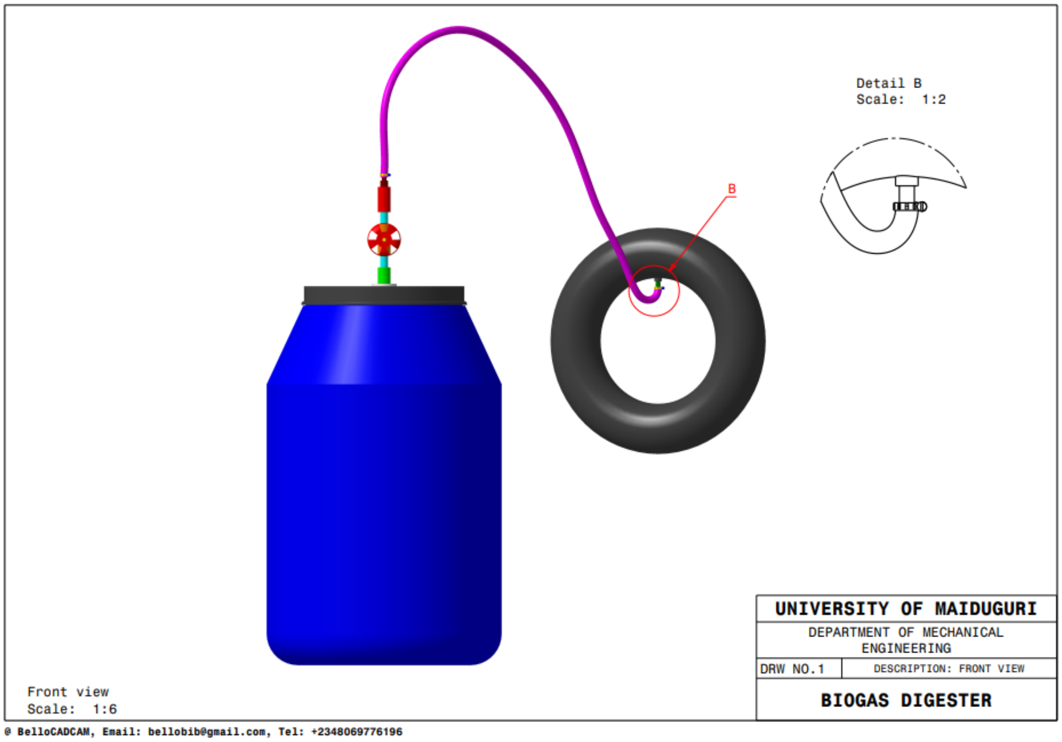

Figure 2: Front View Modelling

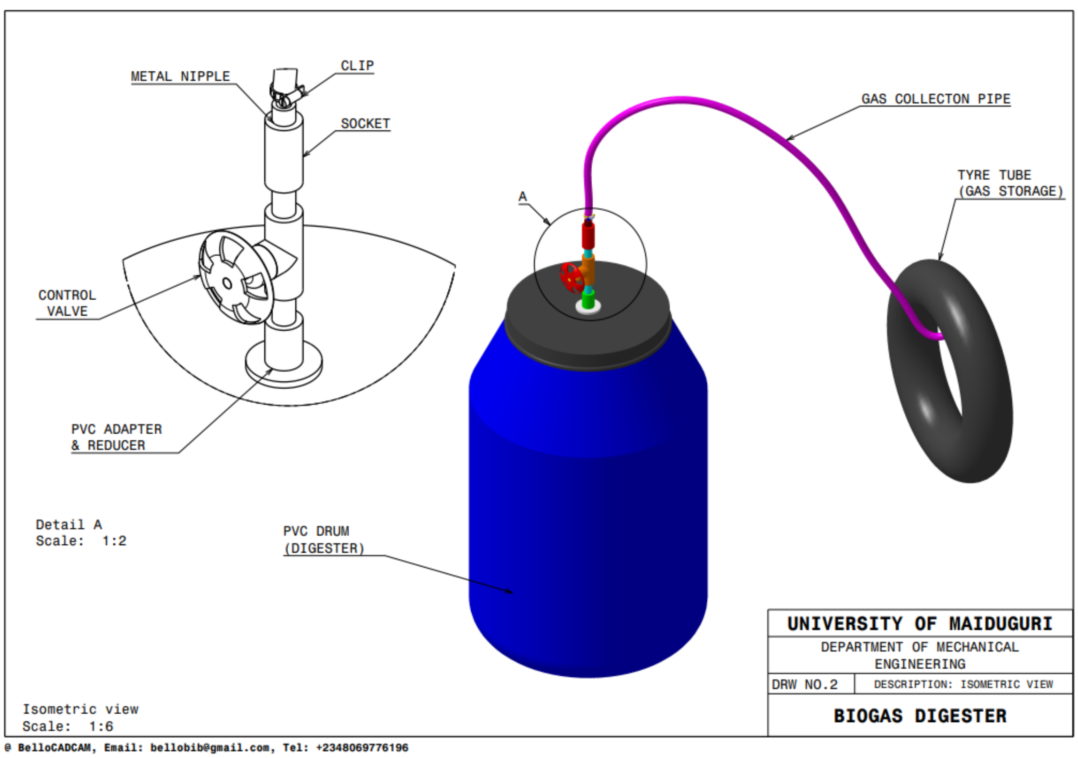

Figure 3: Isometric View Modelling

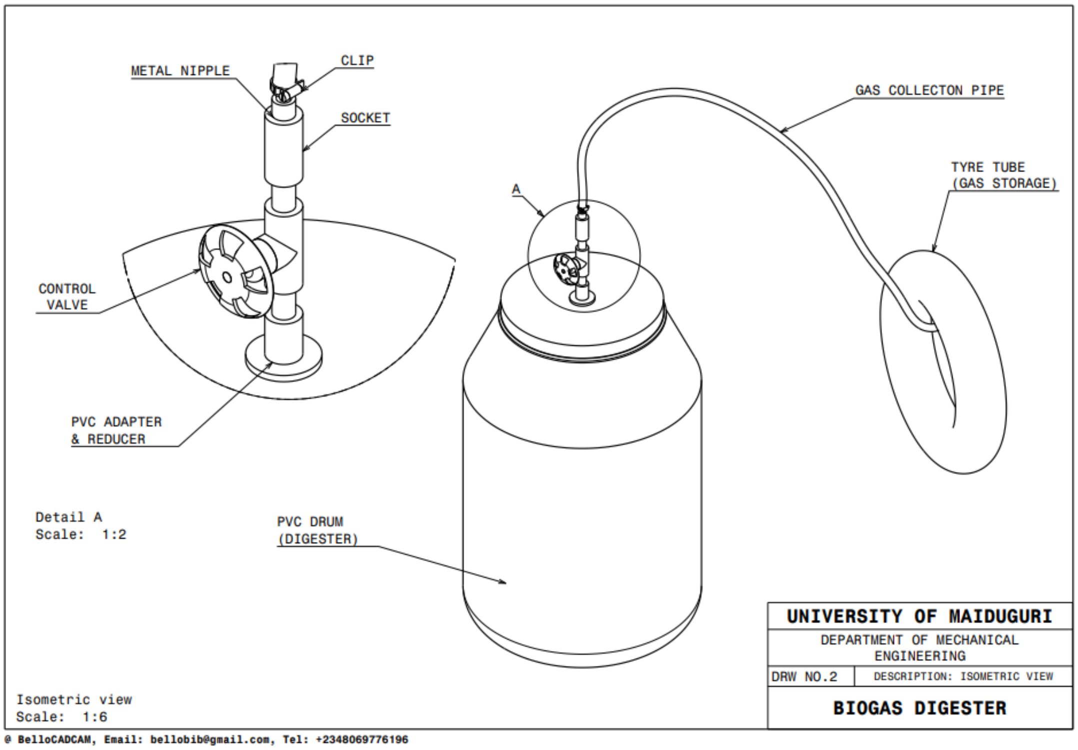

Figure 4: Isometric view

3.1 Experimental Procedure

The digesters were allowed to stay for a retention period of 14 days. The pressure, temperature, and volume were measured using a manometer with water as the manometer liquid.

4.0 Results and Discussions

4.1 Result of Temperature Measurement

The digesters were allowed to stay for a retention period of 14 to 28 days after loading, under an average daily temperature of about 24°C. From the 21st day of filling, the digester started producing methane gas. The pressure, temperature, and volume were determined for seven days using a manometer with water as the manometer liquid. The digester took a long time to start producing methane gas because the temperature was insufficient to activate the bacteria, remaining below 30°C. It took about 21 days to start producing gas as no external heat was applied.

Table 2: Average Ambient Temperature (First week)

Date	Morning T1 (°C)	Afternoon T2 (°C)	Evening T3 (°C)	Average T0 (°C)
16-12-2022	13.2	28.29	20.19	20.56
17-12-2022	13.79	25.38	20.08	19.56
18-12-2022	13.58	24.44	21.31	19.56
19-12-2022	21.21	28.58	20.24	23.34
20-12-2022	14.11	24.30	21.38	19.93
21-12-2022	15.21	26.01	23.39	21.55
22-12-2022	21.49	29.40	21.55	24.08

Table 3: Average Temperature for the Digester (Second week)

Date	Morning T1 (°C)	Afternoon T2 (°C)	Evening T3 (°C)	Average T0 (°C)
23-12-2022	15.53	30.91	21.31	22.58
24-12-2022	15.90	29.50	21.00	22.13
25-12-2022	13.86	27.33	22.05	21.08
26-12-2022	23.98	29.21	20.23	24.47
27-12-2022	18.01	28.88	23.98	23.62
28-12-2022	16.66	26.66	25.10	22.80
29-12-2022	22.55	31.54	23.96	26.01

Figure 5: Graph Showing the Average Daily Temperature during the Retention Time of 14 days (Note: T_A = temperature readings for the first seven days, while T_D = temperature readings for the second seven days).

T_A	T_D
20.56	22.58
19.56	22.13
19.56	21.08
23.34	24.47
19.93	23.62

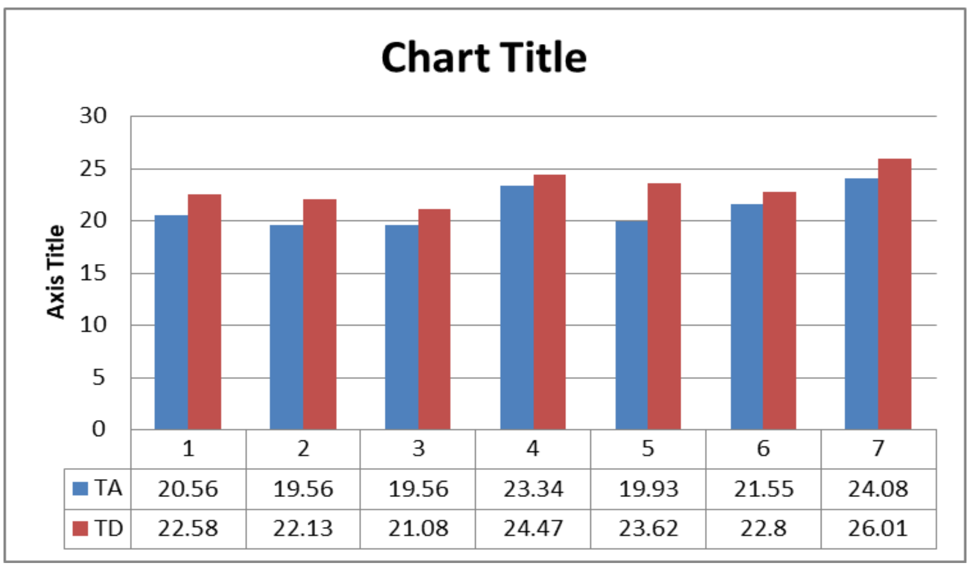

Figure 5: Graph Showing the Average Daily Temperature during the Retention Time of 14 days

4.2 Discussion

Three digesters were constructed from affordable materials. Cow dung was acquired from the school cattle farm, chicken droppings from a commercial poultry farm, and kitchen waste from restaurants in the school commercial area. Due to the low temperature, which was below 30°C, anaerobic digestion took a longer period to start, resulting in little-to-no gas yield in the first 14 days of the retention period. This project was carried out between December and January, which are the cold months in Maiduguri. The average daily temperature, as shown in the table above, was far below the optimal temperature (above 35°C) needed for proper digestion in the digester. Without external heat, the slurry took longer to start digesting.

The biogas volume and digester pressure were measured using a locally constructed manometer. Measurements were taken 14 days after loading the digesters, and subsequent measurements were taken after 7 and 14 days, respectively. The readings were poor due to low yield from the digesters. Despite this, the third digester showed the highest performance compared to the first and second digesters. Uwadia (2005) stated that higher temperatures lead to shorter retention periods and higher gas production rates, while lower temperatures have the opposite effect. This project confirms Uwadia's statement, as we could not reduce the retention period due to low daily temperatures. It is observed that biogas production, though a renewable energy source, cannot be sustained year-round due to seasonal temperature changes. Optimum digester performance and higher gas yields are obtained during hot seasons unless the temperature can be maintained or regulated at a suitable range for proper digestion to ensure year-round production. Due to the low gas yield, purification of the biogas could not be carried out. Figures 6, 7, 8 and 9 show the biogas digester at different stages.

Figure 6: After Construction

Figure 7: After 28 Days

Figure 8: After 7 days

Figure 9: After 14 Days

5.0 Conclusion

Three biogas digesters were constructed using locally available materials, demonstrating the potential for low-cost, accessible renewable energy technologies in Africa. Biogas was produced from different sources of organic material in various ratios, but production was limited, making it difficult to fully evaluate the performance of the digesters or pursue biogas purification. The study took place during the cold Harmattan period when ambient temperatures dropped below 30°C. This, combined with the lack of a stirrer, resulted in minimal biogas production within the 14-day retention period. Extending the period by 7 additional days led to a small amount of biogas, highlighting that low temperatures significantly impact retention time and biogas yield.

This research underscores the need for innovations in biogas technology that account for local climate conditions, emphasizing the importance of integrating renewable energy solutions tailored to Africa's environmental and socio-economic context. The findings also demonstrate the critical role of temperature control and agitation mechanisms in improving the performance of biogas digesters, which could inform future innovations in renewable energy technology development across the continent.

5.1 Recommendations

During the research, unforeseen circumstances affected the performance and efficiency of the digesters. Based on these factors, the following recommendations are made:

- Fresh wastes should be used when making the biogas slurry instead of dry wastes, as fresh wastes allow for proper mixing of the slurry and yield gas faster. Using dry wastes can increase the retention period for biogas production.
- The biogas digester must be airtight and free from any form of leakages, as leaks greatly affect performance. A means of testing and detecting leaks in the digester should be developed and regularly observed.
- The digester should be made from materials that are highly resistant to corrosion and have good heat retention capacity.

References

Abubakar, M. M. (1990). Biogas generation from animal waste. Nigerian Journal of Research Renewable Energy, 1, 69-73.

Agali, C. (2018). Overview of biogas production. Stanford University.

Ahmed, H. M., & Mohammed, K. (2015). The impact of climate change on the African economy. ASRIC Geology, 5, 45-58.

Ahmed Ali Baig, M., Khasim Sharif, S. K., Murthy, G. S. N., & Ramu, K. (2017). Design of bio digester for CMR Technical Campus hostel using kitchen waste.

Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. Progress in Energy and Combustion Science, 34(6), 755–781.

Asere, A. A., & Aliyu, U. O. (1992). Outlook of Nigerian energy predicament. Nigerian Journal of Renewable Energy, 3(1 & 2), 92-95.

Auer, H., et al. (2017). Agricultural anaerobic digestion power plants in Ireland and Germany: Policy and practice. Journal of the Science of Food and Agriculture, 97(3), 719–723.

Bangalore, et al. (2016). Policy incentives and adoption of agricultural anaerobic digestion: A survey of Europe and the United States. Renewable Energy, 97, 559–571. https://doi.org/10.1016/j.renene.2016.05.062

Bishop, C., Shumway, C., & Wandschneider, P. (2010). Agent heterogeneity in adoption of anaerobic digestion technology: Integrating economic, diffusion, and behavioral innovation theories. Land Economics, 86(3), 585–608. https://doi.org/10.3368/le.86.3.585

Black, B. C. (2021, December 6). How World War I ushered in the century of oil. The Conversation.

Course ENV 149. (n.d.). Water.me.vccs.edu. Retrieved December 6, 2021.

Department of Alternative Energy Development and Efficiency. (2021, October 4). Origin of biogas. Retrieved from https://weben.dede.go.th/webmax/content/origin-biogas/

Ferguson, T., & Mah, R. (2006). Methanogenic bacteria in anaerobic digestion of biomass. Environmental Protection, 18–26. Retrieved October 17, 2021.

Filip, K., & Nikko, S. (2013). Combustion of municipal solid waste for power production. In A. Hamdy (Ed.), Advances in Internal Combustion Engines and Fuel Technologies (3rd ed.). STRC.

Fotenal, J. P., Smith, I. W., & Sutton, A. L. (1983). Alternative utilization of animal waste. Journal of Animal Science, 57, 221-233.

Garba, B., Sambo, A. S., & Danshehu, B. G. (1995). Effect of some operating parameters on biogas production rate. Renewable Energy, 6(36), 343-344.

Gijzen, H. J. (2002). Anaerobic digestion for sustainable development: A natural approach. Water Science and Technology, 45(10), 321–328. https://doi.org/10.2166/wst.2002.0364

Grant, S. R., Gorur, S., Young, J. C., Landine, R., Cocci, A. C., & Churn, C. C. (2002). An anaerobic exercise: A comparison of anaerobic treatment technologies for industrial wastewater. Environmental Protection, 18–26. Retrieved October 17, 2021, from [link].

Humenik, F., et al. (2007). Agstar Conference 2004 (PDF). epa.gov. Retrieved December 6, 2021.

Klinkner, B. A. (2014). Anaerobic digestion as a renewable energy source and waste management technology: What must be done for this technology to realize success in the United States? UMass Law Review, 9, 79.

Livestock and Poultry Environmental Learning Community. (2019, October 4). Introduction to biogas and anaerobic digestion. Retrieved from https://lpelc.org/introduction-to-biogas-and-anaerobic-digestion/

Marsh, G. (2008). Rise of the anaerobic digester. Renewable Energy Focus, 9(6), 28–30. Retrieved from [link].

PennState Extension. (2012, October 17). A short history of anaerobic digestion. Retrieved from https://extension.psu.edu/a-short-history-of-anaerobic-digestion

Sidra, I. K., Shehrbno, A., Tamour Abid, C., & Muhammad Noman, Y. (2017). Production of biogas by the co-digestion of cow dung and crop residue at University of the Punjab, Lahore, Pakistan.

Sonya, D., & Venko, B. (2020). Biogas as a source of energy and chemicals. Retrieved December 18, 2021, from https://www.intechopen.com/chapters/70804

Suido, B., & Hamdy, M. (2001). The STI politics in Africa. In A. Hamdy (Ed.), The rise of modern geodynamics (3rd ed.). STRC, Abuja.

Verma, S. (2002). Anaerobic digestion of biodegradable organics in municipal solid wastes. New York: Columbia University.

Vandevivere, P., De Baere, L., & Verstraete, W. (2002). Types of anaerobic digester. In A. Hamdy (Ed.), The rise of modern geodynamics (3rd ed.). STRC, Abuja.

War on India's toxic pollution. (2020). Renewable Energy World.

Wikipedia. (2021, December 18). Energy. Retrieved from https://en.m.wikipedia.org/wiki/Energy

World Health Organization. (2018, February 26). Guidelines for good clinical practice (GCP) for trials on pharmaceutical products. pp. 19-25.