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Article

Biogas production using conventional plastic water tank digester

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Abstract: Agricultural biomass is an essential source of clean energy, particularly through technologies like anaerobic fermentation, which is used to produce biogas. This clean energy can replace fossil fuels, helping to reduce dependency on non-renewable resources. This project focuses on the design of a 0.5 m^3 fixed dome plastic biogas digester, a manual biogas compressor, and biogas production from domestic biodegradable waste such as dry leaves, kitchen waste, and grass. The experiment involved mixing 120 kg of biodegradable waste with 300 kg of water and feeding it into the digester. Three batch experiments were conducted over three months. The first two months did not yield successful results, but in the third month, the digester produced 1 kg of biogas at an ambient temperature of 34 ℃ to 35 ℃. Negative pressure was observed at the start, indicating some aerobic digestion before anaerobic digestion began. The maximum pressure in the digester reached 7172.75 Pa on day nine, with a gas yield of 0.15 kg on the same day. Combustible gas production started after 20 days, and the gas produced over the next 30 days was compressed into cylinders for mobility. This success highlights the potential of biogas technology to contribute to the energy mix and address current energy challenges. The study also investigates the performance and durability of PVC (polyvinyl chloride) used in biogas digesters over a three-month period, considering long-term environmental exposure. PVC is a widely used thermoplastic polymer, known for its chemical resistance, cost-effectiveness, and strength. These properties make it suitable for small- to medium-scale digesters, particularly under mesophilic conditions (35 ℃–40 ℃). The PVC digester-maintained gas retention and structural integrity without significant degradation during the observation period. However, long-term exposure to UV radiation and thermal fluctuations presents challenges, as PVC degrades under UV exposure, leading to brittleness and cracking. Prolonged exposure to high temperatures may also cause PVC to soften, especially in thermophilic conditions (>50 ℃). Predictions suggest that PVC digesters could last 5–8 years with UV protection and under optimal conditions. Without UV stabilization or in harsh environments, their lifespan may be reduced to 2–4 years. Regular maintenance, temperature management, and UV protection are crucial for extending the durability of PVC-based digesters.

Keywords: biogas; anaerobic digestion; plastic digester; anaerobic digestion

1. Introduction

1.1. Background

The basis of life is energy. The most fascinating feature of any civilized society is the availability of energy for domestic, agricultural, and industrial purposes [1]. Africa's energy sources include wood, fossil fuels (coal, petroleum, and natural gas), hydropower, solar energy, biogas, and more [2]. According to the Food and Agriculture Organization (FAO), Nigeria experienced the highest deforestation rate globally, losing 55.7% (9,587,577 hectares) of its primary forest between 2000 and 2005. Additionally, the country consumes 50 million tons of wood fuel annually [3].

Biogas can be used as a means of transportation. The transport sector plays a crucial role in the decarbonization efforts to combat climate change. Greenhouse gas emissions from this sector must be reduced by 40%–42% compared to 1990 levels [4]. This contributes to a more economical and environmentally friendly power system by lowering fuel costs, reducing greenhouse gas emissions, and meeting energy demand [5].

Nigeria’s government operates at three levels: the national government, 36 state governments, and 772 local governments. The country’s energy challenges are widespread, requiring coordination of energy-related decisions across all levels of government [1]. A more pressing issue is the growing population, leading to higher energy demand and the rapid depletion of limited energy resources, potentially triggering a severe energy crisis. Additionally, Nigeria’s energy sector has significant environmental consequences, particularly through pollution and deforestation [1].

In recent years, the cost of energy for domestic, commercial, and industrial use in Nigeria has skyrocketed, largely due to the liberalization and reforms in the oil industry and the energy sector as a whole. This rise in energy costs has become a major factor influencing the prices consumers pay for goods and services [6]. This necessitates the implementation of robust measures and effective policies to optimize the utilization, exploration, and exploitation of our energy resources while also promoting the development and conservation of alternative energy sources. This alternative energy must be accessible and affordable for rural populations, as around 70% of Africa’s total population relies almost entirely on fuel wood [7]. This would diversify our country’s energy mix, boost the economy, and contribute to a safer, cleaner environment. However, the unsustainable use of primary biofuels in many developing nations has led to issues such as deforestation, desertification, erosion, and loss of biodiversity [2]. Hence, efforts should be geared to reverse this trend by proper use of this alternative energy source biomass.

Due to its availability, sustainability, accessibility, and renewability, biogas is a more preferable alternative to fossil fuels. It is locally sourced and produced, making it an ideal energy option for various applications, including heating, lighting, and small-scale electricity generation [8]. Given the points mentioned above, biogas production is seen as a beneficial solution for domestic, agricultural, and industrial applications. Biogas is a combustible gas generated through the anaerobic digestion of biodegradable organic materials, including straw, weeds, human and animal waste, garbage, sludge, domestic sewage, and organic liquid waste from factories [9]. Utilizing plastic materials in the construction of biogas digesters offers advantages like reduced weight, cost-effectiveness, and resistance to corrosion. Below is an outline of a conceptual design for a plastic biogas digester:

1.2. Biogas benefits

“A biogas system generates clean energy for household use. After an initial investment in the system, cooking with biogas becomes quicker and easier than using firewood. Additionally, biogas systems eliminate bacteria in livestock manure, making farms with these systems cleaner and safer. They also produce high-quality, safe fertilizer for agricultural use. By enabling the combustion of methane from organic waste instead of allowing it to escape into the atmosphere—where it contributes to the greenhouse effect—biogas systems can aid in the fight against global warming. Moreover, biogas provides an alternative cooking method, helping to preserve our trees." [10]. It has also been found that at standard temperature and pressure (s.t.p.), 1 cubic meter of biogas can provide as much light as a 60–100 watt bulb for six hours, cook three meals for a family of 5 to 6 people, replace 0.7 kg of petrol, and generate 1.25 kilowatt-hours of electricity [10].

1.3. Biogas generation

Anaerobic digestion (AD) is a natural biological process carried out by bacteria in the absence of air, in which organic material is broken down into stable fertilizer and useful biogas which comprises mainly methane and carbon dioxide. These anaerobic bacteria are an integral component of nature's waste management and are commonly found in soils and waters, as well as in landfill sites [11]. Biogas is generated through the anaerobic digestion of organic waste materials, including cattle dung, vegetable scraps, sheep and poultry droppings, municipal solid waste, industrial wastewater, and landfill waste [12]. Biogas is a clean fuel that can be utilized similarly to other gas fuels for both household and industrial applications, including gas cookers and stoves, lamps, radiant heaters, incubators, refrigerators, and engines [13]. Methane from our bio-waste is 22 times more harmful to the atmosphere than CO_2. However, when burned, this methane produces almost neutral or reduced amounts of carbon dioxide, which has a lesser impact on our ecosystem". Nigeria has been blessed with abundant biogas potential from biomass and is situated along the equatorial tropical Guinea savannah zone. Only a small percentage of it is being utilized. The remaining goes as waste to our ecosystem. Therefore, if an affordable method for converting it into a useful form, such as biogas, is developed, it would be highly beneficial. This would contribute to our country's energy mix, boost the economy, and create a safer, cleaner environment. However, the current materials used for constructing biogas digesters, such as metal and concrete, have limitations and can be too expensive for the average person, highlighting the need for more effective alternatives like plastic. The significance of this project lies in providing an efficient and affordable digester, creating an alternative to fossil fuels, and generating revenue and job opportunities.

The primary goal is to design a low-cost, durable, and portable plastic biogas digester that can be used in rural or semi-urban areas to produce biogas for cooking, heating, or electricity generation, and also generate nutrient-rich slurry as a by-product.

1.4. Advantages of using plastic for biogas digesters

1) Cost-effectiveness: Plastic is generally cheaper than steel or concrete alternatives.
2) Lightweight & Portable: Ideal for small-scale or household systems, particularly in rural areas.

3) Corrosion Resistance: Plastic materials like HDPE and PVC are resistant to chemicals produced during anaerobic digestion.
4) Ease of Manufacturing: Can be produced at scale using mold-based or rotational plastic molding methods.

1.5. Environmental and social impact

1) Waste Reduction: Utilizes organic waste that would otherwise contribute to landfill or methane emissions.
2) Renewable Energy: Provides a sustainable source of biogas, reducing reliance on firewood or fossil fuels.
3) Soil Fertility: The slurry by-product can be used as an organic fertilizer, contributing to sustainable agriculture.

1.6. Safety considerations

1) Gas Leakage: The design must ensure that all gas fittings and seals are airtight to prevent methane leaks, which are a safety hazard.
2) Pressure Control: A pressure relief valve can be incorporated to prevent gas build-up in the system, which could lead to damage or explosion.

2. Literature review

2.1. Research background on biogas generation

The history of biogas utilization reveals independent advancements in both developing and industrialized nations. The biogas history in Europe, particularly in Germany, along with developments in Asian countries, provides the foundation for Germany's efforts and initiatives to promote biogas technology on a global scale [1]. "The history of biogas exploration and utilization in China spans over 50 years. The first biogas plants were constructed in the 1940s by affluent families. Since the 1970s, biogas research and technology have advanced rapidly, with strong support from the Chinese government to promote biogas technology. In rural areas, more than 5 million small biogas digesters have been built, and currently, over 20 million people use biogas as a fuel source [14]. In India, the development of simple biogas plants for rural households began in the 1950s, and there was a significant surge in the number of biogas plants in the 1970s due to robust government support. Today, India has more than one million biogas plants. The historical experiences of Germany, China, and India clearly illustrate how favorable conditions foster biogas development. In Germany, the spread of biogas technology was driven by the need for alternative energy sources in a war-torn economy and during an energy crisis, as well as changes in electricity pricing [14].

2.2. Biogas technology

It is characterized as an ecology-oriented form of appropriate technology that relies on the degradation of organic materials at stable and suitable temperatures to generate a combustible mixture of methane and carbon dioxide, referred to as biogas, while leaving behind a digested slurry known as bio-fertilizer. Biogas is a flammable gas produced during the anaerobic digestion of biodegradable organic materials, including straw, weeds, human and animal waste, garbage, sludge, domestic sewage, and organic liquid waste from factories [9].

2.3. Composition of biogas

Biogas is generally a colorless and flammable gas composed of approximately 50%–70% methane (CH_4, 30%–40% carbon dioxide (CO_2), and trace amounts of other gases, including hydrogen (H_2), hydrogen sulfide (H_2S), nitrogen (N_2), and various hydrocarbons [15].

2.4. Why biogas?

Domestic animal droppings and organic materials, including daily domestic and industrial waste from latrines and urine, pose disposal challenges due to their natural decomposition processes. However, engineers and scientists have recognized that rather than letting valuable gases escape into the atmosphere, we can manage their release to harness the significant energy they provide. This realization serves as the foundation for ongoing research on biomass [1].

Each year, approximately 590 to 880 million tons of methane are released into the atmosphere globally due to microbial activity. Around 90% of this emitted methane originates from biogenic sources, primarily from the decomposition of biomass, while the remaining portion comes from fossil sources, such as petrochemical processes. In the Northern Hemisphere, the current tropospheric methane concentration is roughly 1.65 ppm [14].

2.5. Sources of biogas

Biogas is defined as a mixture of methane, carbon dioxide, and hydrogen sulfide produced through the bacterial decomposition of sewage, manure, garbage, or plant materials [16]. Different materials from which biogas can be generated are shown in **Table 1**. In Georgia, several engineering companies, research institutes, and individuals have expertise in biogas production. Notable among them are Bioenergia Ltd., Konstruktori Ltd., and the Georgian National Centre of High Technology. In the 1990s, Bioenergia Ltd. developed small-scale mesophilic biogas reactors of both fixed-dome and floating-dome types. While these systems are easy to operate, they are less efficient in terms of biogas production. Considering local conditions, these reactors are the most appealing technologies for households with 1–2 livestock. Subsequently, Bioenergia developed more efficient mesophilic biogas reactors with a volume of 6 m^3, which require waste from at least four livestock. The first bioreactor was constructed in Sasireti, Kaspi, in 1994. That same year, Bioenergia Ltd. received a patent, and in 1996, it published and distributed its brochure titled “Construction and Maintenance of Biogas Installations” with support from “World Vision.” Between 1994 and 1996, bioreactors were installed in Gurjaani, Dedoplistskaro, Gardabani, Tsalka, and Chakvi, with some installations supported by the US Agency for International Development (USAID) [17].

Table 1. Different materials from which biogas can be generated [9].

Crop waste	**Sugarcane trash, weed, corn and related crops stubblestraw spoil fodder, etc.**
Wastes of animal origin	Cattle shed wastes (dung, urine litter) poultry litter,sheep and goat droppings, slaughterhouse wastes (blood, meat) fishery wastes, leather, wood wastes etc.
Wastes of human origin	Faeces, urine, refuse.
By-product and wastes from agriculturally basedindustries	Oil cakes, bagasse, rice bran, tobacco waste and seeds, waste from fruit and vegetable processing, press frommud sugar.
Forest litter	Twigs bark, branch and leave.
Wastes from aquatic Growth	Marine algae, seaweeds, water hyacinths, etc.

2.6. The biochemical process of anaerobic digestion

Understanding the fundamental processes of methane fermentation is essential for the planning, construction, and operation of biogas plants. Anaerobic fermentation is facilitated by the interactions of three distinct bacterial communities. The biogas production process is influenced by various parameters, such as ambient temperature changes, which can adversely affect bacterial activity [14].

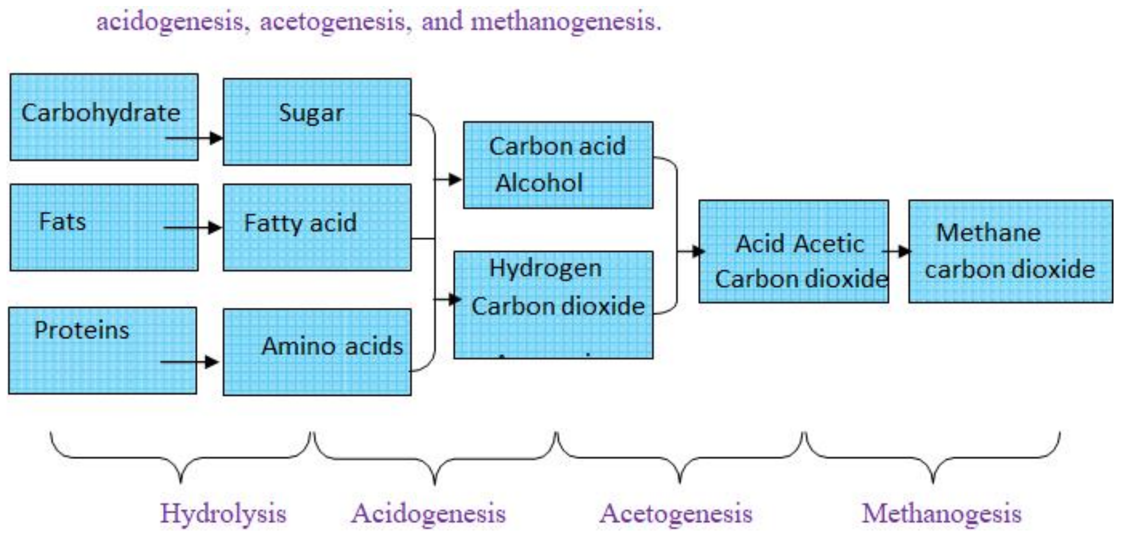


Figure 1. The main process steps of anaerobic digestion [1].

The biochemical process of anaerobic digestion (AD) consists of four distinct steps. As mentioned earlier, anaerobic digestion is a microbiological process that decomposes organic matter in the absence of oxygen. The primary products of this process are biogas and digestate. Biogas is a combustible gas mainly composed of methane and carbon dioxide, while digestate is the decomposed substrate and a by-product of biogas production. Unlike aerobic decomposition, such as composting, anaerobic digestion generates very little heat. The energy chemically stored in the substrate primarily remains in the biogas produced, primarily in the form of methane. Biogas formation occurs through interconnected process steps, where the initial material is continuously broken down into smaller components. Specific groups of microorganisms are involved in each step, successively decomposing the products of the previous stages. **Figure 1** presents a simplified diagram of the anaerobic digestion process, illustrating its four main steps, including hydrolysis.

The process steps depicted in **Figure 1** occur simultaneously in both time and space within the digester tank. The overall speed of the decomposition process is governed by the slowest reaction in the sequence. In biogas plants that process vegetable substrates containing cellulose, semi-cellulose, and lignin, hydrolysis is the rate-limiting step. During hydrolysis, only small amounts of biogas are produced, while biogas production peaks during the methanogenesis phase.

1) Hydrolysis

Figure 2 represents hydrolysis, which is theoretically the initial step of anaerobic digestion, where complex organic matter (polymers) is broken down into smaller units (monomers and oligomers). During this phase, polymers such as carbohydrates, lipids, nucleic acids, and proteins are transformed into simpler substances like glucose, glycerol, purines, and pyridines. Hydrolytic microorganisms release hydrolytic enzymes that facilitate the conversion of biopolymers into simpler, soluble compounds, as illustrated below:

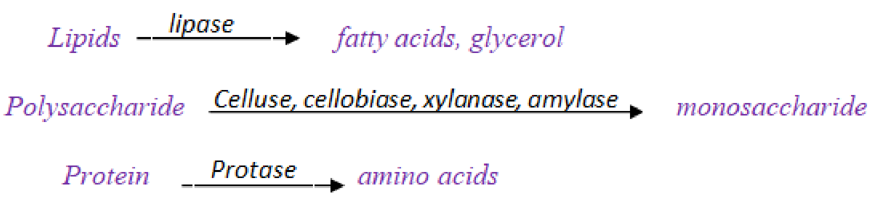


Figure 2. Hydrolysis.

Hydrolysis involves a diverse range of microorganisms that utilize exoenzymes to break down undissolved particulate material. The products generated from hydrolysis are subsequently decomposed by these microorganisms and utilized in their own metabolic processes.

2) Acidogenesis

During acidogenesis, the products of hydrolysis are transformed by acidogenic (fermentative) bacteria into substrates suitable for methanogenesis. Simple sugars, amino acids, and fatty acids are broken down into acetate, carbon dioxide, and hydrogen (70%), along with volatile fatty acids (VFA) and alcohols (30%).

3) Acetogenesis

During acetogenesis, products from acidogenesis that cannot be directly converted to methane by methanogenic bacteria are transformed into substrates suitable for methanogenesis. Volatile fatty acids (VFA) and alcohols are oxidized into methanogenic substrates such as acetate, hydrogen, and carbon dioxide. VFAs with carbon chains longer than two units, as well as alcohols with carbon chains longer than one unit, are oxidized to produce acetate and hydrogen. The production of hydrogen raises the hydrogen partial pressure, which acts as a waste product of acetogenesis and inhibits the metabolism of acetogenic bacteria. In the methanogenesis phase, hydrogen is converted into methane. Acetogenesis and methanogenesis typically occur simultaneously, functioning as a symbiotic relationship between the two groups of organisms.

4) Methanogenesis

Figure 3 represents anaerobic digestion in which the methanogenic bacteria are responsible for producing methane and carbon dioxide from intermediate products. Approximately 70% of the methane generated comes from acetate, while the remaining 30% is produced through the conversion of hydrogen (H) and carbon dioxide (CO_2), as shown in the following equations.

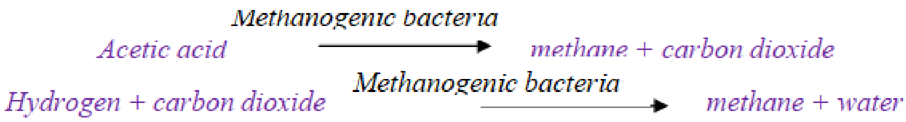


Figure 3. Anaerobic digestion.

Methanogenesis is a crucial phase in the anaerobic digestion process, as it is the slowest biochemical reaction involved. This step is highly sensitive to operational conditions. Factors such as feedstock composition, feeding rate, temperature, and pH significantly impact the methanogenesis process. Overloading the digester, fluctuations in temperature, or a substantial influx of oxygen can halt methane production [1].

2.7. Operational parameters

1) Organic load

The construction and operation of a biogas plant involve a blend of economic and technical factors. To achieve maximum biogas yield through complete digestion of the substrate, a long retention time inside the digester and a correspondingly large digester size are necessary. However, in practice, the design of the system (including digester size and type) and the applicable retention time are typically based on a compromise between maximizing biogas yield and ensuring economic viability for the plant. In this context, the organic load is a crucial operational parameter that indicates the amount of organic dry matter that can be introduced into the digester per volume and time unit, as described by the equation below:

$$BR = \frac{mc}{VR} \tag{1}$$

where *BR* is organic load (kg/dm^3), *m* = mass of substrate fed per time unit (kg/d), *c* is the concentration of organic matter (%), *VR* = digester volume (m^3).

2) Hydraulic retention time (HRT)

A key parameter for sizing the biogas digester is the hydraulic retention time (HRT). The HRT represents the average duration that the substrate remains inside the digester tank. It is related to the digester's volume and the volume of substrate introduced per unit of time, as described by the following equation.

$$HRT = VR/V \tag{2}$$

where *HRT* = hydraulic retention time (days) *VR* = digester volume (m^3), *V* = volume of substrate fed per time unit (m^3/d).

According to the equation above, increasing the organic load results in a reduction of the hydraulic retention time (HRT). The retention time must be sufficiently long to ensure that the quantity of microorganisms lost with the effluent (digestate) does not exceed the quantity of microorganisms reproduced. The duplication rate of anaerobic bacteria is typically 10 days or longer. While a shorter HRT allows for a good substrate flow rate, it yields less gas. Therefore, it is essential to adjust the HRT to align with the specific decomposition rate of the substrates used. By knowing the desired HRT, daily feedstock input, and the decomposition rate of the substrate, it becomes possible to calculate the required digester volume [1]. A well-regulated digester typically has an average retention time of about 20 to 25 days. A shorter retention time increases the risk of washout, a situation in which active biogas bacteria are flushed out of the digester before reaching maturity, resulting in an unstable and potentially inactive bacterial population [18].

2.8. Factors affecting biogas production

1) Temperature and Retention Time

Generally, the anaerobic process is influenced by temperature. Research indicates that biogas fermentation can occur within a temperature range of 0 ℃ to 70 ℃. The anaerobic digestion process can be categorized into three types based on temperature ranges: mesophilic (30 ℃–49 ℃), thermophilic (50 ℃–60 ℃), and psychrophilic (0 ℃–10 ℃). At mesophilic temperatures of 32.2 ℃–37.8 ℃, the retention time for digesting cattle dung or plant waste is between 28 and 45 days. Studies have shown that at temperatures between 35 ℃–45 ℃, the retention time decreases to 20–30 days. In contrast, at thermophilic temperatures of 50 ℃–60 ℃, the retention time is reduced to just 10 days. It is evident that temperatures above 65 ℃ allow only a few bacterial strains to survive, which can decrease the population of pathogenic organisms, including methane-producing bacteria, thus shortening the retention period. Additionally, anaerobic processes at temperatures below 10 ℃ are considerably slower [8].

Experiments indicate that a sudden increase or decrease of 5 ℃ in fermentation temperature can slow down biogas production. A more significant temperature change may even halt biogas generation and lead to acidification of the fermentation system due to the accumulation of volatile acids. Therefore, to achieve optimal results, it is essential to maintain a stable temperature carefully within the chosen operating range [8].

2) Concentration

The concentration in a biogas digester refers to the percentage of total solids in the entire fermentation material. Biogas fermentation necessitates a specific range of material (total solid) concentration, which typically spans from 1% to 30%. For optimal biogas production, the percentage of volatile solids should constitute 10 % of the total slurry [19]. "Literature indicates that at high temperatures, materials decompose more easily, and a low total concentration of 6% is recommended. In contrast, at lower temperatures, decomposition occurs very slowly, making a concentration of about 10% of the total slurry preferable. If the material concentration is excessively high during the digester startup, it can lead to excessive acid production, which inhibits the activity of methanogenic bacteria and causes a decline in pH.

pH is a crucial factor influencing biogas production. Research has shown that anaerobic bacteria thrive in a neutral environment, requiring a pH range of 6.4 to 7.2 for optimal biogas production. In typical digestion processes, maintaining a neutral pH balance is essential for maximizing gas output. However, when the slurry becomes too acidic or too basic, gas production diminishes.

3) Seeding

Seeding involves introducing bacteria or inoculants, which are microbes that break down organic substrates to produce biogas. Without a sufficient quantity of these microbes, biogas production is not possible. Seeding refers to adding slurry containing microbes to freshly prepared slurry. Studies have shown that after feeding the digester with new slurry, it may take several days to start producing gas. However, when seeding is applied, gas production begins immediately. If the amount of inoculum added is inadequate, it can lead to excessive acid production, inhibiting the activity of methanogenic bacteria and causing a decline in pH. Practical experience indicates that the gas yield with the highest seeding amount can be eleven times greater than that with the lowest amount of seeding material.

4) Stirring

This is one of the factors influencing biogas production. Research has shown that gas production declines when stirring is entirely omitted, leading to scum formation. Without stirring, layers develop in the biogas digester: an upper layer that floats, a middle layer of thick liquid, and a bottom layer of residue. Consequently, microbes struggle to access fresh materials, absorb nutrients, and expel waste, resulting in scum formation. In contrast, stirring the digester promotes a uniform distribution of feedstock and seeding bacteria. When microbes come into contact with fresh materials, the digestion rate increases, thereby enhancing gas yield. Additionally, CO_2 and CH_4 can be more easily released from the slurry.

5) Carbon/Nitrogen Ratio (C:N)

C:N ratio is very important in biogas production. There is an increase of 60%–70% methane yields when C:N ratio was changed from 8 to 25 by adding glucose or cellulose. There are different views existing on the proper C: N ratio of feedstock. C:N ratio of between 15 and 30 is required. Research shows that the ratio may not be so strict, but it is commonly known that C:N ratio of 20–30 is acceptable. Various kinds of raw materials vary in their C:N contents [19].

6) Additives or promoters

Certain substances can enhance the degradation of organic matter in a digester, significantly increasing gas production. These substances include enzymes, inorganic salts, organic materials, and various other additives. For example, adding cellulose to the feed digester can lead to a notable increase in gas production. Other effective additives or promoters include urea (NH_2CONH_2), calcium carbonate ($CaCO_3$), and nitrogenous fertilizers, among others.

7) Chemical Inhibitor

Several substances can be toxic or inhibitory to the biogas production process, leading to a reduction in gas yields, sometimes even to zero. These substances can be either organic or inorganic [1].

2.9. Types of digesters by design

For biogas production, organic materials such as animal and plant waste are combined with water and placed in an oxygen-free tank, or in some cases, a plastic membrane for digestion. Balloon plants.

The balloon plant features a digester bag (e.g., PVC) where gas is stored in the upper section. The inlet and outlet are directly attached to the plastic surface of the balloon. Gas pressure is created through the balloon's elasticity and by adding weights on top of it.

Advantages:

Some advantages include low cost, ease of transportation, simple construction, high digester temperatures, and straightforward cleaning, emptying, and maintenance.

Disadvantages:

On the downside, the balloon plant has a relatively short lifespan, high susceptibility to damage, and limited local employment opportunities, resulting in constrained self-help potential. A variant of the balloon plant is the channel-type digester, typically covered with plastic sheeting and a sunshade (see **Figure 3e**). Balloon plants are best suited for environments where the balloon material is unlikely to be damaged and where temperatures remain consistently high [1].

1) Fixed-dome plants

The fixed-dome plant features a digester with a stationary, non-movable gas holder positioned on top. When gas production begins, the slurry is pushed into the compensation tank. Gas pressure increases as the volume of gas stored rises, influenced by the height difference between the slurry levels in the digester and the compensation tank.

Advantages:

Some advantages include relatively low construction costs, the absence of moving parts, and a lack of rusting steel components. If built correctly, fixed-dome plants can have a long lifespan. Their underground design saves space and protects the digester from temperature fluctuations while providing opportunities for skilled local employment.

Disadvantages:

A significant drawback is the common issues related to the gas-tightness of the brickwork gas holder; even a small crack in the upper brickwork can lead to substantial biogas losses. Therefore, fixed-dome plants are recommended only in locations where construction can be supervised by experienced biogas technicians. Additionally, gas pressure can vary significantly based on the volume of gas stored, and digester temperatures are generally lower, even though the underground design mitigates temperature extremes.

2) Floating-drum plants

"Floating-drum plants consist of an underground digester paired with a movable gas holder. The gas holder floats either directly on the fermentation slurry or within its own water jacket. As gas accumulates, the gas drum rises or descends accordingly. A guiding frame prevents the drum from tilting, and if it is floating in a water jacket, it remains free from obstructions, even in high-solid substrates.

Advantages:

Some advantages include the ability to visibly monitor the volume of stored gas. The gas pressure remains constant, determined by the weight of the gas holder. The construction is relatively straightforward, and any construction errors do not significantly impact operational efficiency or gas yield.

Disadvantages:

However, there are some disadvantages, such as the high material costs associated with the steel drum and its susceptibility to corrosion. Consequently, floating-drum plants generally have a shorter lifespan compared to fixed-dome plants and incur regular maintenance costs for repainting the drum. Currently, there are several U.S. patents related to biogas digestion technology, many of which focus on biodiesel production, while others are specifically aimed at the design and construction of digesters for biogas [1].

3. Digester creation

3.1. Conceptual design

For the digestion chamber (primary reactor) material, a polyvinyl chloride (PVC) water tank is adopted, which is UV-resistant and chemically inert. The shape of the digester is cylindrical or dome-shaped for structural stability and ease of installation. The size varies depending on the expected biogas output; small units can range from 1 m^3 to 10 m^3. The function is the main chamber where the anaerobic digestion occurs. The organic waste is broken down by microbes in an oxygen-free environment, producing biogas. The inlet pipe material is PVC or flexible plastic tubing. The design is a funnel or hopper connected to a PVC pipe. The purpose is to allow feeding of organic waste into the digester. It should be wide enough to accommodate the passage of slurry or solid waste. The positioning is sloped downward to ensure easy flow of organic waste into the digester. The outlet pipe material is similar to PVC pipe as an inlet as to discharge the digested slurry, which is rich in nutrients and can be used as fertilizer. The positioning is isolated at the bottom of the digester, ensuring the processed slurry can be collected for further use. The gas outlet is a separate rubber hose. The gas control valve is a simple valve to control the flow of biogas from the digester to the usage point (cooking stove, lamp, or generator). For the agitator/stirrer, it is a simple manual paddle that ensures homogenous mixing of the slurry, improving the digestion process. And the material is corrosion-resistant round metal pipe. There is an anaerobic seal to ensure the chamber is airtight to maintain the anaerobic (oxygen-free) environment required for biogas production. The digester cover must have a robust sealing mechanism, possibly with rubber or silicone gaskets. For the temperature control insulation around the plastic digester to achieve an optimal temperature range (35 ℃–45 ℃) for efficient biogas production. An overflow mechanism is incorporated with an overflow pipe to prevent overloading the digester with too much slurry. The excess liquid can flow out through a separate discharge outlet.

3.2. Specific properties of PVC (polyvinyl chloride)

Polyvinyl chloride (PVC) is a widely used thermoplastic polymer due to its durability, low cost, and resistance to environmental degradation. When used in biogas production systems, such as digesters, its unique properties contribute to system efficiency and longevity, as indicated in **Table 2**.

Table 2. Key properties of PVC relevant to biogas production.

Property	**Value/description**	**Impact on biogas digester**
Chemical Resistance	Excellent resistance to acids, bases, salts, and organic compounds.	Withstands corrosive biogas (H_2S and CO_2), preventing degradation.
Temperature Tolerance	Softens at 60 ℃–80 ℃ (glass transition temperature). - Maximum operating temperature: 60°C (continuous).	Suitable for mesophilic (35 ℃–40 ℃) and some thermophilic (50 ℃–60 ℃) digestion.
Durability and Strength	High tensile strength: ~52–60 MPa	Provides structural integrity to digesters.
Water Resistance	Impermeable to water, with low water absorption.	Prevents leaks and gas loss in biogas systems.
Low Thermal Conductivity	~0.14 W/m·K	Reduces heat loss, maintaining digester temperature.
Cost-Effective	Relatively low production and installation costs.	Reduces the overall cost of digester construction.
UV Stability	PVC degrades under prolonged UV exposure but can be treated with stabilizers.	Suitable for indoor or shaded digesters.

3.3. How PVC properties influence biogas digester performance

1) Chemical Resistance:
   (1) Biogas contains hydrogen sulfide (H_2S) and carbon dioxide (CO_2), which can corrode metals and some materials.
   (2) PVC's excellent resistance to these corrosive gases ensures long-lasting performance and minimizes maintenance.
2) Temperature Tolerance:
   (1) Most biogas digesters operate in the mesophilic range (35 ℃–40 ℃), where PVC performs reliably without softening or deforming.
   (2) For thermophilic digestion (50 ℃–60 ℃), PVC can tolerate short-term exposure but is less ideal for continuous use above 60°C.
3) Durability and Strength:
   (1) PVC pipes and linings provide robust structural support, essential for maintaining gas-tight conditions in digesters.
   (2) The material can withstand internal pressure and mechanical stress, ensuring gas containment.
4) Low Thermal Conductivity:
   (1) PVC's insulating properties help maintain stable internal temperatures, reducing heat loss and improving digestion efficiency.
   (2) This is particularly beneficial for digesters in cooler climates.
5) Water Resistance:

PVC is impermeable to water and gases, preventing leaks that can compromise digester performance and biogas yield.

6) Cost-Effectiveness:

PVC is affordable and easy to install, making it a cost-efficient choice for constructing small- to medium-scale digesters.

7) UV Stability:

While PVC degrades under prolonged sunlight exposure, UV-stabilized PVC is available for outdoor digesters, extending the lifespan of the material.

PVC is an ideal material for biogas digesters in terms of cost, durability, and resistance to harsh chemical and thermal conditions. Its low thermal conductivity ensures better temperature regulation, enhancing microbial activity for efficient biogas production. The key advantages of PVC for biogas digesters:

(1) Long-lasting in corrosive environments.
(2) Suitable for mesophilic temperature ranges (35 ℃–40 ℃).
(3) Low cost and easy installation.
(4) Prevents gas leaks and heat loss.

4. Design

4.1. Design for fixed dome digester

The plastic tank is treated as a thin-walled pressure vessel. The total pressure in the tank is the pressure developed by the gas and the slurry [20].

$$P_T = P_g + P_{sl} \tag{3}$$

$$P_s = \rho g h \tag{4}$$

where ρ = density of the slurry = 1133kg/m^3. The stresses induced by the total pressure according to Khurmi and Gupta (2005) are:

1) Hoop stress

$$\sigma_{t1} = \frac{pd}{2t} \tag{5}$$

2) Longitudinal stress

$$\sigma_{t2} = \frac{pd}{4t} \tag{6}$$

3) Maximum shear stress

$$\tau \frac{pd}{4t}_{max} \tag{7}$$

where P is total pressure (N/m^2), d is the diameter of the vessels (m),t is the thickness of the vessel (m) [21].

The yield stress of the plastic σ_y is between 50 MPa and 65 MPa [1].

4.2. Design for cover digester

The gas on top of the slurry will build up pressure, which induces the longitudinal stress above. Hence, the bolt should resist this pressure. Therefore, under this, it involves the design for the bolt and cover plate.

4.3. Design for bolt

Assuming the gas will only try to escape through the mouth and no gas leakage, the upward force F_g, acting on the digester cover due to gas, must be resisted by n number of bolts fastening the lid.

$$F_g = \frac{\pi D^2 P}{4} = \frac{\pi d_c^2 \sigma_{th} \times n}{4} \tag{8}$$

where D is the diameter of the digester (350 mm), d_c n is the number of bolts, P is the internal pressure, and σ_{th} is the permissible tensile stress of the bolt.

The number of bolts is calculated using,

$$n = \frac{\pi D_P}{S_b} \tag{9}$$

where S_b is the inter-bolt spacing (80 mm), D_P pitch diameter (mmm) [21].

4.4. Design for cover plate

To ensure leak-proof conditions, AISI/SAE 1023 sheets are used for rigidity. The thickness t is given as:

$$t_1 = k_1 d \sqrt{\frac{P}{\sigma_1}} \tag{10}$$

where k_1 is the coefficient (0.35, 0.42), d_1 is the diameter pressure, d_1 is the allowable stress of the material (500 MPa) [21].

4.5. Design for stirring shaft

The drag force of the stirrer blade in slurry is given by the equation below.

$$F_D = \frac{1}{2} C_D \rho (\frac{\pi DN}{60})^2 A \tag{11}$$

where F_D is the drag force (N), C_D is the coefficient of drag, ρ is the density (kg/m^3), A is the area (m^3).

The torque T to rotate the stirrer is:

$$T = 2F_D \times R \tag{12}$$

The power P expected to turn slurry is:

$$P = \frac{2\pi NT}{60} \tag{13}$$

where N is the revolution per minute (rpm) [21].

5. Fabrication

The fabricated items are a top-opening metal cover, a cover holder, a stirrer, a biogas scrubber, and a water manometer. The remaining components were obtained from the market and assembled. **Figure 4a** shows the digester drawing. **Figure 4b** shows the digester after it was constructed and assembled for experimentation. There is a scrubbing unit attached to the digester, and it is connected to the digester using a rubber hose. A conventional CNG gas cylinder was used for biogas storage connected to the digester chamber using a rubber hose. Two pressure measuring devices are used (a digital pressure gauge, a water manometer constructed for the purpose) and a thermometer for temperature recording. **Figure 4c** shows the metal cover drawing, **Figure 4d** shows the stirrer drawing, **Figure 4e** shows the metal cover handle drawing, and **Figure 4f** shows the metal stirrer handle drawing.

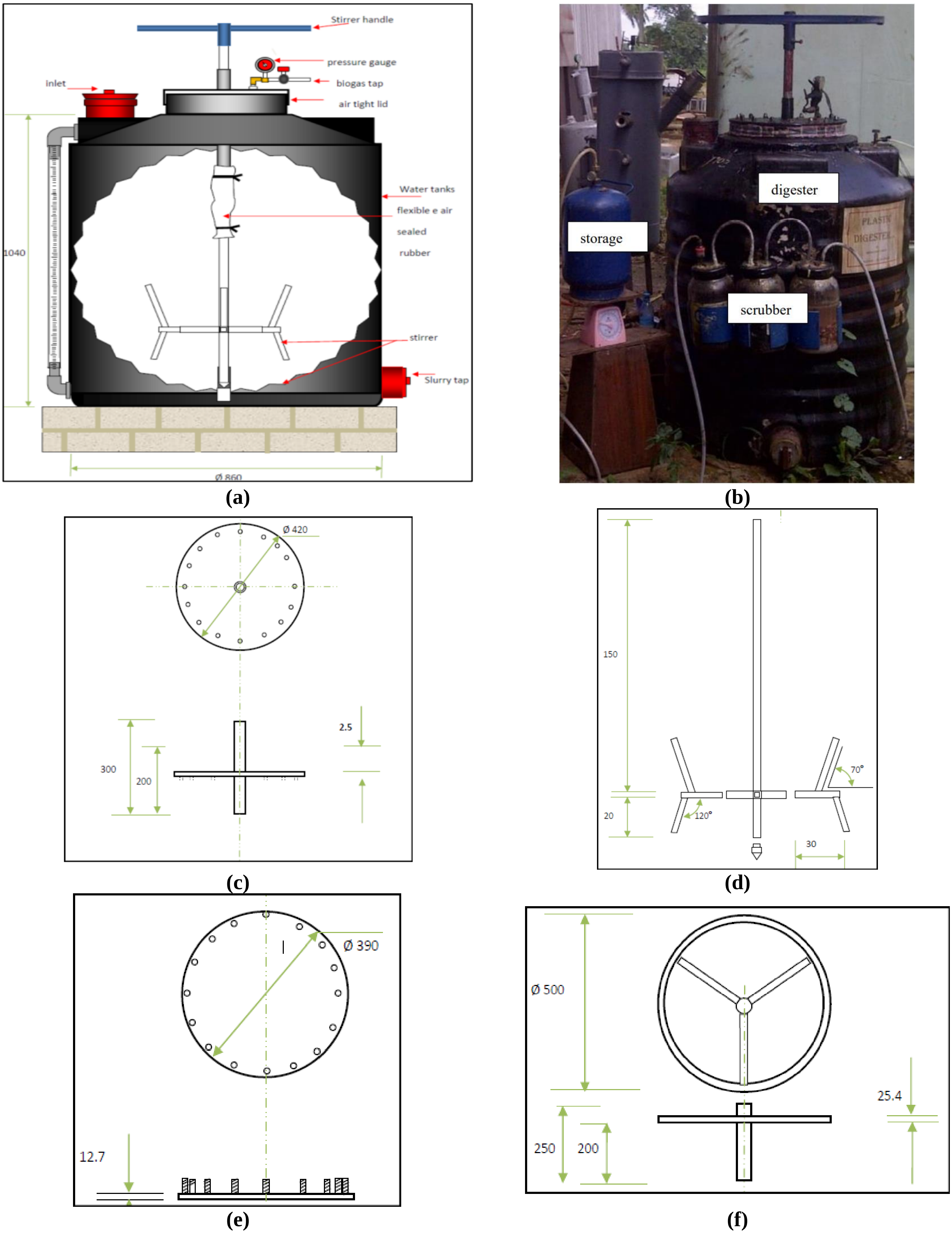


Figure 4. The plastic biogas digester **(a)** drawing; **(b)** after construction; **(c)** metal cover; **(d)** stirrer; **(e)** metal cover holder; **(f)** stirrer handle.

6. Digester testing

6.1. Experiment test and result

Experimental tests are performed to test the performance of the digester. The digester was fed with cow dung and other agricultural biodegradable waste and made airtight as shown in **Table 3**:

Table 3. The biomass plus water charged into the digester.

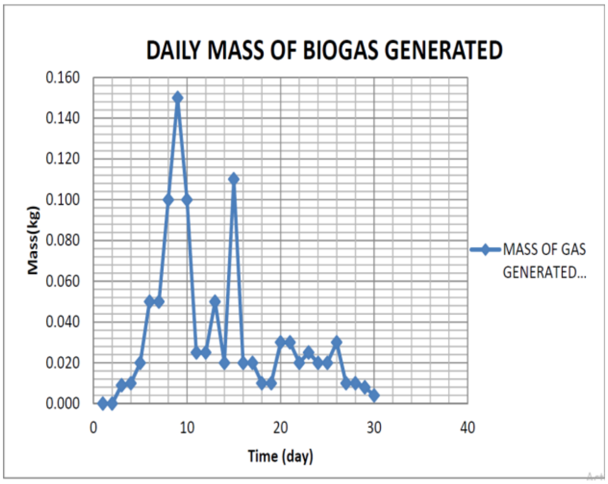
SN	Biomass	Mass (kg)
1	Cow dung	40
2	Kitchen waste (onion, eba, tomato, fish, santana, bean, rice, plantain)	50
3	Dry leave of umbrella tree	5
4	Sliced grass from field	25
	Total	120
5	Water	300
6	Total	420

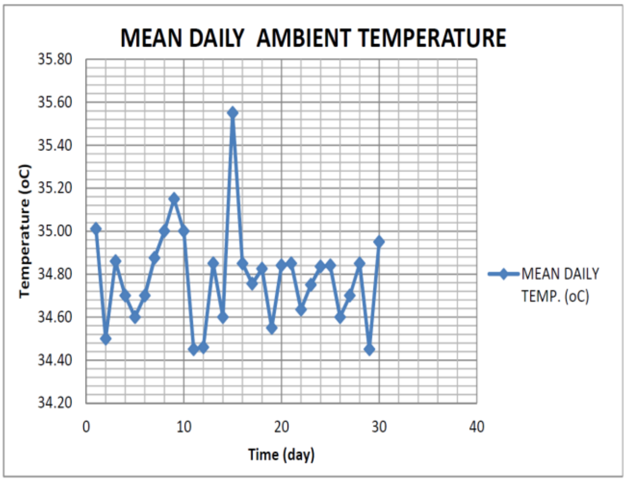
After one day, the biogas started generating and building some pressure in the digester. The result of the daily pressure, temperature and gas generated is shown in **Figure 5**. The daily gas generated is calculated by subtracting the initial mass of the cylinder from the final one.

$$m_g = m_f - m_i \tag{14}$$

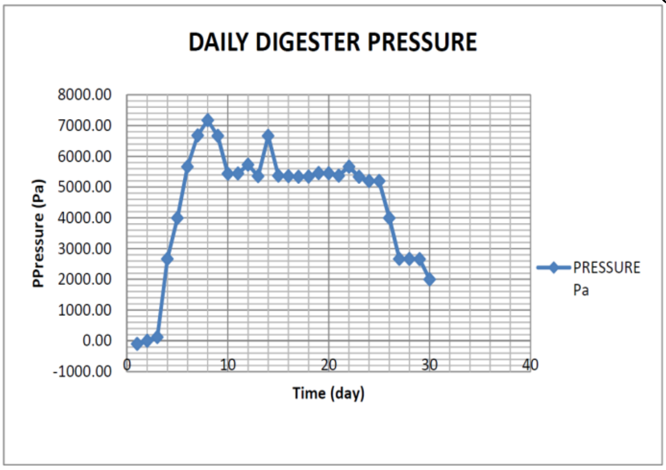
where m_g is the mass of produced, m_f is the final mass of the cylinder, m_i is the initial mass of the cylinder.

From **Figure 5c**, it indicates there is a negative pressure inside the digester; possibly aerobic digestion took place by removing oxygen and creating a vacuum before the commencement of anaerobic digestion. And it also indicates that the biogas production lags only one day before it starts, possibly because of seeding which triggers immediate biogas generation [1]. When the gas started generating, **Figure 5a** shows the production rises and reaches (0.15 kg) corresponding to a maximum pressure of 7000 Pa, then fluctuates, rises again to (0.11 kg) and finally decreases to a minimum of 0.004 kg on the 30th day with a corresponding mean temperature of 34.95 ℃. The maximum production is on day 9 which is 0.15 kg, and the corresponding mean temperature on this day is 35.5 ℃. This shows that the anaerobic bacteria are more active on day 9. The fluctuation in gas generation is due to the fluctuation in temperature. This happened due to the fact that the experiment was conducted during the rainy season. **Figure 5b** shows the mean daily temperature range (i.e., from 34 ℃–35 ℃). This favors mesophilic biogas digestion. And this is responsible for gas generation in **Figure 5a** above and the pressure range in **Figure 5c**, obeying Gay-Lussac's law for gas [22]. **Figure 5c** shows the pressure development by the plastic digester for 30 days. The pressure reached a peak (7172.75 Pa) on day nine and then fluctuated to a minimum. The pressure subsided to zero daily due to daily evacuation of the biogas using the manual compressor. For 30 days, the cumulative gas produced is 0.977 kg which is approximately 1 kg.





(a) (b)



(c)

Figure 5. (a) Daily biogas production for 30 days; **(b)** the daily ambient temperature for 30 days; **(c)** daily biogas pressure for 30 days.

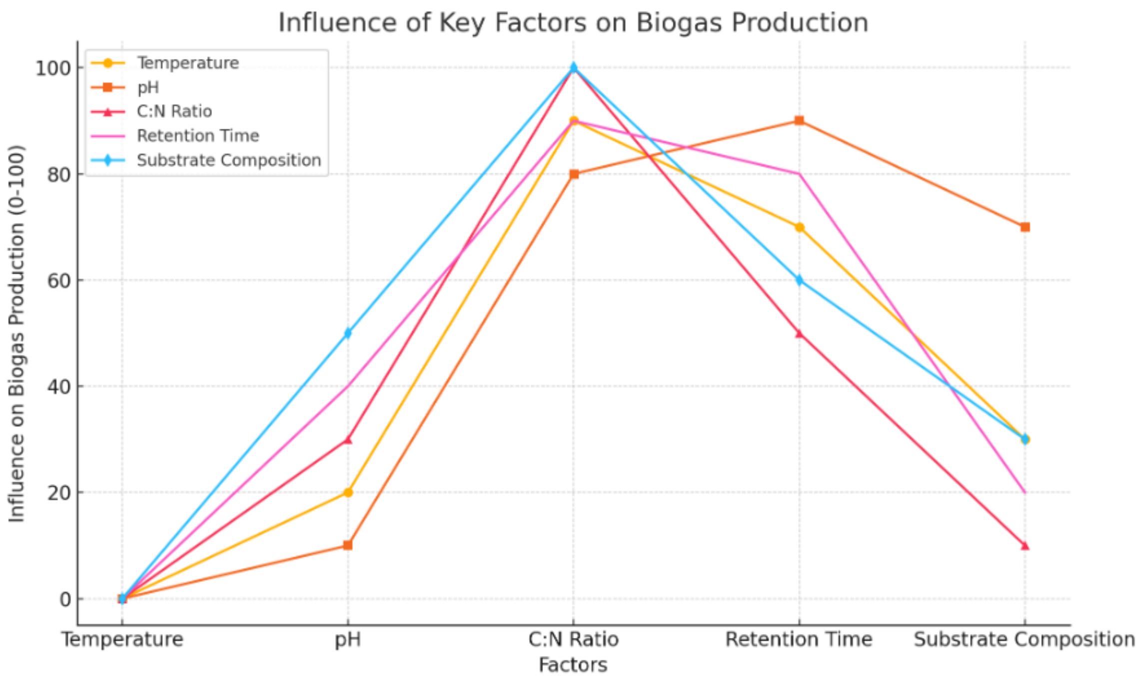


Figure 6. Influence of key factors on biogas production.

Figure 6 shows the factors influencing biogas production, with the primary variables that impact the anaerobic digestion process. These include:

1) Temperature (mesophilic vs. thermophilic ranges)
2) pH (optimal range: 6.5–7.5)
3) Carbon to Nitrogen (C:N) ratio (ideal ratio: ~25–30:1)
4) Retention Time (hydraulic retention time, HRT)
5) Substrate Composition (type and biodegradability of feedstock)

This chart shows the relative influence of temperature, pH, C:N ratio, retention time, and substrate composition on biogas production. For optimal biogas yield, it's crucial to:

1) Maintain appropriate temperature ranges (mesophilic or thermophilic).
2) Keep pH near 6.5–7.5.
3) Ensure a balanced C:N ratio (~25–30:1).
4) Allow adequate retention time for anaerobic digestion.
5) Use biodegradable substrates with high organic content.

6.2. Biogas yield estimates (liter per kg of substrate)

1) Cow dung: 40–60 liters/kg
2) Kitchen waste: 100–200 liters/kg
3) Dry leaves: ~50 liters/kg (difficult to decompose due to lignin content)
4) Grass: 50–100 liters/kg (variable depending on grass type)

Water is necessary for anaerobic digestion but does not contribute to biogas production.

Step-by-Step Approximation:

1) Cow dung (40 kg)

Biogas yield: 50 liters/kg (average) = 40 kg × 50 liters/kg = 2000 liters.

2) Kitchen waste (50 kg)

Biogas yield: 150 liters/kg (average), 50 kg × 150 liters/kg = 7500 liters.

3) Dry leaves (5 kg)

Biogas yield: 50 liters/kg = 5 kg×50 liters/kg = 250 liters.

4) Grass (25 kg)

Biogas yield: 75 liters/kg (average) = 25 kg × 75 liters/kg = 1875 liters.

Total Biogas Yield:

2000 liters + 7500 liters + 250 liters + 1875 liters = 11,625 liters.

6.3. Biogas concentration

Biogas consists of ~60% methane (CH_4) and ~40% carbon dioxide (CO_2) by volume (depending on feedstock and digestion conditions). So, the methane yield is approximately:

11,625 liters × 0.6 = 6975 liters of CH4.

Biogas Concentration in Terms of the Total Input Weight

The total weight of input materials (excluding water) is:

$$40 + 50 + 5 + 25 = 120\ \text{kg}.$$

Concentration of biogas per kg of input material:

$$\frac{11,625}{120} \approx 97\ liters/kg.$$

Final Summary:

1) Total Biogas Yield: ~11,625 liters
2) Methane Yield: ~6975 liters
3) Biogas Concentration: ~97 liters/kg of organic input material.

The flammability test was conducted on the gas produced on the 8th day and it was discovered that it is non-combustible, showing that methane gas was not yet generated. On the 20th day, the flammability test was repeated, and it was found that the gas was combustible. This shows that the generation passes through some reaction stages before the actual methane gas production.

6.4. Combustion value of biogas

Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), with traces of hydrogen sulfide (H_2S) and water vapor. The energy content of biogas depends on its methane content.

1) Energy Content of Methane (CH_4): ~ 9.94 kWh/m^3 (~35.8 MJ/m^3)
2) Biogas typically contains 50%–70% CH_4, so its energy value ranges between: 5.0 kWh/m^3 to 7.0 kWh/m^3 (∼18.0 to 25.2 MJ/m^3)5.0

For your case:

1) If biogas production is 11,625 liters (~11.625 m^3)
2) Assuming 60% methane content, the average combustion value is approximately 6 kWh/m^3.

Total Energy Content

$$11.625\ \text{m}^3 \times 6\ \text{kWh/m}^3 = 69.75\ \text{kWh}.$$

6.5. Applications of produced biogas

Biogas is versatile and can be used in several applications, primarily due to its clean-burning nature and renewable source. Common uses include:

1) Cooking Fuel
   (1) Biogas can replace LPG, wood, or charcoal for cooking.
   (2) 1 m^3 of biogas provides energy equivalent to ~0.43 kg of LPG.
2) Electricity Generation
   (1) Biogas can power small gas engines to generate electricity.
   (2) ~1 m^3 of biogas produces 1.5 kWh–2.0 kWh of electricity, depending on engine efficiency.
   (3) Example: Your 11.625 m^3 could generate ~17 kWh–23 kWh of electricity.
3) Heating
   Used for water heating, space heating, and industrial heat generation.
4) Lighting
   Biogas lamps can be used where electricity access is limited.

5) Transportation (After Upgrading to Biomethane)
   (1) Biogas can be purified (removing CO_2 and H_2S) to produce biomethane, which is comparable to natural gas.
   (2) Compressed biomethane can fuel CNG vehicles.
6) Fertilizer Production

The digestate (solid and liquid residue) remaining after biogas production is rich in nutrients like nitrogen, phosphorus, and potassium. It serves as an excellent organic fertilizer.

Summary of Energy Equivalents for your 11,625 liters (11.625 m^3) of biogas with ~60% methane:

(1) Cooking: Equivalent to ~5 kg of LPG
(2) Electricity: ~17 kWh–23 kWh of power
(3) Heating: Sufficient for domestic water heating needs

7. Conclusion

In the current energy crisis in Nigeria and globally, biogas generation presents a viable alternative. A plastic digester offers significant advantages over metallic digesters, including lower installation costs (₦115,000 compared to ₦150,000–270,000), better thermal insulation, non-corrosiveness, and lightweight mobility. Biodegradable waste, often discarded, can be harnessed to address energy needs through biogas generation. In this study, a plastic digester produced 1 kg of biogas from 120 kg of bio-waste over 30 days. With extended use, substantial biogas production can supplement the country's energy demand. The design of plastic digesters is cost-effective due to the use of cheaper materials, and the biogas generated can be manually compressed using simple off-grid compressors, making the technology safe and accessible. PVC, as the primary material, offers good chemical resistance, durability, and efficiency under mesophilic conditions (35 ℃–40 ℃). However, long-term exposure to UV radiation, high temperatures, and mechanical stress can degrade its performance, causing brittleness and cracking. To extend the lifespan of PVC digesters, UV stabilization, proper temperature regulation, and regular maintenance are essential. With adequate protection, PVC digesters can remain efficient and reliable for small-scale biogas production systems, lasting up to 5–8 years under optimal conditions.

Conflict of interest: The author declares no conflict of interest.

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