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Design, Fabrication and Energy Potential Assessment Of Small Scale Anaerobic Digester For Biogas Production

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Abstract— Anaerobic digestion is a green and sustainable technology in which organic material is converted into burnable gas. This technology is used in many countries to fulfill mainly the energy needs of agricultural and domestic sector. The process is called anaerobic digestion because it is performed in the absence of oxygen. Different researches showed that biogas can also be generated from food waste. In this project, a small scale anaerobic digester is designed and fabricated to convert the kitchen waste into biogas. An experiment was performed to check biogas production potential of different samples. It was observed that the sample containing carbohydrates produced the most amount of biogas. This sample was selected for further testing and data collection.

Keywords— Anaerobic Digestion, Municipal Solid Waste, Scrubbing, Retention Time.

I. Introduction

Anaerobic digestion relates back to one of the earliest technologies of the history. Biogas was used for heating bath water during the 10th century BC in Syria and in Persia during the 16th century, (http://www.biogasworks.com). This technique got advanced with scientific research and, Jan Baptista Van Helmont, Robert Boyle and Stephen Hale in the 17th century, proved that flammable gases can be evolved from decaying organic matter. In 1776 Count Alessandro Volta also performed an experiment and proved that there was a relationship between the amount of flammable gas produced and the amount of decaying organic matter (Lusk, 1997; Fergusen and Mah, 2006). Methane gas production from cattle manure by the anaerobic digestion process was demonstrated by Sir Humphry Davy in 1808 (Cruazon, 2007). The industrialization of this technology began in Bombay, India in 1859, with the installation of the first anaerobic digestion plant. This technique made its way to England in 1895, where methane gas generated in a well-designed sewage treatment facility and where this gas was used as a fuel for the street lamps. With the advancement in the field of microbiology, the anaerobic digestion further advanced. In 1930 the bacteria involved in this process were identified in a research led by Buswell and others (Lusk, 1997). Before 1920 this process was done in anaerobic ponds but as the technology advanced, this process was done in a more controlled environment which finally led to the use of closed tanks, heating and mixing equipments to maximize the biogas production. This technique and design was spread to the whole world and was booming but suddenly slowed down due to the use of low-cost coal and petroleum. This technology made a comeback in World War II due to the shortage of fuel and at the end of the war this technology was forgotten once again. In India and China, this technology is still embraced (Humanik, 2007). In developing countries, this technology is used for fulfilling the energy needs but in the developed countries, this technique is used for waste treatment.

II. Anaerobic Digestion

This is a step by step biological reaction in which large size organic wastes are converted into small and simple organic compounds by bacteria which results in the formation of a gas mixture called biogas, and some other solid remaining called digestate which can be used as compost in agricultural. [1]. This process involves the stabilization and degradation of organic materials in anaerobic conditions with the help of microbial organisms, which results in biogas production [2]. The main products of this process is the biogas including methane (50-75%), carbon dioxide (25-50%), hydrogen (5-10%), and nitrogen (1-2%) [3]. This process does not requires any external energy (in some conditions) but to enhance the biogas production we modify the process by adding the temperature control system and stirring mechanism. These two are the power consuming processes in the AD plant which maintains the design temperature, and the stirring mechanism. These processes are optional and can be avoided but if used, will result in increased biogas production.

There are different types of bacteria which survive at different temperature ranges. The bacteria which lives in the temperature range of 30 – 40 oC are called mesophilic bacteria and the bacteria which can survive in hotter conditions are called thermophilic bacteria which range from 55 – 60 oC. The mesophilic condition is easy to achieve however the thermophilic process has an advantage of quick starting time and higher loading bearing capacity [4].

TABLE 1: COMPOSITION OF BIOGAS

Name of the gas	Chemical Formula	Composition in biogas (%)
Methane	CH4	50-70
Carbon dioxide	CO2	30-40
Hydrogen	H2	5-10
Nitrogen	N2	1-2
Water vapors	H2O	0.3
Hydrogen sulphide	H2S	Traces

A. Stages Involved In Biogas Production Process

The biological decay of the organic compounds is done in four different stages. Each of which is discussed below:

1) Hydrolysis

The raw material is composed of longs chains of organic polymers. So in the first step these long chains of complex matter are broken down into small pieces and dissolving the smaller molecules into the solution is called hydrolysis. In this step the carbohydrates and proteins are broken down into single molecules of sugars and amino acids. (Sleat & Mah, 2006).

2) Acidogenesis

In this step the single molecules of sugar and amino acid produced in the first stage is further broken down into fatty acid and ethanol and also producing hydrogen sulfide and carbon dioxide as by-product. This process is very similar to the process in which milk become sour. (Boone & Mah, 2006).

3) Acetogenesis

This is the third stage of the anaerobic digestion process. In this stage the molecules produced in the second stage are further digested by the acetogens which largely produce acetic acid, hydrogen and carbon dioxide. (http://www.biotank.co.uk).

4) Methanogenesis

This is the fourth and final stage of the whole process in which the methanogens consumes the intermediate products of the third stage and convert it into methane gas (Ch4), carbon dioxide (CO2) and water (H2O). These are the major products of the anaerobic digestion process with small percentage of hydrogen sulfide (H2S) and some traces of other gases (less than 1%). This process is very sensitive to the pH level. Both the high and low pH level negatively affects the production rate of biogas. The perfect pH level range is between 6.5 and 8. (Martin, 2007). The remaining material which is not converted into biogas can be used as fertilizer of compost for the agriculture purposes.

The complete process of the biogas plant is shown in figure 1 below.

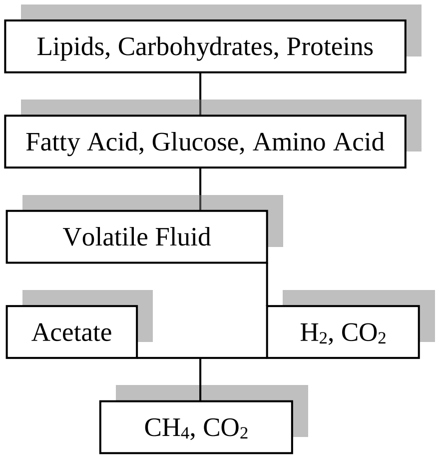

Figure 1: Process breakdown of Anaerobic Digestion

Major reactions occurring in this stage is given below:

$$CH_3COOH \longrightarrow CH_4 + CO_2$$
$$2\,CH_3CH_2OH + CO_2 \longrightarrow CH_4 + 2\,CH_3COOH$$
$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O$$

B. Processing the Raw Biogas

Raw biogas can be used for cooking and other activities but it contains other gases which decreases its calorific value and also makes it harmful for using in generators or vehicles, so it is very important to process the raw biogas and make it useful and safe. The technique of processing the raw biogas and removing the impurities is called scrubbing. This process improves the calorific value and the safety of the biogas.

C. Scrubbing Of Biogas

Scrubbing of biogas is mainly done for the removal of carbon dioxide and hydrogen sulfide. To upgrade the quality of biogas, first we have to remove all the sulfur from the biogas. This step should be done before the removal of CO2 because the CO2 removal process from biogas react antagonistically to the hydrogen sulfide; which means if the concentration of hydrogen sulfide is smaller, then there is a better effect of elimination of carbon dioxide from biogas. The hydrogen sulfide and carbon dioxide removal can be done in the same process line, but the process of H2S removal should be performed first [5]. This process can also be done in two separate steps. These steps are discussed below.

1) Removal Of Hydrogen Sulfide

H2S removal can be done by either of the two different easy ways. The first way is to add small amount of air (about 3-6% by volume) into the biogas reactor. Air can be supplied using pump but this is very critical because adding more air will minimize the effect of anaerobic digestion and hence decrease the biogas production.

Another technique for the removal of Hydrogen sulfide is to pass the gas mixture through a catalyst iron oxide. This is done by passing the gas through oxidized steel wool. When the raw biogas comes into contact with steel wool, the iron oxide converts into elemental sulfur.

2) Removal Of Carbondioxide

For this process, a 40:60 ratio solution by weight of NaOH and water can be used. The mixing of NaOH and water is exothermic process and releases enormous amount of heat. After the dissipation of heat, the raw biogas is passed through the solution, which minimizes the CO2 contents. A solution of limestone and water can also be used for the same purpose.

3) Removal Of Moisture

Moisture should also be removed from the raw biogas in order to get the full energy content of the biogas. This process is very simple. Silica gel which is easily available can be used for the removal of moisture content.

D. Factors Affecting Anaerobic Digestion

Anaerobic digestion is a delicate process which is done under very controlled environment. It is affected by various parameters which are discussed below.

1) Temperature

The process of anaerobic digestion is very much dependent upon temperature. This process works under specific temperature ranges as discussed below. Changing the temperature form the design temperature and the bacteria that is responsible for the biogas production dies and the process stops. Temperature also influences the methane yield and digestate (effluent) quality. Generally, the bacteria which can grow in temperature range of 10-30 oC is called psychrophilic. The bacteria working in the temperature range of 30-40 oC are mesophilic. Most of the biogas plants work on mesophilic conditions. The third temperature range is from 50-60 oC and is called thermophilic conditions. This condition has some advantages, metabolic rates are much higher, the growth rates are higher, and also the rates of the destruction of pathogens are very high, which results in higher biogas production [6].

2) pH

The value of pH is very important for the anaerobic digestion process. The life of the bacteria depends on the pH value. It has been observed that the pH value ranging from 6.5 to 8 is the best condition for the AD process. [7]. The value of pH depends on the amount of carbohydrates. The high the carbohydrate, the higher the production rate of methane gas, but when certain limit is reached, the value of pH increases so much which results in negatively affecting the bacteria and hence the biogas production decreases [8]. Increasing the pH value more than 7.5 and towards 8 can lead to proliferation of methanogens which inhibits acetogenesis process [9].

3) Loading Rate

This is also known as organic loading rate (OLR). It is the amount of organic raw material being fed into the biogas plant per unit time (daily, hourly etc.). Loading rate is another very important factor in the anaerobic digestion process. The loading rate of the system should not be very high as it may result in slowing down the biological fermentation process which in turn will result in an average or very low biogas production. The system is usually overloaded due to the presence of degrading substances in the system such as insoluble fatty acids which can cause hindrances in the path of biogas production [10]. Due to high loading rate, the amount of acidogenic bacteria increases which results in pH fall and hence results in the elimination of methanogenic bacteria or methane producing micro-organisms hence the system crashes [11].

4) Retention Time

This is the duration of the feedstock in the anaerobic digester. It is measured in no. of days (n) which is calculated as:

n (No. Of days) = Operating volume V / Flow rate Q

It is the average time required for the organic material residing in a digester to decompose considering the COD or chemical oxygen demand of the influent or the particles residing in and also the BOD or biological oxygen demand of the liquid waste materials. The organic matter decomposes better in longer retention time [11]. Retention time also depends on other factors such as content of the solid waste material and the operating temperature of the AD plant. The dry digestion and the wet digestion have different retention times and generally the dry systems or highly solid wastes have usually high retention time than that of wet system or liquid type waste. The retention time for a biogas digester is designed keeping in mind the composition of the waste [12].

5) Composition Of The Food Waste

The composition of the waste material has also a big impact on the biogas production rate and different raw material may affect the anaerobic digestion in a different way. The composition of the food waste generally depends on the many factors such as culture, habitat, time of the year, biotic and abiotic factors and also the environment of the region [12]. To predict the production rate of the biogas, it is very important to know the composition of the raw material. The biogas production rate depends upon four major components which are proteins, lipids, cellulose, and carbohydrates. The presence of high lipids content usually has high bio-methanization efficiency but it requires high retention time due to its complex structure. On the other hand carbohydrates and protein has less retention time as compared to lipids [13].

6) Carbon, Nitrogen C/N Ratio

This is the ratio of carbon to nitrogen in the slurry mixture also denoted as CN ratio. 25-30:1 is the optimum value of C:N for the maximum biogas output [14]. Nitrogen makes the cell structure while carbon provides the required energy. At the above discussed C:N, carbon is used about 20 to 30 times faster than the nitrogen. When there is excess quantity of carbon in the waste, then the nitrogen will be consumed first and carbon will be left behind, which will result in slowing down the digestion and which will eventually stop the process. If there is too much nitrogen in the raw material, then carbon is exhausted and the digestion stops. The remaining nitrogen will combine with the available hydrogen forming ammonia. This will result in killing the bacteria [15].

7) Toxicity

The growth of bacteria is stimulated by small quantities of mineral like potassium and sodium. There is a negative impact of the high concentration of detergents and heavy metals. They impact the rate of gas production. Antibiotics, soaps and organic solvents appears to be toxic for the growth of the bacteria in the digester. These types of substances should be kept away from the digester [16].

8) Depth To Diameter Ratio

According to studies done on the biogas technologies, it is revealed that if the diameter to depth ratio is kept in the range of 0.66 to 1.00, then the biogas. The reason might be that the temperature varies in different depths of the container and most of the activities happen at the lower half of the material [17].

9) Degree Of Mixing

Mixing the material results in improvement in biogas production. This mixing should be gentle because violent mixing results in killing the bacteria.

TABLE 2: PROPERTIES OF BIOGAS

Properties	Range
Net calorific value (MJ/m^3)	20
Air required for combustion (m^3/m^3)	5.7
Ignition temperature (^{0}C)	700
Density (kg/m^3)	0.94

III. METHODOLODY

A. Raw Material Source

In this project, food waste or kitchen waste was used as raw material for the production of biogas which was collected from the waste bin of the kitchen and cafeteria of the department.

B. Composition Of Kitchen Waste Of USPCAS-E Kitchen

The food waste collected from the kitchen and cafeteria of the department mainly consisted of bread pieces, cooked pulses, cooked rice, cooked meat (chicken and beef) and others. The waste also contained tissue papers, disposable plastic containers, cups and disposable cutlery. A survey was done for the composition of the kitchen waste. An Average composition of kitchen waste was analyzed on various occasions.

Compositions of Kitchen Wastages are:

- Cooked Rice and pulses
- Cooked Vegetables
- Cooked meat
- Bread

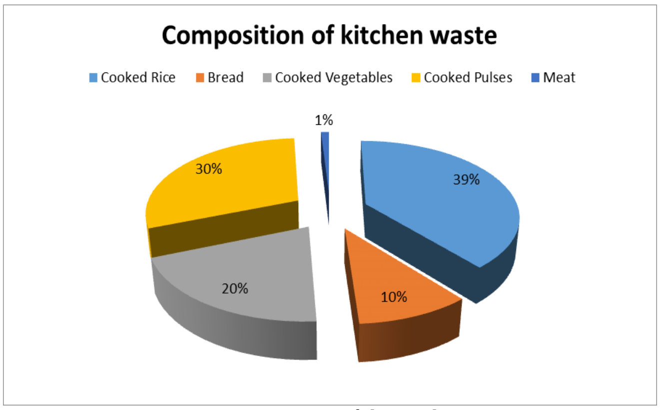

Figure 2: Composition of the Kitchen waste

C. Design Of The Reactor

This design contains two sections. In one section, raw biogas is generated and in the second section the raw biogas is processed and purified. In this project, a container of 160 liters volume was used. The container is a PVC container.. The top portion of the container consists of two pipes, one was used for intake of the organic waste or loading the raw material into the plant and the second pipe was used to collect the gases and to transfer it for the next treatment. The top lead also contains a mount for motor, which will be used to give circular movement to the raw material.

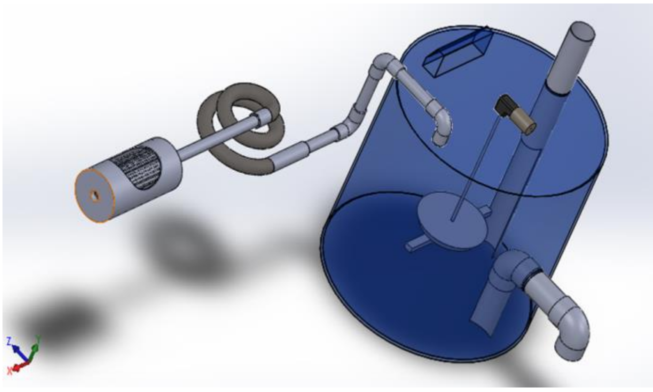

Figure 3: CAD Model of the Anaerobic Digester

D. Design Of The AD Plant

All the components of this plant were designed in Solid Works. The assembled design, the exploded view of the assembly as well as the CAD design of each individual component is shown below.

1) Feeding Funnel (Optional)

This is used to feed the raw material (Waste food) easily into the AD. This is an optional part which can be omitted. In this experiment, it is not used because an end cap is attached after feeding he raw material into the digester, so that the gases do not escape the digester.

2) DC Motor

This motor is attached to the stirring mechanism of the AD. It is programmed in such a way that it rotates for one complete revolution after every one hour. This mechanism is used in one digester plant only to check if adding the agitation mechanism increase the gas production rate or not.

3) AD Container

This is the main compartment of the AD in which the anaerobic digestion process happens. In this project, 160 liters of PVC tank is used. The container has four holes which are used for feeding of raw material, removal of extra materials, gas extractions and for the motor shaft. The top lid also contains the sensors and gauges to check the internal conditions of the AD plant.

4) Stirrer Blade

This is a mechanical stirrer, which is used for the stirring of the raw material. By this process the raw material inside the AD plant is constantly.

5) Control Panel

This is the monitoring system of the AD. Here the real time data of the AD such as temperature, pressure, methane content, CO2 content, H2S content, humidity, PH and the oxygen content is monitored, and then adjusted accordingly.

6) Scrubber

This part removes the unwanted gases from the methane gas, mainly the carbon dioxide and hydrogen sulfide. The scrubber contains two portions. An involute portion and a mesh structure. The involute portion is used to remove the carbon dioxide and the mesh portion removes the H2S. As the bubbles of gases will enter the scrubber, the gas will tend to move upwards, that's why the scrubber is designed to make the flow of the gases easy.

7) Piping

Piping PVP piping will be used to transfer the gases from AD to scrubber, and then from scrubber to the storage tank.

E. Material/Parts

TABLE 3: LIST OF PARTS USED IN THE PROJECT

S.No	Parts Names	Quantity
1	160 liters containers	2
2	1.5 liters bottles	2
3	2.25 liter bottles	2
4	Dc Motor	1
5	Battery	1
6	Stirrer Blade	1
7	3 inch pipe	4
8	1.5 inch pipe	2
9	Steel Wool	2
10	1 inch Rubber Pipe	2
11	¼ inch Rubber Pipe	2
12	3 inch Elbow joint	4
13	1.5 inch Elbow joint	8
14	Pressure Gauges	4

IV. EXPERIMENT

In this experiment, first the composition of the kitchen waste of the university campus was studied. The waste mainly consists of bread pieces, a portion of cooked vegetables and rice. For the experiment, four samples were made and were tested at temperature ranges of (30 – 34 oC). The experiment contains a total of four combinations of material as shown in Table-5

First different types of food waste samples were made and fed into 1.5 liters bottles and 2.25 liters bottles. Pressures gauges were fixed in the lids of the bottles. Digital temperatures sensors were installed to record the instantaneous temperature of the samples. pH sensor was also installed. In one bottle, u-tube monometer was installed to check the pressure. The experiment was performed and all the data was recorded.

A. Manufacturing Procedure Of large Scale Digester

In this experiment, a 160 liters PVC water tank is used. A total of four holes were drilled into the tank. Three of the holes were drilled on the top lid of the tank and one on the vertical wall near to the base. One of the holes on the top lid is three inches and the remaining two are one inch and 1.5 inch respectively. The fourth hole is also three inches, which is drilled on the vertical wall. Then pipes were installed in these holes in their respective sizes. A 3 inch pipe is inserted into the 3 inch hole on the top. The 3 inch diameter pipe is designated as the feeding pipe for the raw material. The lower portion of the pipe is cut to avoid chocking. This gives the pipe an easy path. The edges are sanded to have smooth surface. The pipe is pushed through the hole and twisted as it moves downward until it touches the lower surface of the tank. Due to the 450 cut, the raw material can be fed into the reservoir tank without clogging the pipe. A valve is installed on the upper end of this pipe and above the valve; a funnel is attached so that the raw material can be fed easily into the tank.

The second pipe which has 1 inch diameter is designated as the gas outlet pipe. A horizontal hole is drilled into the pipe at a height just below the top led of the tank. This pipe is also pushed into the tank. A valve is also installed on the upper end of this pipe and then connected into another pipe for further processing the gas. The feeding pipe and the gas outlet pipe are installed at the same side because at this configuration most of the food waste settles and most of the gas arises and collects.

The third pipe is installed at middle of the vertical wall of the tank. This pipe is used for the removal of extra material (fertilizer/composed) from the tank when new material is added.

V. Results & Discussion

The experiment was performed to find the maximum pressure generated by different samples and also to find the volume of gas generated by a unit mass of sample.

Three different masses of bread, manure were taken in different containers. The combinations of each sample are shown in the Table 4 below:

Table 4: Mixture ratios of raw materials with manure

Sample 1
260 grams bread + 260 grams manure + 1/10 part water of the total volume
Sample 2
520 grams bread + 520 grams manure + 1/10 part water of the total volume

A. Results

First three samples were selected for the experiment. In one sample, mixed vegetables were added to the manure in 50:50 ratio and 1/10 part water of the total volume. In second sample, only manure was taken and added with 1/10 part of water. In third sample bread was added with manure in 50:50 ratio and 1/10 part water. From literature it is observed that biogas generation starts at about 7th or 8th day. But in this experiment it was observed that the third sample having mixture of bread and manure started gas generation after 6 hours, which is very surprising. So for this experiment, the third sample was selected for further investigation.

Selecting the third sample (bread + manure), a total of 4 containers were taken, 2 containers of 1.5 liters volume, 2 containers of 2.25 liters volume. Two samples of different weights were made. For the 260 grams bread sample, this experiment was performed in a 1.5 liter bottle. A pressure gauge was attached on the top lid of the bottle to find the pressure curve and the maximum pressure that can be generated by sample. The pressure curve was obtained by measuring the pressure against time. To find the volume of the gas generated, a balloon was attached at the top of the second 1.5 liters bottle to find the volume of gas generated from the sample. The same mechanism was also applied to the remaining two samples. Using this method the pressure generation curve, the maximum pressure and the volume of gas generated per unit mass of the sample were recorded.

B. Data Gathered

The following data was gathered for all the samples.

1) Sample 1 (260 Gram Bread + 260 Gram Manure + 1/10 Part Water)

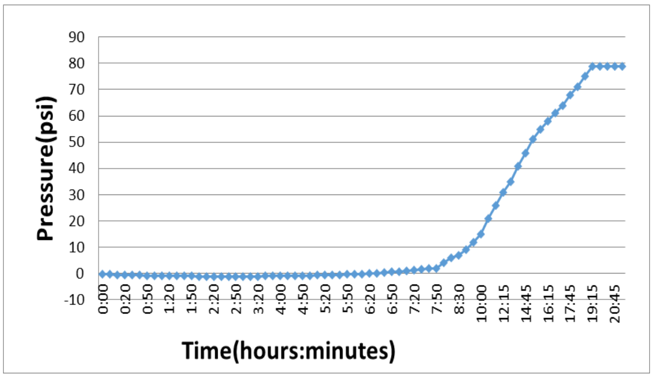

Figure 4: Graph of the Biogas generation pattern

The above graph shows that when the reaction starts, immediately the pressure drops and goes to negative value. We can divide this graph into three sections. In the first section we observe that the pressure decreases for about three hours. In second section the graph is a straight line with almost no changes. This negative pressure stays for about three hours. Then in the third section of the graph, we can see that the pressure starts rising. In about two hours the pressure comes back to zero psi. Then the positive pressure starts rising. From the graph we can see that once the positive pressure starts rising, then it increases exponentially for about two and half hour. Then after that the pressure increases linearly with time. The graph is split into two portions, which are shown below:

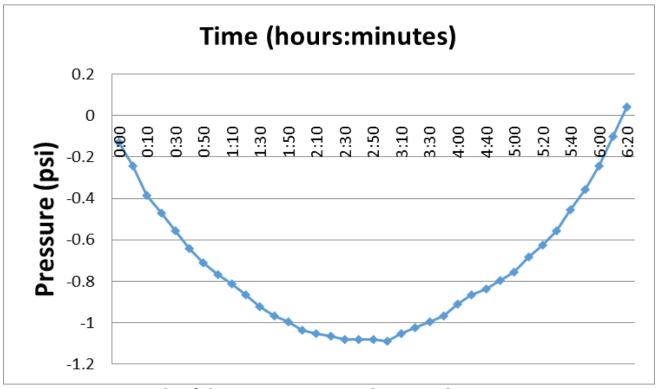

Figure 5: Graph of the gas generation showing the negative pressure

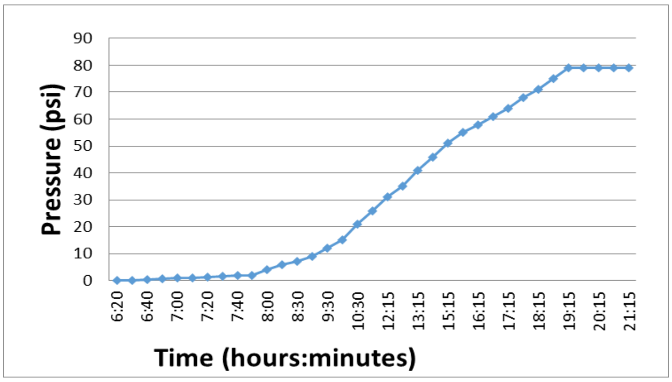

Figure 6: Second half of the graph showing positive pressure generation

Looking at this portion of graph, we can see that when the reaction starts, a negative pressure is generated. The pressure gradually decreases until it reaches a pressure of -1.08 psi, where this pressure stays for about six hours.

C. Volume Of Gas Generated From Sample 1

For the measurement of gas generated from sample 1, a balloon was attached to the opening of the 1.5 liters bottle. As the gas generation started, the balloon started swelling. The experiment was performed for 23 hours because after 21 hours the gas generation stopped and the pressure reached the equilibrium position. The volume of the balloon was 2.1 liters. This means that 260 grams of bread mixed with 260 grams of manure and 1/10 part water results in the generation of 2.1 liters of biogas.

D. Sample 2 (520 Grams Bread + 520 Grams Manure + 1/10 Parts Water)

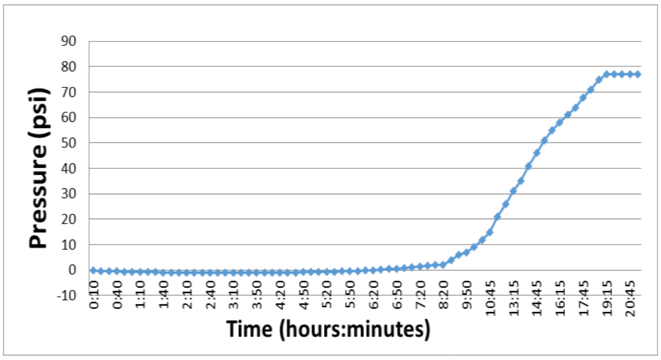

Figure 7: Pressure generation curve of sample 2

It can be observed from that in the initial stages, the reaction initially creates a negative pressure of -1.08 psi for about 1 hour. Then positive pressure starts to develop. From the graph we can see that the relation between the gas generation and time is almost linear until the maximum pressure of 79 psi reaches, where it stays unchanged until the environment is altered.

E. Volume Of Gas Generated From Sample 2

From the balloon major and minor axis diameter, I found out that the volume of gas generated from 520 grams of bread mixed with 520 grams of manure and 1/10 part water generated 3.1 liters of biogas.

The total mass of sample 1 (without water) was 520 grams (.52 kg) which generated 2.1 liters of biogas. From extrapolation I found out that 1 kg of mixture can generate biogas of 4.04 liters. From the sample 2, we got 3.1 liters of biogas from a mass of 1040 grams (1.04 kg). From interpolation, it was calculated that per 1 kg of material we can get 3 liters of biogas. Taking the average of both the readings, it is concluded that 1 kg of material can generate an average of 3.52 liters of gas. Plotting this of a graph we can see the potential of biogas generation from different capacity plants.

TABLE 5: GAS GENERATION POTENTIAL

S No	Material (KG)	Gas potential (Liters)
1	1	3.52
2	10	35.2
3	100	352
4	1000	3520

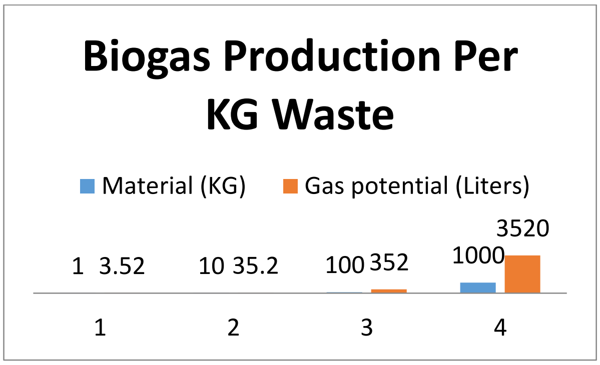

Figure 8: Biogas production (liters) per KG of waste

VI. CONCLUSION

From this experiment we can conclude that biogas technology can also work on small scale even on standard atmospheric conditions. Different organic materials have different time to decompose and to produce biogas. The material which took the least time to produce biogas is the mixture of bread, manure and water in the ratio of 10:10:1 respectively. It can also be concluded from the experiment the aforesaid sample has very high biogas production potential and can be very successful on different scales. As observed from the pressure generation graph that the pressures obtained in this process were very high, almost twice the pressure of a car tire, so it is of the most importance that the system should be so strong and leak proof to avoid possible danger. The gas generated in this process is highly flammable so extra precautions and care should be taken while working on this experiment. This experiment involves different materials which possess strong smell, so leaks should be properly blocked.

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