



Energy Evaluation and Qualitative Analysis of Biogas Produced from Co-Digesting Kitchen Waste and Cow Dung

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Authors' contributions

This work was carried out in collaboration between all authors. Author AW designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors LDB and MM managed the analyses of the study. Author KFO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Anaerobic digestion is an effective method for organic pollution reduction and bio-energy production and has increasing applications worldwide. Produced biogas consists mainly of 50–70% methane (CH₄) and 30–50% carbon dioxide (CO₂). The most common utilization route of biogas is for electricity production, often combined with utilization of the excess heat. This widens up the opportunities to utilize biogas in distant energy consumption locations. The most common methods for biogas upgrading include water washing, pressure swing adsorption, polyglycol adsorption, and chemical treatment, which are performed outside the anaerobic reactor and require investments in

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external compressors, pumps, membranes, etc. Therefore, the cost for biogas upgrading is relatively high. In situ biogas upgrading has been investigated previously and several methods have been proposed, where CH₄ rich biogas could be obtained directly from the anaerobic reactor. In this research, we investigated the energy evaluation and qualitative analysis of biogas produced from co-digesting kitchen waste and cow dung. Biomass Kitchen waste was collected, as feedstock for a home-made laboratory-scale anaerobic digester (10L capacity) to produce biogas in the Masinde Muliro University of Science and Technology (MMUST) Physics laboratory for 27 days. This was done at a temperature range of 25°C - 35°C and in an alkaline environment maintained by adding a medium of sodium hydroxide. The power potential for the biogas collected was found to be 22,461.77 W/m³. Comparing this with the Literature value of 37,258.9 W/m³ for pure methane, it was found that 60.29% of the biogas sample tested was methane. The gas chromatogram on five gas samples collected from individual kitchen waste substrates showed slightly higher percentages of methane content in the biogas collected from starch and pure cow dung in relation with other tested samples. Biogas production significantly increased when co-digestion of kitchen waste was done with cow dung. An even higher biogas yield was realized in the samples maintained in alkaline environment. This study forms a basis upon which large scale biogas production from kitchen waste can be done for domestic and commercial use.

Keywords: Anaerobic co-digestion; biogas; gas analysis; kitchen waste.

ABBREVIATIONS

MMUST : Masinde Muliro University of Science and Technology

AD : Anaerobic Digestion

FID : Flame Ionization Detector

ECD : Electron Capture Detector

GC : Gas Chromatography

WWTP : Waste water treatment plant

TS : Total solids (% of wet weight)

VS : Volatile solids (% of total solids or % of wet weight)

1. INTRODUCTION

The Kenya's economy mainly depends on the energy resources available. With the advent of industrial revolution use of fossil fuels has been growing and to date the sources are being depleted. Dependence on this fossil fuel as primary energy source has led to global climate change due to the pollution of the environment causing human health problems [1]. With increasing prices of oil and gas the world looks towards alternative green energy resources. Anaerobic digestion (AD) of biomass to produce biogas offers a very attractive route to utilize certain categories of biomass for meeting partial energy needs. Biogas comprises of 55% - 70% methane gas, 30% - 45% carbon dioxide and tress gases [2]. AD can successfully treat the organic fraction of biomass [3]. Kitchen and animal waste co-digesters seems to offer promising results. Other sources of waste materials considered as a feedstock for anaerobic digestion process are: municipal solid

waste (MSW), agricultural animal waste, crop residues, biomass, and energy crops and waste water treatment plant sludge (WWTPS). This study focused on the co-digestion of kitchen waste and cow dung.

Co-digestion is the simultaneous digestion of more than one type of waste in the same unit [4]. Advantages include better digestibility, enhanced biogas production/methane yield arising from availability of additional nutrients, as well as a more efficient utilization of equipment and cost sharing [5]. Studies have shown that co-digestion of several substrates, for example, banana, spent grains and rice husk, pig waste and cassava peels, sewage and brewery sludge, among many others, have resulted in improved methane yield by as much as 60% compared to that obtained from single substrates [6-9]. Co-digestion of sewage sludge with agricultural wastes or MSW can improve the methane production of anaerobic digestion processes. Primary sludge is rich in anaerobic bacteria and is abundantly available nearby. This study sought to evaluate co-digestion of kitchen and primary sludge (PS) cow dung, to improve biogas yield in a laboratory - scale digester build to work at constant high pressure. Given that, kitchen waste can be found in every home, it is most suited for the supply of biogas to homesteads as compared to cow dung. With kitchen waste, even those staying in town places can still run digesters to get biogas.

To the best of our knowledge not much work has been done to investigate the quantity and quality

of biogas produced from mixing domestic kitchen waste with cow dung. Hence there is insufficient information on the outcome of co-digesting kitchen waste with cow dung. There is great need for such details to aid the house holds that want to exploit biogas energy as a way of managing waste and cutting down on energy costs.

The main objectives of this research were, to assess the energy and power potential of the biogas produced by co-digesting kitchen waste and cow dung and to establish the quantitative and qualitative analysis of Methane, Nitrogen dioxide and carbon dioxide in the biogas produced in. This study sought to evaluate co-digestion of kitchen and primary sludge (PS) cow dung, to improve biogas yield in a laboratory-scale digester built in-house by the author, to work at constant high pressure. This problem was studied experimentally. Gas chromatography was used to investigate the biogas quality.

Gas Chromatography (GC or GLC) is a commonly used analytic technique in many research and industrial laboratories for quality control as well as identification of compounds in a mixture [10]. GC is also a frequently used technique in many environmental and forensic laboratories because it allows for the detection of very small quantities. A broad variety of samples can be analyzed as long as the compounds are sufficiently thermally stable and reasonably volatile.

2. MATERIALS AND METHODS

2.1 Materials

Samples which included cow dung slurry and biomass kitchen waste (KW) (organic fraction of the household waste) were collected from the Masinde Muliro University of Science and Technology (MMUST) farm and catering unit respectively. Approximately 5 kg of each fraction were collected in plastic cans. The following common kitchen waste samples were collected: Fruit peelings, vegetable remains, Potato peelings, raw starch and corn meal / cooked starch. Preparation of the culture took place before the experiments started by collecting slurry from an already operating biogas plant. The kitchen waste (KW) samples were prepared individually by crushing them using a fruit blender, to increase their surface area and the

volume ration. Samples of the crushed KW were then taken to evaluation of the total solid (TS) and volatile solid (VS). The remaining samples were used as feedstock for the anaerobic digester which was built by the author in the Physics Laboratory at MMUST.

The digester design chosen was the batch digester semi mixed by shaking and operated at the mesophilic temperature (25°C - 35°C). The batch digester was preferred to the continuous flow digester since we were assessing the given batch of substrate till no more gas is produced. It was also cheaper and easier to assemble and run.

Two parallel sets of experimental set ups were assembled in the MMUST physics laboratory for a period of 30 days. We had the laboratory-scale digester and a set of 21 bio-digesters for individual KW samples for the determination of the methane potential of different kitchen waste substrates. The 21 set ups were assessed in three different conditions; Seven were in the pure state while cow dung was added to the other set of seven. The remaining seven had 1M sodium hydroxide added to create an alkaline environment. The laboratory-scale digester set up was put up to assess the overall biogas production from a mixture of kitchen waste and cow dung. The volume of biogas produced by each set up was measured and its quality assessed. Analysis of the quality of the biogas collected was done in the Maseno University Chemistry Laboratory using a gas Chromatography machine while the gas energy potential was assessed in the MMUST Physics Laboratory.

The main digester was designed and built by the author in-house as shown in Fig. 1. The biogas system was installed with a heating system.

2.2 Sample Preparation

Experiments for the methane potential estimation of the samples were carried out in 500 ml plastic bottles. Three parallels for each sample were assessed. They were labeled as shown in Table 1 as S1 – S7, which was further subdivided into S1a...1c, S2a...2c, S3a...3c up to S7a...7c.

For each of the 'a' samples, 100 g of the substrate were mixed with water to a volume of 350 ml (100% v/v). For the 'b' samples, 100 g of the substrate were mixed with water to a volume

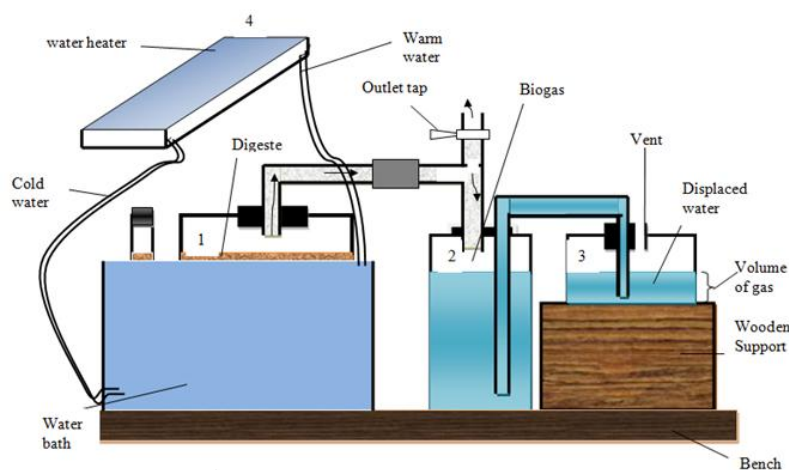


Fig. 1. Designed laboratory- scale biogas system with the digester in a water bath
The laboratory-scale biogas system, Fig. 1, comprised of: the digester (1), the gas storage chamber (2), the pressure sustaining chamber (3) and digester heating system (4)

of 315 ml (90% v/v) and a volume of 35 ml (10% v/v) of cow dung (made by mixing 5 g of cow dung and water to make the mixture of 35 ml) added to make the total working volume to be 350 ml. The 'c' samples were as the 'a' samples with an addition of 5 ml of 1 molar sodium hydroxide to create a basic environment. S_{6a} was pure cow dung, S_{6b} clean water and S_{6c} was cow dung in a basic environment. Water was used to verify the gas collected was not dissolved air in water but biogas. The three parallels served as controls and corrections of the amount of biogas produced from the substrates under study. A total of twenty-one bottle bio-digesters were prepared. The bio-digesters were sealed with rubber corks with openings through them. Syringes were connected to these bottle digesters by means of glass tubes and rubber tubes (see Figs. 2 and 3). The digesters were maintained at a room temperature and shaken periodically to mix the substrate.

To keep the ratio of the feedstock to the cow dung constant, the samples were not diluted any further to maintain the total solid (TS) and volatile solid (VS) per litre of sample. The pH was held constant by adding 1M NaOH in a set of the samples.

Fig. 3. shows the laboratory –scale digester, a plastic container of 10 litres connected, by means of rubber tubes, to a gas reservoir (chamber 2) and then a water reservoir (chamber 3 placed in a raised position). The sludge inlet and gas outlet were connected carefully to create anaerobic environment. A water bath (heated by

an electric iron box) was used to keep the digester at a temperature range of 25°C - 35°C. Cold water from the lower section of the water bath moved down to the heat source while warm water rose to the water bath by Convection.

Table 1. The samples used in the experiment

S/No.	Sample label	Name of sample
1	S ₁	Fruit peelings
2	S ₂	vegetable remains
3	S ₃	Potato peelings
4	S ₄	Raw starch
5	S ₅	Mixture of all kitchen waste
6	S ₆	Cow dung Culture
7	S ₇	Corn meal / cooked starch

The figure also shows the 21 set ups that were put up to assess the biogas potential for individual kitchen waste substrates. Biogas was collected and held in 60 ml syringes connected to the 500 ml plastic bottle digesters by flexible rubber tubes

2.3 The Gas Chromatography (GC) Analysis

A GC analysis was done using a GC machine of serial number N9235, Model 8610C (manufactured on 14th Sep, 2012). This was done in the Maseno University Chemistry Laboratory. We used nitrogen gas as our carrier gas and the rate of flow was 27 ml/minute. The detectors used were Flame Ionization Detector (FID) current 350 for CH₄, CO₂ and Electron

Capture Detector (ECD) current 350 for NO₂. GC involves three steps: Injection of the sample into the GC at the inlet. Separating of the sample into individual compounds which took place in the column in the oven of a gas chromatograph machine and detection of gas constituents in the sample. As each compound entered the detector an electrical signal proportional to the amount of the compound detected was generated. The signal was generally sent to a data analysis system – such as Agilent Chem Station where it showed up as peaks on the chromatogram and displayed on a computer display system. We have several detectors and one is chosen based on the type of analysis required [10].

2.4 Total solid (TS) and Volatile Solid (VS) Determination

Total solids (TS) and volatile solids (VS) were determined using standard methods [11]. 50 g of each fresh sample was put in a porcelain cup and weighed on a weighing scale. Afterwards the samples were left to dry for six hours at 105±5°C in the incubator. The dried samples were then weighed again. The dry matter (total solid) was calculated using equation 1:

$$TS\% = \frac{W_d}{W} \times 100 \quad (1)$$

where, W_d is Dried sample weight and W is the sample weight [12] [11].

The dried samples were placed in smaller porcelain cup and the same procedure was followed. The porcelain cups were first weighed empty and then with the dried samples. Afterwards they were put in the oven at 550°C and then weighed again. The volatile solids were calculated using equation 2:

$$VS = \frac{W_c - W_i}{W_d} \times 100 \quad (2)$$

where: W_c is the Cup and the dried sample weight and W_i is the cup and incinerated sample weight [12,11].

2.5 Conversion of Substrate Mass to Biogas

From literature we learn that the volume of biogas to be collected from a given mass of substrate can be expressed using equation 3.

$$Volume = 0.056m^3 / kg \times m_s \times 1000l / m^3 \quad (3)$$

where, 0.056 m³/kg is the optimum conversion rate of kitchen waste substrates, m_s is the mass of the substrate that was used in this set up and 1000l/m³ is the volume conversion. [13].

2.6 Biogas Energy

The flame was found to heat water and appreciable heat energy as calculated using equation 4:

$$E = m_c c_c \Delta\theta + m_w c_w \Delta\theta \quad (4)$$

where 'E' is the heat energy dissipated, ' m_c ' the mass of calorimeter, c_c (390 Jkg⁻¹K⁻¹) specific heat capacity of copper, m_w the mass of water, c_w (4200 Jkg⁻¹K⁻¹) the specific heat capacity of water and $\Delta\theta$ the change in temperature.

2.7 Biogas Power Potential

The power potential of the biogas produced was determined by dividing the energy arrived at, in the table 4 above, by the time taken for the said heat energy to heat water. This was made possible using equation 5

$$power = \frac{E}{t} \quad (5)$$

where, E is the heat energy calculated in equation 3 and t is the time taken for the energy to be dissipated.

3. RESULTS AND DISCUSSION

3.1 The Total Solid and the Volatile Solid

The total solid and volatile solid for the substrates under study were assessed (see Table 2). The percentage of total solid in most of the KW was low. This is because most KW samples have high water content. Dry samples up only leave a small percentage of matter when the water part vaporizes. However, the percentage the dry matter that is volatile is so significant. It is this volatile solid that is broken into biogas during the anaerobic digestion process. Cooked starch, raw starch and fruit remain presented higher percentages of volatile

solids pointing at their good gas production potential. This clearly shows that mixing the primary sludge with kitchen waste rich in starch (co-digestion) was a promising biogas source. Kitchen waste is rich in volatile solid and mixing it with cow dung rich in biogas forming bacteria,

gives a high gas yield as obtained in the results of the tests done on individual feedstock.

The results in Table 2 compare closely with results of other research experiments done elsewhere [13].

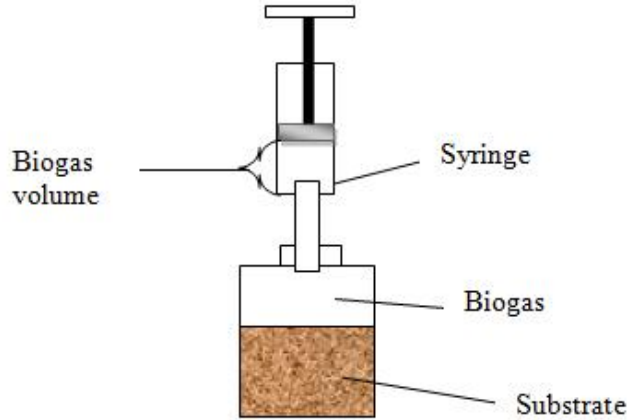


Fig. 2. The experimental set up for each sample of kitchen waste



Fig. 3. The two experimental set ups on adjacent tables in the research room

Table 2. Assessment of the total solid and Volatile Solid in the sample substrates

Substrate	Sample ID	Sample weight W(g)	Dry weight W _d (g)	TS%	Ash weight W _a (g)	VS %
Fruit remains	S ₁	29.4	2.9	9.86	0.5	82.75
vegetables	S ₂	20.3	1.6	7.88	0.3	81.25
Potato peelings	S ₃	38.7	11.6	29.97	3.4	70.68
Raw starch	S ₄	11.3	9.6	84.95	1.7	82.29
A mixture of all substrates	S ₅	20.3	6.4	31.53	1.7	73.44
Cow dung	S ₆	20.0	4.1	20.50	3.2	78.04
Cooked starch	S ₇	21.6	8.5	39.35	1.1	87.06

In this study, we notice that 1980 g or 1.98 kg of a mixture of substrate in the digester produced 32,872 cm³ or 0.032872 m³ of biogas. This translates to a biogas yield in cubic metres per kilogram of substrate as 0.016602 m³/kg. Considering that there were experimental errors, the worked conversion rate is competitive and viable. Without errors, results obtained from equation 3 shows a conversion rate that predicts that a gas volume of 110.88 litres could have been produced from the substrate mass of 1.98 kg that was used.

3.2 Assessment of Energy and Power

3.2.1 The flame test

The gas was taken through a flame test, as shown in Fig. 4, to verify its ability to burn.

The collected biogas was then used to heat water in a copper calorimeter both of known masses as shown in Fig. 5. The temperature change was measured using a thermometer. The results were tabulated and the energy dissipated calculated using equation 4. It was clear that the gas produced in the digester contained methane which is a fuel since it burned with a bright flame.

3.2.2 Energy calculation for the biogas produced

The combustion of pure methane produces a blue flame and a great amount of heat. One cubic meter of biogas, produces 6-7 hours of 60 watt and can cook 3 meals or Generate 1.25 kW electricity [14]. Water and a copper calorimeter of known masses were heated and the temperature change measured using a thermometer, see Fig. 5. Using equation 4 the

energy dissipated was determined and tabulated in Table 3.

3.2.3 Calculation of the power potential

An average power of 18.87 W realized for an average volume of 840 cm³ of the gas burned as shown in Table 4 worked using equation 5. In this study it was assumed that no heat was lost to the environment. However, the actual value for the power generated in ideal conditions is more than what was realized in this study. Working out the power potential of 1m³ of biogas we get an estimate value as shown in the calculation below. Equation 6 (a), (b), (c) and (d) is an interpretation of the power potential (equation 5) of biogas collected per unit volume

$$\text{Power} = \frac{18.86789W}{840cm^3} \times 1000cm^3$$

$$\text{Power} = 22.46177W / \text{Litre.}$$

or

$$\text{power} = \frac{22.46177W}{1litre} \times 1000litres / m^3$$

$$\text{Power} = 22,461.77W / m^3$$

(6 a, b, c, d)

where, 840 cm³ is the average volume of the gas that was used in the energy evaluation tests.

Comparing this with the LPG gas used for cooking which is predominantly butane, we note that 25 m³ of biogas gives the same energy as 10 m³ of LPG gas. Meaning that, taking the ratio of the fuel value of LPG to the fuel value of pure methane, we get 5:2 [15]. The said amount of biogas can be produced daily from 40kg of kitchen waste. [16]. 1m³ of methane generates 37,258.9J of energy when pure [15]. This converts to 37,258.9W/m³. In this study, the



Fig. 4. Biogas burning with a bright flame

results point at a power rating of 22,461.77 W/m³ translating to 60.29% of the expected power rating of pure methane. This proves that only 60.29% of the biogas collected is methane. The rest of the gas is carbon dioxide and trace gases.



Fig. 5. Biogas is used to heat water in a copper calorimeter

3.3 Gas Chromatography Analysis of Extracted Biogas

Biogas samples from selected substrates were studied to establish the chemical constituents of the collected gas. This was done using a gas chromatograph machine shown in Fig. 6 (a) and (b) The gas samples were stored using syringes with tightly fitted rubber tubes and clips to prevent the gas from escaping. (see Fig. 6 (c))

3.3.1 Qualitative analysis of biogas samples using retention times

Using the gas chromatograph, the gas samples were taken through separation process subject to retention times to establish methane prevalence and other gases. Gas chromatography is known to be the optimal analytical tool for quantifying the components of biogas including methane, carbon dioxide, hydrogen sulfide, nitrogen dioxide and siloxanes [17]. Baseline separation of Methane, CO₂ and NO₂ gas were obtained and their retention times tabulated as shown in Tables 4 and Fig. 8(a), for the selected samples. From Table 4 and Fig. 7(a) it was possible to use the standards as the marker compounds, hence detect the presence of the main gases. The gases were separated based on the different strengths of interaction with the stationary phase ("like-dissolves-like"-rule). Methane interacted fairly faster after NO₂ due to its less polarity as compared to CO₂.

This enabled us to confirm the existence of the methane in the biogas samples obtained from kitchen waste. Literature has established GC analysis as immediate tool in analyzing the above in waste, however, less has been done on mixtures of cow dung and kitchen wastes. This is a confirmation of the isolation of methane that has been detected previously from waste material as the main compound [18].

3.3.2 Quantitative analysis of biogas samples using peak areas

To establish the percentage constituents in the biogas samples tested, peak areas of the gas profiles were used as shown in Table 5 and Fig. 8. It is clear that the gas samples collected from S₆ (cow dung) and S₇ (cooked starch) had a higher percentage of methane as compared to the other samples. Similar results were established by Harold, 2007, when he tested biogas samples from cow dung and energy crops such as corn which have a high percentage of starch. The biogas from cow dung is known to contain 65% methane and the cooked starch releases 62% [18]. S₆ had a higher peak area of 7738.2116 ppm out of the 5ml of the gas tested comprising of CO₂ as shown in Table 5 and Fig. 8. However, it also had the highest peak area (53250.4331 ppm) for methane, an indication that the sample had more nutrients needed by the microbes for the production of methane.

The other samples that were tested had significant amounts of methane though the amount of carbon dioxide collected was notably large. This indicates that though the samples could be good candidates for biogas production, precautions need to be taken to eliminate large amounts of CO₂. In the previous investigations, this elimination was done using Absorption and Adsorption [19]. Biogas consists principally of methane and carbon dioxide but can also contain small amounts of a wide range of other compounds including NO₂ [20,18]. Some of them don't contribute to the energy content, and may be corrosive, poisonous or be responsive for releasing bad smells in the neighbourhood or during the burning process.

Knowledge about biogas content is thus valuable, to establish the extent of pollution to the environment and give precautions [17]. There are minimal amounts of CO₂ and NO₂ in S_{6a} and S_{7a} as shown in Fig. 8. This advantages the use of biogas from the two sources, with high prevalence of methane (85.97% and 85.1%, respectively).

Table 3. Energy and power rating of the biogas collected on burning

	Volume of gas used (cm ³)	Masses of water and calorimeter(g)	Change in temperature $\Delta T(^{\circ}C)$	Heat energy E(J) gained by water and calorimeter	Time taken t(s)	Power dissipated P (watts)
Calorimeter		47.3				
Test 1	1573	41.1	15	2866.00	153.26	18.70
Test 2	553.8	33.0	8	1256.37	63.31	19.84
Test 3	398.7	33.0	6	942.28	52.17	18.06
Average power						18.86

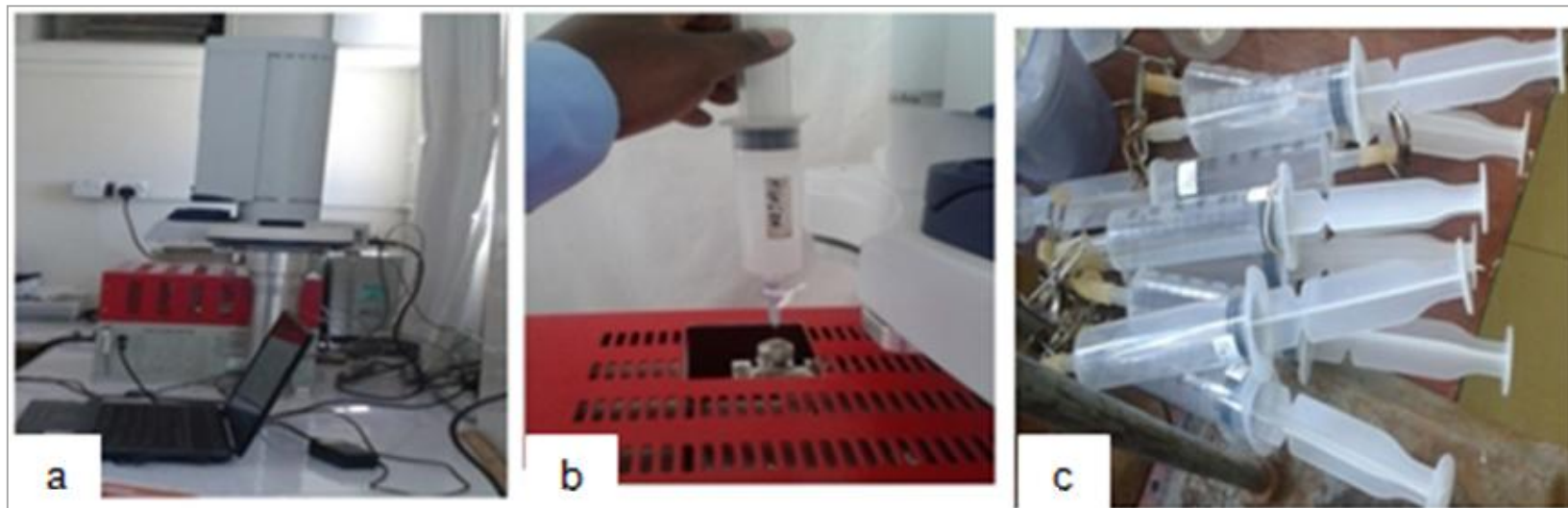
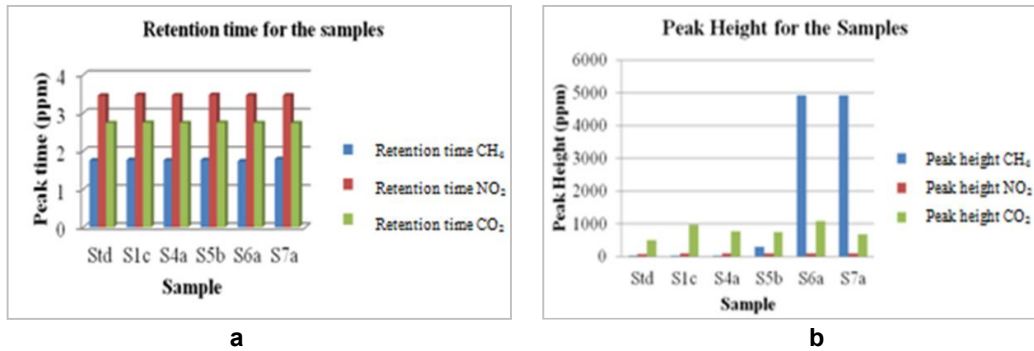


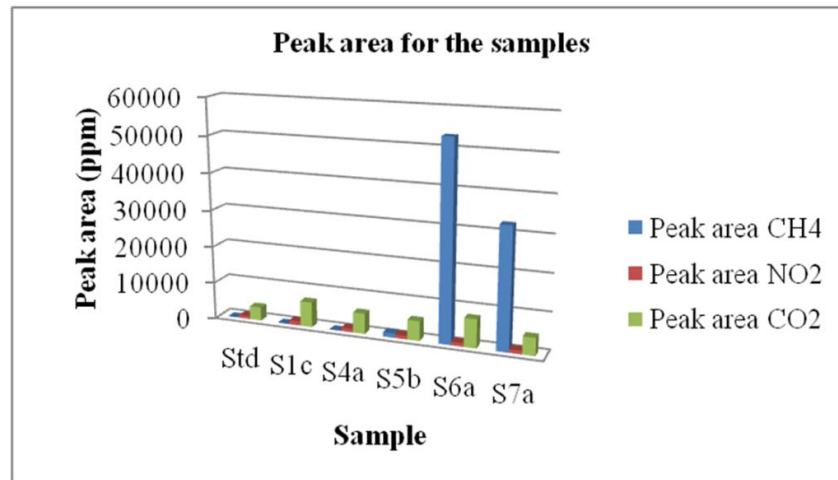
Fig. 6. (a) The gas Chromatograph machine connected to a display computer (b) Gas being injected into the GC system (c) Biogas stored in Syringes ready for testing

Table 4. Retention time for Methane CH₄, Nitrogen dioxide NO₂ and Carbon dioxide CO₂

Sample ID	Amount injected	Retention time (min) CH ₄	Retention time (min) NO ₂	Retention time (min) CO ₂	Unit
Std (carrier gas)	5 ml	1.756	3.456	2.733	ppm
S1c	5 ml	1.766	3.473	2.743	ppm
S4a	5 ml	1.756	3.463	2.733	ppm
S5b	5 ml	1.766	3.473	2.743	ppm
S6a	5 ml	1.733	3.463	2.733	ppm
S7a	5 ml	1.79	3.46	2.730	ppm

**Fig. 7. (a) Comparison of Retention time and (b) peak height for the tested gas samples****Table 5. Peak area for Methane CH₄, Nitrogen dioxide NO₂ and Carbon dioxide CO₂**

Sample ID	Amount injected	Peak area CH ₄ (ppm)	Peak area NO ₂ (ppm)	Peak area CO ₂ (ppm)	Totals	% of CH ₄	% of NO ₂	% of CO ₂
Std	5 ml	36.2154	801.9786	3628.455	4466.649	0.811	17.95	81.23
S _{1c}	5 ml	50.3645	1100.93	6861.205	8012.499	0.629	13.74	85.63
S _{4a}	5 ml	44.2785	947.9118	5550.316	6542.506	0.677	14.49	84.83
S _{5b}	5 ml	1190.59	951.4714	5353.829	7495.893	15.88	12.69	71.42
S _{6a}	5 ml	53250.4	952.0428	7738.212	61940.69	85.97	1.537	12.49
S _{7a}	5 ml	32618.3	939.2674	4770.065	38327.6	85.1	2.451	12.45

**Fig. 8. Peak area for the gas samples collected**

4. CONCLUSION

The study has shown that 1.98 kg of kitchen waste mixed with cow dung produced 0.032872 m³ of biogas. At a conversion rate of 0.056 m³/kg we see a prediction of a gas volume of 110.88 litres (from the mass of substrate digested) could be generated in a more efficient digester. The power potential of the biogas produced by co-digesting kitchen waste and cow dung was assessed. It was found to be 22,461.77 W/m³. From literature it is established that pure methane has a power potential of 37,258.9W/m³. These points at the methane percentage in the biogas collected in this study to be 60.29%. From the chromatograph peak area results of this study, we see that of the tested kitchen waste, the following had the highest methane content: raw starch (S_{5a}) 15.88%, pure cow dung (S_{6a}) 85.97% and cooked starch (S_{7a}) 85.1%. The study has demonstrated that the various food wastes in the kitchen have a great biogas potential and can be exploited for both domestic and even commercial use especially when co-digested with cow dung. The study has revealed vital details that will guide in the establishment of an eco-friendly biogas system that each household will want to put in place for the supply of the much needed clean and affordable energy.

ETHICAL APPROVAL

No ethical considerations were made. There were no animals used in the laboratory work

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX



Fig. 9. The setup of the laboratory scale biogas digester system

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