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Original Research Article

Investigation of the energy (biogas) production from co-digestion of organic waste materials

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ABSTRACT

Biogas production rate was investigated from the co-digestion of 39 kg each of food waste, cow dung and water; 39 kg each of food waste, poultry droppings and water as well as 39 kg each of food waste, fruit waste and water in 43 litres plastic digester setup. Although organic waste mix ratios with higher moisture content can influence decomposition rate, HRT and biogas yield, 1:1:1 mix ratio was used in this investigation. The total rate of biogas produced from the co-digestion of food waste with poultry droppings and water (39 kg) in the ratio of 1:1:1 was 4120 g of raw biogas and 3700 g of purified biogas within with Hydraulic Retention Time 32 days, whereas, the co-digestion of food waste with cow dung and water (39 kg) in the same 1:1:1 ratio yielded a total raw biogas of 5830 g and 4920 g of purified biogas with HRT of 35 days. However, co-digestion of food waste with fruit waster and water (39 kg) in the same ratio yielded a total raw biogas of 5010 g and purified biogas 4330 g with HRT of 33 days. Raw biogas produced from each organic feedstock was channelled through a scrubbing unit comprising distilled water and Type B silica gel. After the raw biogas had passed through the distilled water stream, its pH dropped drastically from neutral range to ultra-acidic range (7-3.2), while it also had milky color and sour taste, indicating the presence of carbonic acid (H_2CO_3) as a result of carbon dioxide (content in the raw biogas) dissolution in the distilled water. Color of the Type B silica gel changed from crystal pink to crystal blue, indicating the absorption of water content in the biogas by silica gel particles. Organic waste is a renewable energy resource that can offset Nigeria's increasing demand for energy if harnessed and processed into cooking gas and organic fertilizers before disposal, in which case can also prevent Green House Gas (GHG) emissions into the atmosphere.

Keywords: Food waste, Co-digestion, biogas production, Renewable energy, Methane

1. Introduction

A number of Nigerian families, particularly in the rural areas depend mainly on traditional biomass fuel such as fire wood and charcoal [1]. Food waste is a renewable energy resource unlike fossil fuel (non-renewable energy) and the cost per Kilowatt hour (KWh) of utilising renewable energy is cheaper compared to fossil fuel [2]. However, continuous utilisation of biomass (wood fuel) in households has become a major driver of deforestation, increased biodiversity loss, depletion of wild and other natural resource base, changes in vegetation types, land degradation, climate changes [3]. Due to rapid human population in the world, high rate of consumption and urbanisation has been the result, which has led to massive increase in Municipal Solid Waste (MSW) generation [4]. Recent reports have indicated that these MSW which can salvage the increasing energy demands are piled up in various rural and urban areas in Nigerian cites without major concern about its effects or efforts to convert the waste materials into useful energy that can add value to the development of the nation, and prevent the consumption of wood fuel as well as its effects on the ecosystem [1]. Biogas is a mixture of gases produced from the breakdown of biodegradable waste matter, of which methane is predominant. Biogas can be produced as digested gas using anaerobic digesters or as landfill gas from landfills, which provides viable options that can suite the cravings for energy or salvage the growing energy demand in Nigeria. In recent times, studies have shown that co-digestion of organic substrates can yield a large quantity of biogas than the digestion only one type of substrate. Co-digestion of organic matter involves the digestion of multiple feed stocks of different origins such as the digestion of poultry waste with pic dung, food waste etc. [5-8]. Olmedo et al. [9] discussed that biogas has been used widely as a major source of cheap, renewable and affordable energy for domestic purpose, operating Internal Combustion Engines (ICE), power generation and gas turbines in some European countries (such as Germany, Austria, Denmark, Sweden), United States, Hongkong etc. Moreover, countries such as China, India and Nepal have used biogas for cooking for a long time and its usefulness have led to the development of standards and testing methodologies for domestic biogas stoves in China and India [10, 11]. However, there are still many countries such as Nigeria where the advancement in biogas technology is no yet available and affordable [12]. In Canada, heartland landfill yields about 18 cubic meters of landfill gas per minute, which can be recovered and transported to a landfill gas utilization facility to generate approximately 12,274 MWh of electricity on yearly basis or sufficient energy for about 1600 homes [13]. Biogas can be produced from a number of biodegradable materials such as Municipal Solid Waste (MSW), domestic waste, agricultural waste, waste from agri-food industry, sewage, manure etc. and it is a renewable energy resource with calorific value half that of natural gas [14]. According to Lijun et al. [15], biogas is a type of gas (generated in an airtight system, through fermentation and breakdown of biodegradable or organic matter by anaerobic bacteria in the absence of oxygen) that contains 45-65 % Methane (CH_4), 25-35 % of Carbon dioxide (CO_2) and 10-20 % traces of moisture, elements and chemical compounds such as Hydrogen Sulphide (H_2S), Siloxane, Hydrogen (H_2) etc. Although CO_2 has zero heating value for combustion in air/oxygen, biogas is still a high-quality fuel gas due to methane content which can be as high as 70% in biogas produced from municipal solid wastes, making biogas a potential energy source for household consumption [9, 16]. Moreover, Methane and Hydrogen can be subjected to combustion or oxidized with oxygen to generate energy, which enables the use of biogas as fuel in turbines, domestic stoves and IC engines. However, Methane is highly poisonous in the atmosphere and contributes to global warming as it is a major Green House Gas (GHG) that is 21 times more potent than CO_2 when released into the atmosphere [17-19]. Moreover, Environmental Protection Agency's Global Anthropogenic Emissions for non CO_2 GHGs report shows that Nigeria is ranked 9th position for estimated anthropogenic methane emissions in the world, with about 2.23 Million Metric Tons of Carbon Equivalent (MMTCE) of world methane emission generated in Nigerian dumpsites [20]. From the following estimations, Nigeria is obviously a potential contributor to the global methane and CO_2 emission. This study is focused on the investigation of the energy content of some organic waste typically found in Nigerian dumpsites. It will also promote the diversion of organic waste from open dumpsites, thereby creating a sustainable environment and preventing GHG emissions for public health benefits.

2. Materials and Methods

The experimental setup comprised a bio-digester equipped with ball valves at the inlet and outlet, biogas gas extraction hose, pressure gauge (5 bar), biogas scrubbing units interconnected with plastic hoses in which gases produced as a result of substrate decomposition passed through prior to entering the gas storage vessel. As shown in Figure 1, the first scrubbing chamber contains distilled water (H_2O) to absorb Carbon dioxide (CO_2) which is the primary impurity present in biogas, whereas, the second scrubbing chamber contains Type B silica gel which is moisture absorbent that absorbs and dries up moisture content present in the biogas. Deflated motorcycle tube of known mass (496 g) was mounted right after the silica gel scrubbing chamber to serve as storage vessel for the purified biogas which in the process of entering the rubber tube causes it to inflate.

2.1. Volume of bio-digester

To save time and cost, the vessel used as the bio-digester was purchased in the market, after which the instrumentation and pipping were fitted according to the design. To determine the volume of the bio-digester, circumference (C) taken as the distance measured around the mid-section of the bio-digester is given by equation (1);

$$C = 2\pi r \quad (1)$$

Recall that,

$$2r = \text{Dimeter (D)} \quad (2)$$

Volume (V) is given by equation (3);

$$V = \pi r^2 h \quad (3)$$

Where r is the radius given by equation (4);

$$r = \frac{1}{2} D = \frac{1}{2} * 318.3 \quad (4)$$

Applying the measured values in equations 1-4, a total volume of 43,000 cm^3 (43 litters) was obtained for the bio-digester. The aforementioned formulas and steps were also used to determine a total volume of 2,041 cm^3 (2 litters) for the scrubbers, assuming all the scrubber vessels to be of the same sizes.

1	Substrate inlet	6	Ball Valve outlet	11	Silica gel scrubber	16	Hose connector
2	Pressure guage	7	Ball valve inlet	12	Purified biogas outlet	17	Motocycle tube
3	Digester	8	Transparent hose	13	Wet biogas inlet		
4	Raw biogas inlet	9	Gate valve (raw biogas)	14	Dry biogas outlet		
5	Substrate outlet	10	Water Scrubber	15	Gate valve (purified biogas)		

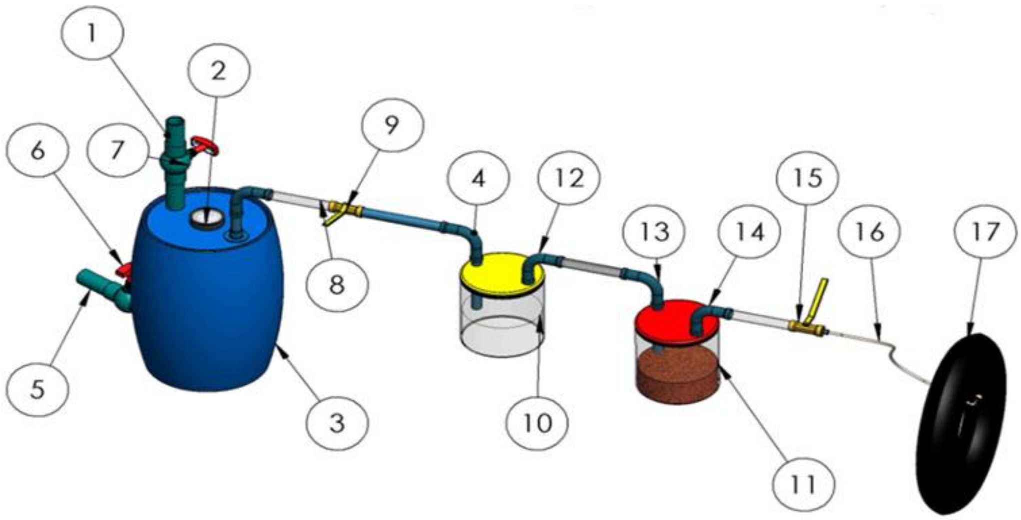


Figure 1. Experimental set-up for anaerobic digestion of organic waste

2.2. Experimental procedure

The experiment was carried out for three different set of organic feedstock namely; Food waste (13 kg) + poultry dropping (13 kg) + distilled water (13 kg); Cow dung (13 kg) + Food Waste (13 kg) + Distilled water (13 kg); and Fruit waste (13 kg) + Food Waste (13 kg) + Distilled water (13 kg).

- Using weighing balance, the total mass of each set of the three substrates used for the experiment were 39 kg. Food waste used for the experiment includes Rice, Beans, Garri, Yam, Fufu, Ripe plantain, Ripe banana etc. Organic feedstocks used for the experimentation are presented in Figure 2.
- Distilled water and each set of substrate were thoroughly mixed together until the mixture became slurry.
- The distilled water and substrates mixture were poured into the bio-digester (shown in through the inlet and after which, the digester inlet valve was closed.
- The initial gauge pressure was recorded at 0.0 bar.
- pH of water in the scrubbers were tested (using digital handheld pH meter) before and after scrubbing to determine its acidity as a result of toxic gases absorbed.
- The same procedures were applicable to all the three set of substrates introduced into the digester.
- Composition of the raw and purified biogas produced from each of the three set of substrates were determined using Optima 7 biogas handheld device. For example, the composition of raw and purified biogas produced form food waste + poultry dropping + distilled water is shown in Figure 3.

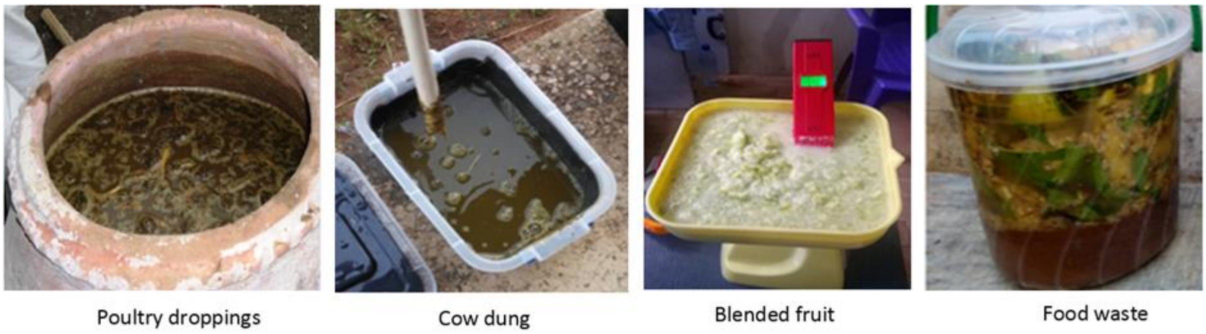


Figure 2. Organic feedstocks used for the experimentation

- As shown in Figure 4, the experimental setup consisted of three different units with each unit comprising of 43 liters digester, 2 liters scrubbing vessels, control valves, pressure gauge, motorcycle tube etc.

Technical specifications of the biogas analyzer and pH meter are presented in Table 1 as follows;

Table 1. Technical specifications of the biogas analyser and pH meter

Pen Type ph Meter (pH-2011)		**Optima 7 Biogas**	
Range	0.00-14.00 pH	Temperature	5ºC-45ºC
Resolution	0.01 pH	Battery	Lithium-ion Battery 6-8 Hours
Accuracy	±0.1 pH	Weight	750 g with 7 Sensors
Battery	4x1.5 V (AG-13)	Dimension	110mmx225mmx52mm
Temperature Compensation	0ºC – 50º C	CO_2 Accuracy	±0.3%
Dimension	151mmx33mmx20mm	CH_4 Accuracy	±0.3%
Weight	53 g	H_2S Accuracy	±5 ppm
Acidity	1-6	Gas Flow Velocity	1-40 m/s
Alkalinity	8-14	Power specification	90-240 Vac/50-60 for battery charging with USB port
Neutrality	7	Biogas Sampling Line	3x2 mm Viton with 5 m length and stainless steel gas inlet port

Figure 3. Optima Biogas 7 for determination of biogas composition

The main components are an infrared sensor, a sample chamber or light tube, a wavelength sample chamber, and gas concentration is measured electro-optically by its absorption of a specific wavelength in the infrared (IR). The IR light is directed through the sample chamber towards the detector. The detector has an optical filter in front of it that eliminates all light except the wavelength that the selected gas molecules can absorb. Ideally other gas molecules do not absorb light at this wavelength, and do not affect the amount of light reaching the detector to compensate for interfering components. Optima 7 Biogas analyser also comprises a Teflon filter for protection against dirt and soiling, with robust stainless steel connectors (gas ports) through which one end of a hose was connected while the other end was connected to the motorcycle tube which was used to store the biogas produced from each category of substrates. Different gas composition present in the biogas exhibited cross sensitivity in the infrared spectrum, and that enabled the percentage of individual gases in the biogas sample to be measured.

The expression of relationship between pH and methane yield is given by equation (5);

$$\frac{dCH_4}{dt} = \left(Vm_{max}X_m \frac{AC^{-1} \times 10^{-pH}}{AC^{-1} \times 10^{-pH} + K_aK_m}\right) x \left(\frac{K_{im}K_a}{K_{im}K_a + AC^{-1} \times 10^{-pH}}\right) \quad (5)$$

where Vm_{max} is the maximum yield rate of methane (in volume at 0° C and 1 atm pressure) per g of methanogenic bacteria per day; X_m-methanogenic food waste substrate (g/kg); K_m, Saturation constant of methane yield (g/kg); K_{im}, inhibition constant of acetate on methane yield (g/kg); K_a, the dissociation constant for acetate ($1.728 x 10^{-5}$) and A_c is ionized acetate concentration (g/kg). The generalized stoichiometric reaction for the overall biogas generation is given by the expression in equation 6;

$$C_{99}H_{149}O_{59}N \rightarrow \{50.88\}CH_4 + \{43.73\}CO_2 + \{0.85\}C_5H_7O_2N + \{0.15\}NH_4^+ + \{0.15\}HCO_3^- \quad (6)$$

Figure 4. Experimental set-up in the laboratory

3. Results and Discussion

Table 2 represent different results obtained from the co-digestion of food waste with poultry dropping, food waste with cow dung and co-digestion of food waste with fruit waste. Substrates ratio digested for food waste, cow dung and fruit waste were in equal proportion of 13 kg each, in the ratio of 1:1:1 respectively.

Figure 5-7 represents biogas productivity curves plotted from co-digestion of food waste with three different categories of organic waste each (Cow dung, poultry droppings, fruit waste). Figure 8 represents the total biogas composition from Co-digestion of organic Waste Measured with Optima 7 Biogas.

As shown in Table 2, it can be observed from the results that biogas yield from the co-digestion of food waste with cow dung was comparably higher than the result of biogas yield obtained from the co-digestion of food waste with poultry dropping and result of biogas yield obtained food waste with fruit waste. However, results of biogas yield obtained from the co-digestion of food waste with fruit waste was comparably higher than results of biogas yield obtained from co-digestion of food waste with poultry dropping. Observing the trend of water acidity in terms of pH before and before absorbing raw biogas, there are significant variations which led to the conclusion that the more raw biogas absorbed by distilled water in the water scrubber vessel, the higher the acidity of the water and the lower the pH of the water.

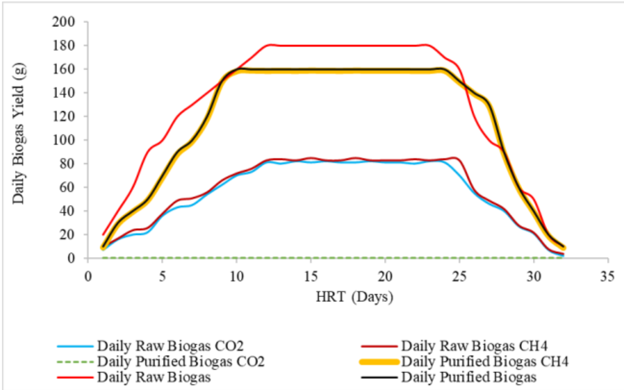


Figure 5. Biogas productivity curve plotted from co-digestion of food waste with poultry droppings

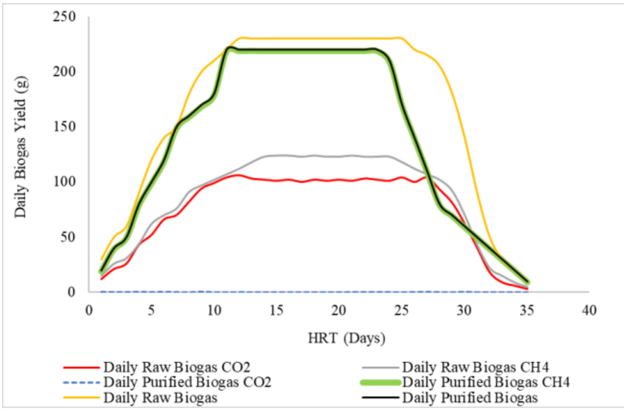


Figure 6. Biogas productivity curve plotted from co-digestion of food waste with cow dung

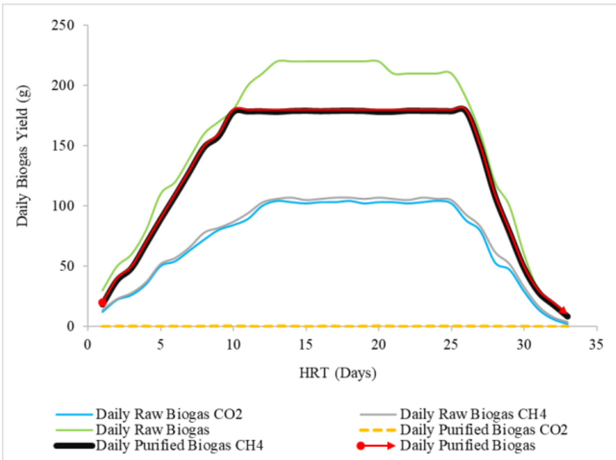


Figure 7. Biogas productivity curve plotted from co-digestion of food waste with fruit waste

Table 2. Co-digestion of food waste with poultry dropping, cow dung and fruit waste

HRT (Days)	Food Waste, Poultry dropping 39kg			Cow dung, Food Waste 39kg			Fruit, Food Waste 39kg		
	Raw Biogas (g)	Purified Biogas (g)	Water Acidity Test-pH	Raw Biogas (g)	Purified Biogas (g)	Water Acidity Test-pH	Raw Biogas (g)	Purified Biogas (g)	Water Acidity Test-pH
1	20	10	6.4	30	20	6.8	30	20	6.7
2	40	30	5.3	50	40	5.4	50	40	5.2
3	60	40	4.2	60	50	4.4	60	50	4.2
4	90	50	4.1	90	80	4.2	80	70	4.7
5	100	70	3.9	120	100	4.0	110	90	3.9
6	120	90	3.4	140	120	4.0	120	110	4.0
7	130	100	3.2	150	150	3.9	140	130	3.8
8	140	120	3.3	180	160	3.5	160	150	3.9
9	150	150	3.4	200	170	3.6	170	160	4.1
10	160	160	3.3	210	180	3.2	180	180	3.9
11	170	160	3.2	220	220	3.3	200	180	4.0
12	180	160	3.4	230	220	3.4	210	180	3.9
13	180	160	3.3	230	220	3.3	220	180	4.0
14.	180	160	3.4	230	220	3.2	220	180	3.8
15.	180	160	3.6	230	220	3.2	220	180	3.9
16.	180	160	3.3	230	220	3.2	220	180	3.9
17.	180	160	3.5	230	220	3.3	220	180	4.1
18.	180	160	3.4	230	220	3.3	220	180	4.0
19.	180	160	3.6	230	220	3.2	220	180	3.8
20.	180	160	3.3	230	220	3.2	220	180	3.9
21.	180	160	3.3	230	220	3.5	210	180	3.8
22.	180	160	3.3	230	220	3.4	210	180	4.0
23.	180	160	3.3	230	220	3.6	210	180	3.9
24.	170	160	3.2	230	210	3.7	210	180	3.8
25.	160	150	3.7	230	170	3.7	210	180	4.1
26.	120	140	3.9	220	140	3.8	190	180	4.2
27.	100	130	4.1	215	110	3.7	160	150	4.2
28.	90	90	4.1	205	80	3.9	120	110	4.3
29.	60	60	4.2	180	70	3.9	100	80	4.4
30.	50	40	4.3	140	60	4.2	60	50	4.4
31.	20	20	4.4	90	50	4.3	30	30	4.5
32.	10	10	4.6	50	40	4.3	20	20	4.6
33.	-	-	-	30	30	4.4	10	10	4.7
34.	-	-	-	20	20	4.5	-	-	-
35.	-	-	-	10	10	4.8	-	-	-
36.	-	-	-	-	-	-	-	-	-
Total	4120	3700	-	5830	4920	-	5010	4330	-

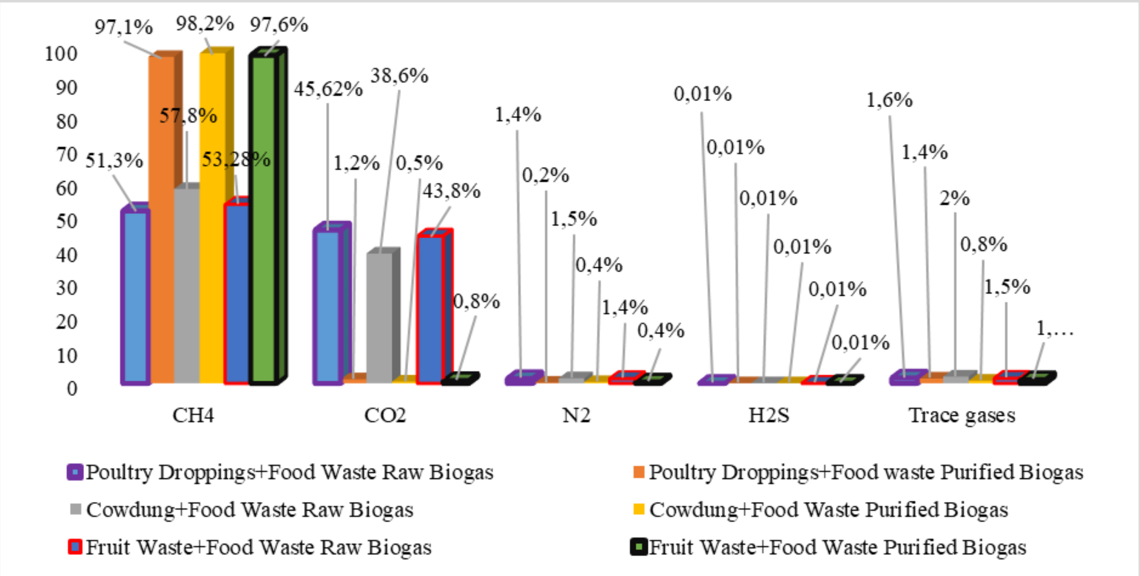
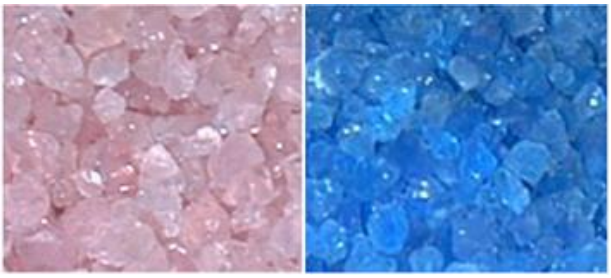


Figure 8. Biogas composition measured with Optima 7 biogas device



(a) Before reaction with raw biogas (b) After reaction with raw biogas

Figure 9. Effect of wet biogas on silica gel used as drying agent

The acidity of the water which is categorize as carbonic acid which forms as a result of CO_2 interaction with water molecules. Furthermore, water content present in the biogas living the water scrubber vessel entered another scrubber vessel containing Type B crystal pink silica gel and its interaction with water molecules present in the biogas changed its initial color from crystal pink to crystal blue as shown in Figure 9. The biological breakdown of organic materials generated biogas which was channelled through a scrubbing until containing distilled water, and carbon dioxide content in the biogas dissolved within the water molecules to forms carbonic acid (H_2CO_3) which produced slightly sour test similar to soda drinks and carbonated water. During the water and carbon di oxide reaction, Carbonic acid may lose protons to form bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). In this case the proton is liberated to the water and thus, pH of the water is decreased. Relative, H_2CO_3 concentration is actually CO_2 in equilibrium with water. The chemical reaction between CO_2 and H_2O can be expressed as;

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (8)$$

or

$$CO_2 + H_2O \rightarrow HCO_{3^-} + H^+ \quad (9)$$

The moles of CH_4 and CO_2 can be determined from the stoichiometric reaction stated in equation (6), and can be converted into masses from the molecular weight of 16 and 44 g/mol.

4. Conclusion

Anaerobic digestion of organic substrate is a proven technology for processing source-separated organic wastes and its application has increased significantly in recent times, particularly in the area of biogas production. The result has shown that co-digestion of food waste with other organic substrates such as animal excrements can yield more biogas than the process where only one type of substrate is digested for biogas production. The result has also shown that the concentration of carbon dioxide in biogas production is dominant, and could interact with other gases present in biogas to form acidic compounds or gases which depending on the toxicity could have negative effects on public health and environment. This observation was conspicuous in the Water Acidity Test, where pH of the water dropped significantly from 7-3.2, indicating the presence of carbonic acid. This however necessitates proper purification of biogas before usage. However, co-digestion of food waste with cow dung which produced the highest amount of raw biogas of 5010 g and purified biogas of 4330 g also had the longest HRT of 35 days. In addition, the amount of raw biogas reduced significantly after purification.

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Nomenclature

A_c	Ionized acetate concentration
C	Circumference of Digester
CH_4	Methane
Cm^3	Centimetres Cube
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate
D	Diameter of Digester
g	gram
g/mol	gram per mole
GHG	Green House Gas
h	Height of Digester
H_2	Hydrogen
HCO_3^-	bicarbonate
H_2CO_3	Carbonic acid
H_2O	Water
H_2S	Hydrogen Sulphide
HTR	Hydraulic Retention Time
ICE	Internal Combustion Engines
IR	Infrared
K_a	Dissociation constant for acetate
Kg	Kilogram
K_{im}	Inhibition constant of acetate on methane yield
K_m	Saturation constant of methane yield
KWh	Kilowatt hour
MSW	Municipal Solid Waste
MMTCE	Million Metric Tons of Carbon Equivalent
MWh	Megawatt hour
pH	Potential of Hydrogen
π	Pi
r	Radius of Digester
V	Volume of Digester
Vm_{max}	Maximum yield rate of methane per gram of methanogenic bacteria per day
X_m	Methanogenic food waste substrate