DEVELOPMENT AND ASSESSMENT OF LOCALLY IMPROVISED BIOGAS REACTOR FOR BIOGAS PRODUCTION FROM CO-DIGESTION OF COW DUNG WITH FRUIT AND VEGETABLE WASTES

Babashola Dapo Odugbose*[1], Oluwatunmise Israel Dada[1], Basit Olaniyi Bakare[1], Adebayo Bamidele Adelase[1], Kayowa Oluwapelumi Arowosafe[2]

[1]*Department of Agricultural Engineering, Faculty of Engineering, College of Engineering and Environmental Studies (CEES), Olabisi Onabanjo University, Ibogun Campus, P.M.B 5026, Ifo, Ogun State, Nigeria.*
[2]*Department of Farm Power and Machinery, National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State, Nigeria.*
*Email: odugbose.babashola@oouagoiwoye.edu.ng

ABSTRACT
Fruits and vegetables are very much in abundance in our environment and so is the waste generated from them, since they are highly perishable. This is an integral portion of the tonnes of food lost annually throughout the food and supply chain – during agricultural production, to food processing, and finally to household consumption. These wastes eventually constitute nuisance to the environment in form of pollution. In order to utilize these wastes for energy production, biogas was produced from the co-digestion of cow dung (CD) with fruit and vegetable wastes (FVW) using a designed and fabricated bio-digester. The CD, fruit wastes (FW) – watermelon (WFW) and pawpaw (PFW), and vegetable wastes (VW) were crushed and blended to pulp. From these, three slurry samples were prepared in ratios 1:2 with water. All samples contained 12.5 kg CD and 10 kg VW. In addition, Sample A contained 15 kg WFW, Sample B contained 15 kg PFW, and Sample C contained 10 kg each of WFW and PFW. Three bio-digesters were used, corresponding to one bio-digester per sample. Each sample was loaded once and readings taken over a period of 31 days at two hours interval between 8 am - 6 pm daily. All digester slurries were agitated regularly at each interval except for Sample C slurry in order to determine the influence of slurry agitation on biogas production. Results showed that daily temperature range was 34-44°C which is in the range of optimum mesophilic temperature for anaerobic digestion. The highest cumulative biogas yield (32.85 kg, mean 1.06 kg) was recorded in Sample A digester, followed by Sample B (29.60 kg, mean 0.95 kg), and lowest in Sample C (15.22 kg, mean 0.49 kg). From the study, it was concluded that slurry agitation improves biogas yield. Also, biogas is better produced from the co-digestion of cow dung with WFW and VW than from the co-digestion of cow dung with PFW and VW or the mixture of cow dung, PFW, WFW and VW. This study has therefore succeeded in contributing to environmental waste reduction as well as converting wastes to wealth by generating energy from wastes.

KEYWORDS: Anaerobic digestion, bio-digester, bio-waste, cow dung, biomass, fruit and vegetable waste

1. INTRODUCTION
Biogas is a mixture of gases produced by the breakdown of organic matters (biomass) by bacteria in the absence of oxygen; a process called anaerobic digestion (Tanigawa and Stolark, 2017). The major constituents of biogas are methane and carbon dioxide with several impurities – trace gases (Deublein and Steinhauser, 2008). Due to the high methane content of biogas, it is inflammable. As a result, biogas-generating innovation is a favourable dual-purpose initiative that should be embraced – waste is converted to energy in form of fuel

(Yeboah, 2016), and it helps in waste management for healthy environment and wealth creation.

Many different forms of biomass can theoretically be used to produce biogas. For example, fresh or ensiled plant materials (e.g. corn, grass, cereal, beet, clover), animal excrements (e.g. slurry or manure), agricultural or food processing residues (e.g. feed remnants, chaff, whey, glycerine, straw), and organic household waste (e.g. fruit waste, vegetable waste). For biogas production from feedstocks, a bio-digester is required. This is a vessel in which organic feedstock (substrate) is converted into biogas anaerobically by decomposition in four stages – hydrolysis (breakdown of complex biopolymers into monomers), acidogenesis (production of carboxylic acid, CO_2, hydrogen and alcohol from monomers), acetogenesis (acetic acid production), and methanogenesis (methane production) (Cioabla *et al.*, 2012; Deublein and Steinhauser, 2008). Apart from biogas as primary product from a bio-digester, the secondary product is sludge residue or digestate (Sagagi *et al.,* 2009). Digestate can be utilized for soil amendment, or as starting material for high quality compost preparation (Nguyen, 2012).

Some very common concepts of feedstock supply for anaerobic digestion in a bio-digester are single-phase, two-phase digestion, dry fermentation, and co-digestion. Single-phase digestion involves the use of a digester with only one compartment where all the four microbiological stages take place. Two-phase digestion, on the other hand, involves the use of a digester with two separate compartments that correspond to two microbiological processes viz. hydrolytic/acidogenic phase and acetogenic/methanogenic phase (Okudoh *et al.*, 2014). Dry fermentation is a single-phase digestion process that involves pre-mixing of relatively dry feedstock, such as cassava biomass, with an inoculum e.g., cow manure (Okudoh *et al.*, 2014). Co-digestion, which involves simultaneous digestion of multiple organic substrates in one digester (AgSTAR, 2012), is deemed the best of these concepts as it improves biogas yield by complementing missing nutrients for micro-organisms digestion (Deressa *et al*., 2015).

In co-digesting various feedstocks for optimum biogas yield in a bio-digester, an optimum temperature is also needed (Singh *et al.*, 2017). As reported by Wu *et al.* (2006) and El-Mashad *et al.* (2004), anaerobic digestion can be carried out in three conditions – ambient (< 25 °C), mesophilic (25-45 °C) and thermophilic (> 45 °C) conditions. Of these three conditions, thermophilic anaerobic condition has been recorded to give higher yield due to improved microbial activities, giving rise to better substrate degrading power of microorganisms (Cinar and Kuchta, 2020; Wang *et al.*, 2019; Singh *et al.*, 2017). On the contrary, lower temperatures, such as that of ambient, has been found to inhibit microbial activities in anaerobic digestion (Wang *et al.*, 2019). Though thermophilic anaerobic condition gives rise to high microbial reactions and biogas production, it is counterbalanced by high energy consumption (Singh *et al.*, 2017), resulting in higher biogas production cost. Therefore, mesophilic anaerobic condition is preferred for anaerobic digestion of agricultural wastes as it is more stable and requires less energy consumption (Cinar and Kuchta, 2020; Franqueto, 2020; Wang *et al.*, 2019; Cho *et al.*, 2013; Cai *et al.*, 2004). At household level, food waste can be added to bio-digesters to complement human faeces and urine (Hien *et al.*, 2014). This increases the amount of gas available for cooking and reduces the amount of waste that must be shipped to landfills or centralized recycling facilities (Croxatto Vega *et al.*, 2014). The pollution that results from temporary storage of the food waste at household level is also avoided by such strategy (Yen *et al.,* 2017).

As reported by FAO (2011), about 1.3 billion tonnes of food is lost globally throughout the food and supply chain annually. This loss range from initial agricultural production to its processing and finally to household consumption. In Nigeria, FVW are very much in abundance and so is the waste generated from them, since they are highly perishable. With the high moisture content of the wastes from fruits and vegetables, landfill disposal of these wastes is quite challenging; thus, generating high environmental complications even for short-term disposal (Scano *et al.*, 2014). Heaps of such rotten organic refuse encourage the breeding of flies and vermin, and runoff can pollute nearby streams.

As seen from the projects of Rahmat *et al.* (2019), Budiyono *et al.* (2018), Yen *et al.* (2017), Deressa *et al*. (2015), and Hien *et al.* (2014), converting these FVW into biogas generates some energy and likewise benefit the environment. Besides, as a waste to energy strategy, the cost for raw material is cheap, available in high quantities and the biogas yield is relatively high as biogas produced from manure (Deublein and Steinhauser, 2008). In order to contribute to environmental waste reduction as well as provide communities with sustainable means of converting wastes to energy, this study aims at assessing biogas production from the co-digestion of cow dung with FVW in a designed and fabricated locally improvised bio-reactor.

2. MATERIALS AND METHODS

2.1 Materials

The materials used to setup the bio-digester include 50 L plastic drums, thermometers (thermocouple), 1 L plastic containers, transparent plastic containers, steel wool, manual agitators, pipes and fittings, gas valves, sockets valves, T-valves, hoses, and tyre tubes. Feedstock materials used are cow dung, fruit wastes (watermelon and pawpaw), vegetable wastes (vegetable, pea, carrot and lettuce), and water. Equipment used include blender and electronic beam balance.

2.2 Methods

2.2.1 Substrate collection

The FVW, which sum up to 40 kg PFW, 40 kg WFW, and 40 kg VW, were collected fresh from market vendors at Ketu market, Lagos State and Sango-Ota market, Ogun State. The FVW were first washed to remove foreign materials before putting in separate transparent plastic containers. For cow dung, 50 kg of fresh cow dung was collected from a cow barn located in Mushin, Lagos State and put inside a transparent plastic container for transportation. The cow dung samples were carefully collected to avoid sampling along foreign materials such as sand and debris. The collection and transportation of both FVW and cow dung were done on the same day, and transportation was under ambient conditions. The samples were processed for usage immediately they arrived the location of experiment.

2.2.2 Slurry preparation

Size reduction was performed on the FVW by manual cutting (Figures 1 – a, c, e), and subsequently blended to pulp with an electric blender (Figures 1 – b, d, f). This was aimed at abetting decomposition of the substrate in the bio-digester. With the blended FVW, three slurry samples were prepared in ratios 1:2 with water as described by Adeniran *et al*. (2014). Cow dung was also crushed and mixed thoroughly with the use of a small pestle until it attained a pulpy form before co-mixture with the FVW (Figure 2). The electronic beam balance was used to weigh the samples. All samples were made up of 12.5 kg cow dung and 10 kg vegetable waste (VW) with varying quantities of watermelon and pawpaw fruit wastes (Table 1). Sample C contained cow dung and wastes from water melon, pawpaw, and vegetables. It had the highest substrate composites by mass because it is made up of the mixture of all the FVW in the same quantity. This was done to determine if the commixture of cow dung with all the FVW of the same quantity would give a better biogas yield. Samples A and B both contained cow dung and VW in addition to WFW for Sample A and PFW for Sample B. The quantity of WFW in Sample A was made higher than that of VW to determine if WFW has a better capacity of influencing better biogas yield. Similarly, for Sample B, PFW was made higher than VW. Table 1 shows the quantity of substrates used for slurry in each sample.

Table 1: Bio-digester Slurry Samples Composite

	Sample A (kg)	Sample B (kg)	Sample C (kg)
Cow dung (CD)	12.5	12.5	12.5
Watermelon fruit wastes (WFW)	15	-	10
Pawpaw fruit wastes (PFW)	-	15	10
Vegetable wastes (VW)	10	10	10

Figure 1: Substrates preparation – (a) cut watermelon (b) blended watermelon (c) cut vegetable (d) blended vegetable (e) cut pawpaw (f) blended pawpaw

Figure 2: Cow dung substrate preparation

2.2.3 Bio-digester set-up and loading

Three 50 litres blue cylindrical containers (Figure 3) were adopted as digesters. Each digester has diameter 38 cm and height 63 cm. The lid of each digester was bored in four places – 5 cm diameter for slurry inlet, 2.5 cm diameter for gas outlet, 1.4 cm diameter for manual agitator, and 0.3 cm diameter for the thermometer holder. Apart from bores on the lid, 5 cm diameter slurry outlet was also bored at bottom side of each digester. The manual agitator was used to stir the slurry in order to ensure proper mixture which gives rise to enhanced gas production. Temperature in the digester was measured with the attached thermometer. All perforations were adequately sealed to prevent gas leakage. The setup is shown schematically in Figure 4.

Attached to each digester were a 1 L air-tight plastic container (scrubber) containing steel wool and a black tube (gas receiver) of inner diameter 27 cm and outer diameter 64 cm, both of which were connected end-to-end to the digester through a rubber hose which was tightened to the gas outlet (Figure 4). The function of the rubber hose is to convey biogas generated from the digester to the gas receiver. The function of the steel wool present inside the scrubber is to refine the biogas by scrubbing hydrogen sulphide before it is released to the gas receiver. Due to large surface area of the steel wool, this method is very effective to absorb and remove hydrogen sulphide (Riyadi, *et al.,* 2018) from raw biogas. The valves were used to control the flow of gas into the gas receiver. The gas received was then measured by weighing the tube with an electronic beam balance. After each reading was taken, the control valve from the gas outlet was closed and that of the exhaust pipe opened to allow residual gas inside the gas receiver to be emptied for the next reading (Figure 4).

According to the method of Pham *et al.* (2014), where bio-digesters used were buried underground (at a depth of about 260 cm), each digester in this study was placed half-way into the ground at depth of 31.5 cm (Figure 4) to achieve a more stable internal temperature. Adequate space was provided at the upper part of the fermentation chamber for the storage of the biogas produced before delivery through the hose. Each bio-digester was loaded in one batch, with no other replica, according to the amount stated in Table 1, and readings taken over the period of 31 days.

Figure 3: Bio-digester experimental set-up

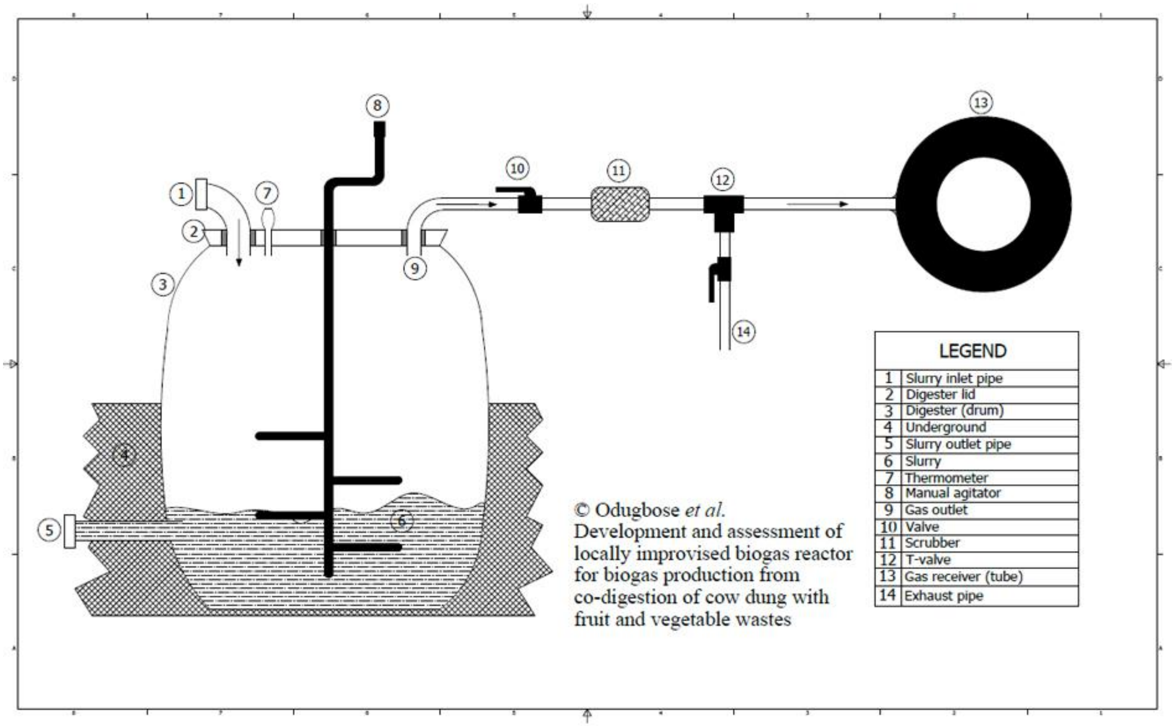

Figure 4: Schematic diagram of bio-digester experimental setup

2.2.4 Data collection

a. Temperature measurement

The temperature in each digester was monitored and recorded at two hours interval daily between 8am-6pm for 31 days. The average temperature was then calculated with equation (1), developed by the Authors using the arithmetic mean formula.

b. Biogas production

The slurries in samples A and B bio-digesters were gently stirred every two hours interval daily, between 8am-6pm, with the manual agitator, while sample C was left unstirred in order to determine the influence of agitation on biogas production. The weight of the empty gas receiver (T_w) – 0.920 kg – was determined by weighing the empty tube before the experiment, after which the gas produced was allowed to flow through the rubber hose, and into the gas receiver. The gas generated exerted pressure on the tube and made it to rise. The amount of gas produced (V_y) was measured and recorded every two hours (between 8am-6pm), at the end of each interval, making it 5 measurements per day. This was done by deducting the weight of the empty gas receiver tube (T_w) from the weight of the gas receiver after gas was received (V_x). Biogas production in all digesters was then monitored, recorded and analysed over a period of 31 days. The average amount (V_{AV}) of the gas produced was then calculated with equation (2), developed by the Authors from the arithmetic mean formula.

2.2.5 Data analysis

MS Excel was used to analyse the data collected and represent it in graphical form.

$$T_{AV} = \frac{1}{n}\sum_{x=1}^{n}(T_x) \text{.....................} equation\ (1)$$

n = Total counts of interval = 5

Where
T_{AV} *= Average temperature (°C)*
T_x *= Temperature recorded at interval (°C)*

$$V_{AV} = \frac{1}{n}\sum_{x=1}^{n}(V_x - T_w) \text{ ....}equation\ (2)$$

Where
V_{AV} = *Average amount of biogas produced (kg)*
T_w = *Empty gas tube weight (kg) = 0.920kg*
V_x = *Gas receiver weight after gas is received (kg)* $= V_y + T_w$
V_y = *Amount of biogas produced (kg)*
n = *Total count of experiments = 5*

3. RESULTS AND DISCUSSION

3.1 Temperature of digesters

A number of studies on anaerobic digestion of waste have indicated that temperature of digestion have strong influence on the rate of biogas production (Wang *et al*., 2019; Singh *et al*., 2017; Cho *et al*., 2013; Cai *et al*., 2004). The recorded temperatures from each digester are presented in Tables 2-4, with graphical representation of the average daily temperatures in Figure 5. The temperature range in this study is 34-44 °C (Figure 5). This is in the range of optimum mesophilic temperature of 32-45 °C for anaerobic biogas production reported by Obiukwu and Grema (2014), as cited in Stuckey (1986), and Bardiya *et al.* (1996) or that of 25-45 °C reported by Wu *et al.* (2006), as cited in El-Mashad *et al.* (2004). The range of temperature in this study is attributed to seasonal change as the study was carried out during rainy season. The range is below the temperature range of > 45 °C which has been reported (El-Mashad *et al.*, 2004) for optimum biogas production in thermophilic condition of anaerobic digestion. As a result, it was difficult to attain higher temperature as no temperature control measure was put in place. Moreover, mesophilic temperatures of 30-40 °C have been reported to give optimum biogas production for anaerobic digestion of agricultural organic wastes and have been widely adopted (Wang *et al*., 2019; Cho *et al*., 2013; Cai *et al*., 2004). The study of Malý and Fadrus (1971), shows that "increase in temperatures increases the rate of biological activity, but the total organic removal, given a sufficiently long fermentation time, was independent of temperature."

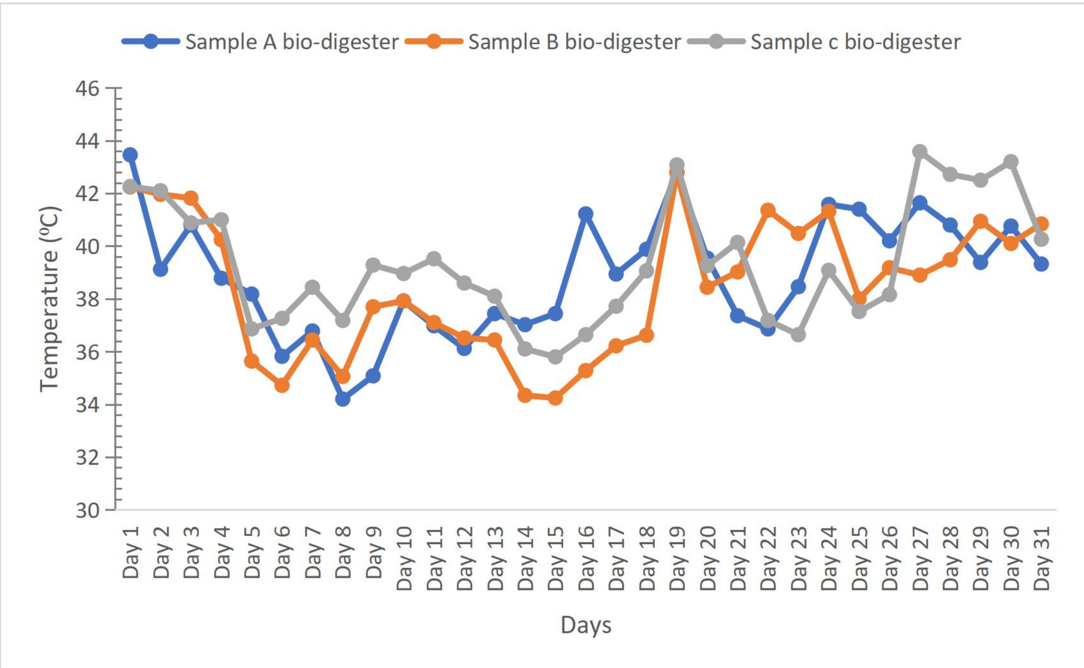

Figure 5: Daily average temperature (°C) variations in each digester

Table 2: Temperature (^{o}C) Variations in Sample A Bio-digester

Day	Date	T_1 (^{0}C)	T_2 (^{0}C)	T_3 (^{0}C)	T_4 (^{0}C)	T_5 (^{0}C)	T_{AV} (^{0}C)
Day 1	3/10/2021	37.80	45.40	47.80	45.90	40.40	43.46
Day 2	3/11/2021	29.60	41.10	41.90	43.00	40.00	39.12
Day 3	3/12/2021	30.10	47.10	45.80	41.10	39.90	40.80
Day 4	3/13/2021	27.20	42.00	47.00	39.60	38.10	38.78
Day 5	3/14/2021	26.10	44.30	45.50	36.50	38.50	38.18
Day 6	3/15/2021	31.10	45.10	27.30	36.70	38.90	35.82
Day 7	3/16/2021	40.00	43.20	28.00	35.40	37.30	36.78
Day 8	3/17/2021	22.00	41.00	36.10	34.10	37.80	34.20
Day 9	3/18/2021	36.00	40.00	30.00	33.20	36.20	35.08
Day 10	3/19/2021	37.60	48.90	33.00	33.50	36.60	37.92
Day 11	3/20/2021	38.60	45.50	32.00	33.70	35.10	36.98
Day 12	3/21/2021	39.00	40.00	34.00	32.10	35.50	36.12
Day 13	3/22/2021	34.10	48.90	39.00	31.10	34.10	37.44
Day 14	3/23/2021	35.10	45.00	40.00	30.70	34.30	37.02
Day 15	3/24/2021	37.70	43.30	41.00	30.50	34.70	37.44
Day 16	3/25/2021	35.10	48.10	44.00	45.70	33.20	41.22
Day 17	3/26/2021	37.10	44.20	36.00	46.10	31.30	38.94
Day 18	3/27/2021	37.00	44.30	44.00	42.40	31.70	39.88
Day 19	3/28/2021	45.80	42.00	44.00	43.10	39.10	42.80
Day 20	3/29/2021	36.00	45.00	45.90	39.90	30.90	39.54
Day 21	3/30/2021	37.00	42.10	46.80	31.00	29.90	37.36
Day 22	3/31/2021	35.10	46.00	45.50	30.00	27.70	36.86
Day 23	4/1/2021	36.20	47.10	43.30	39.10	26.60	38.46
Day 24	4/2/2021	37.00	44.00	42.90	47.40	36.60	41.58
Day 25	4/3/2021	39.90	42.00	44.10	42.10	38.90	41.40
Day 26	4/4/2021	37.70	43.10	42.20	44.00	34.00	40.20
Day 27	4/5/2021	42.00	41.10	42.10	47.00	36.00	41.64
Day 28	4/6/2021	36.00	40.90	43.10	44.10	39.90	40.80
Day 29	4/7/2021	33.00	39.90	44.10	39.90	40.00	39.38
Day 30	4/8/2021	36.70	41.90	47.70	36.60	40.90	40.76
Day 31	4/9/2021	31.10	40.60	45.20	40.10	39.60	39.32

Where: T_1 = Temperature (8 am - 10 am), T_2 = Temperature (10 am - 12 pm), T_3 = Temperature (12 pm - 2 pm), T_4 = Temperature (2 pm - 4 pm), T_5 = Temperature (4 pm - 6 pm), T_{AV} = Average temperature.

Table 3: Temperature (^{o}C) Variations in Sample B Bio-digester

Day	Date	T_1 (^{0}C)	T_2 (^{0}C)	T_3 (^{0}C)	T_4 (^{0}C)	T_5 (^{0}C)	T_{AV} (^{0}C)
Day 1	3/10/2021	37.60	45.60	48.30	40.00	39.70	42.24
Day 2	3/11/2021	38.60	45.90	45.60	42.00	37.70	41.96
Day 3	3/12/2021	39.00	48.90	46.10	41.00	34.10	41.82
Day 4	3/13/2021	33.00	44.70	33.40	58.60	31.50	40.24
Day 5	3/14/2021	34.10	46.50	35.70	32.50	29.40	35.64
Day 6	3/15/2021	31.20	42.10	38.90	32.70	28.70	34.72
Day 7	3/16/2021	32.50	43.30	39.60	33.10	33.70	36.44
Day 8	3/17/2021	32.70	41.50	34.60	33.70	32.80	35.06
Day 9	3/18/2021	35.50	44.70	35.70	37.90	34.70	37.70
Day 10	3/19/2021	33.40	43.50	33.40	43.70	35.60	37.92
Day 11	3/20/2021	31.60	41.70	31.50	42.90	37.80	37.10
Day 12	3/21/2021	32.70	43.90	32.70	41.50	31.80	36.52
Day 13	3/22/2021	32.40	42.50	34.90	35.70	36.70	36.44
Day 14	3/23/2021	33.50	43.10	33.40	34.30	27.40	34.34
Day 15	3/24/2021	31.80	47.10	33.70	31.80	26.80	34.24
Day 16	3/25/2021	34.70	45.40	33.90	34.60	27.80	35.28
Day 17	3/26/2021	33.60	45.70	38.50	33.90	29.40	36.22
Day 18	3/27/2021	32.80	42.70	34.30	44.70	28.60	36.62
Day 19	3/28/2021	45.80	43.00	41.10	44.00	40.00	42.78
Day 20	3/29/2021	32.20	44.30	45.80	39.90	30.00	38.44
Day 21	3/30/2021	33.40	43.90	45.50	39.00	33.30	39.02
Day 22	3/31/2021	42.00	47.70	48.10	32.00	37.00	41.36
Day 23	4/1/2021	41.10	46.50	42.20	37.10	35.50	40.48
Day 24	4/2/2021	42.10	47.70	42.10	38.10	36.60	41.32
Day 25	4/3/2021	33.10	44.30	44.10	33.00	35.50	38.00
Day 26	4/4/2021	32.10	47.70	43.10	39.90	33.10	39.18
Day 27	4/5/2021	39.10	46.10	42.20	32.00	35.10	38.90
Day 28	4/6/2021	40.00	42.10	48.20	37.10	30.00	39.48
Day 29	4/7/2021	39.60	44.10	42.10	39.90	39.00	40.94
Day 30	4/8/2021	37.70	44.30	43.70	37.70	37.10	40.10
Day 31	4/9/2021	40.90	41.70	42.70	39.90	39.00	40.84

Where: T_1 = Temperature (8 am - 10 am), T_2= Temperature (10 am - 12 pm), T_3 = Temperature (12 pm - 2 pm), T_4 = Temperature (2 pm - 4 pm), T_5 = Temperature (4 pm - 6 pm), T_{AV} = Average temperature.

Table 4: Temperature (°C) Variations in Sample C Bio-digester

Day	Date	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (°C)	T_{AV} (°C)
Day 1	3/10/2021	37.70	45.60	48.30	40.00	39.70	42.26
Day 2	3/11/2021	37.10	48.10	45.60	42.00	37.70	42.10
Day 3	3/12/2021	35.00	48.20	46.10	41.00	34.10	40.88
Day 4	3/13/2021	36.00	45.50	33.40	58.60	31.50	41.00
Day 5	3/14/2021	38.40	48.30	35.70	32.50	29.40	36.86
Day 6	3/15/2021	40.00	46.00	38.90	32.70	28.70	37.26
Day 7	3/16/2021	38.60	47.20	39.60	33.10	33.70	38.44
Day 8	3/17/2021	37.80	47.00	34.60	33.70	32.80	37.18
Day 9	3/18/2021	40.00	48.10	35.70	37.90	34.70	39.28
Day 10	3/19/2021	36.60	45.50	33.40	43.70	35.60	38.96
Day 11	3/20/2021	38.20	47.20	31.50	42.90	37.80	39.52
Day 12	3/21/2021	39.70	47.30	32.70	41.50	31.80	38.60
Day 13	3/22/2021	36.30	46.90	34.90	35.70	36.70	38.10
Day 14	3/23/2021	38.40	47.00	33.40	34.30	27.40	36.10
Day 15	3/24/2021	38.60	48.10	33.70	31.80	26.80	35.80
Day 16	3/25/2021	38.00	48.90	33.90	34.60	27.80	36.64
Day 17	3/26/2021	39.00	47.80	38.50	33.90	29.40	37.72
Day 18	3/27/2021	39.20	48.50	34.30	44.70	28.60	39.06
Day 19	3/28/2021	41.50	48.80	41.10	44.00	40.00	43.08
Day 20	3/29/2021	36.20	44.10	46.10	39.90	30.00	39.26
Day 21	3/30/2021	38.00	44.20	47.70	38.80	32.00	40.14
Day 22	3/31/2021	32.00	45.20	45.50	32.20	31.00	37.18
Day 23	4/1/2021	33.00	44.10	44.10	33.00	29.00	36.64
Day 24	4/2/2021	39.10	47.10	47.10	32.10	30.00	39.08
Day 25	4/3/2021	31.20	45.10	45.10	34.10	32.10	37.52
Day 26	4/4/2021	32.30	46.20	46.20	36.10	30.00	38.16
Day 27	4/5/2021	39.10	48.90	48.90	39.90	41.10	43.58
Day 28	4/6/2021	34.10	46.10	46.10	45.10	42.20	42.72
Day 29	4/7/2021	33.10	44.10	44.10	47.10	44.10	42.50
Day 30	4/8/2021	39.10	46.10	46.70	44.20	39.90	43.20
Day 31	4/9/2021	40.20	45.90	42.10	43.00	30.10	40.26

Where: T_1 = Temperature (8 am - 10 am), T_2 = Temperature (10 am - 12 pm), T_3 = Temperature (12 pm - 2 pm), T_4 = Temperature (2 pm - 4 pm), T_5 = Temperature (4 pm - 6 pm), T_{AV} = Average temperature.

Critically studying the temperature fluctuation in Tables 2-4 within the 10-hour daily data collection, it was discovered that temperatures in the bio-digesters behaved in a parabolic manner, i.e., the temperatures rise and fall with peak temperatures majorly in the second and third readings, corresponding to 12 pm and 2pm respectively. At this hours of the day, temperature is expected to be highest. An exception would however be recorded when there is cold weather. Since the bio-digesters were exposed to ambient atmospheric and environmental conditions, the temperature fluctuation inside the digesters (Figure 5) can thus be said to have been influenced by the combined effects of the ambient weather conditions.

3.2 Biogas Production

The amount of biogas produced for each sample, as recorded, is presented on Tables 5–7. As shown in Figure 6, at the end of the retention period of 31 days, Sample A (cow dung, WFW, VW) recorded the highest cumulative biogas yield of 32.85 kg. This was followed by Sample B (cow dung, PFW, VW) with 29.60 kg biogas yield. Sample C (cow dung, WFW, PFW, VW) recorded the lowest biogas yield of 15.22 kg. Since Sample C bio-digester was not agitated, production of biogas can be deduced to be influenced by slurry agitation. This is in line with the findings of Rusin *et al.* (2017), which also show that biogas production is directly proportional to optimum slurry agitation.

The results (Figure 6) also show that biogas production from the co-digestion of cow dung with WFW and VW gave a better yield than from the co-digestion of cow dung with PFW and VW. In recent studies, watermelon (*Citrullus lanatus*) has been found to have a track record of higher biogas yield. Akpan *et al.* (2019) reported a higher biogas yield from the co-digestion of cow dung with watermelon than that from cow dung and pawpaw (*Carica papaya*) or cow dung and banana (*Musa acuminata*). Watermelon waste was also reported to produce the highest biogas yield in comparison with banana waste and orange waste by Hussaini *et al.* (2021). Watermelon biogas production strength was also corroborated by Tambuwal and Okoh (2018), who reported higher biogas yield from the co-digestion of cow dung with watermelon than co-digestion of cow dung with pumpkin (*Telfairia occidentalis*). From the proximate analysis conducted on *Citrullus lanatus* by Olayinka and Etejere (2018), the rind of *Citrullus lanatus* contains higher carbohydrate and protein than its pulp – for rind, 5.22 ± 0.06% carbohydrate, and 0.53 ± 0.02% protein. According to Deublein and Steinhauser (2008), the hydrolysis of carbohydrate occurs within few hours while that of proteins within few days. This connotes that watermelon would hydrolyse quickly leading to faster microbial reaction which would translate to better biogas production. Therefore, it can be deduced that the higher proportion of watermelon in Sample A substrate influenced better biogas production in the sample.

From the hypothesis, Sample C was expected to produce the highest yield of biogas since it is the mixture of all the wastes, and moreover, it has 30 kg of FVW compared to 25 kg in Samples A and B. However, the results (Figures 6 and 8) show that reverse is the case; it performed the least. Critically studying the results in relation with the composites of the sample, it can then be inferred that probably the lesser amount of substrates for WFW and PFW, which are 10 kg each, caused the poor performance.

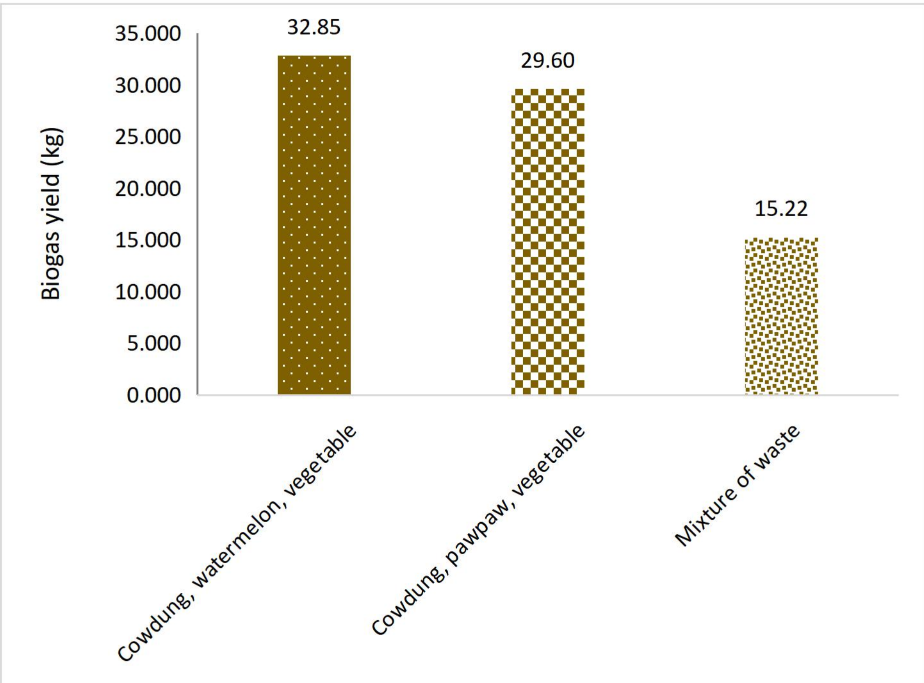

Figure 6: Cumulative biogas yield (kg) of various mixtures of slurry

The performance of the digesters in term of amount of biogas is presented in Figure 7. As clearly seen from Figure 7, gas production was lower at the end of the process for Sample C bio-digester, and slightly lower at the end of the process for Sample B bio-digester. Sample A bio-digester has the highest performance as the biogas produced increased with increase in retention time. It is also clear that Sample C bio-digester has the lowest overall performance.

The daily average amount of biogas produced for this study ranges between 0.11 and 1.11 kg. In this study, the relationship between daily biogas production and temperature cannot actually be inferred as there is no clear distinction in variation of biogas produced with temperature (Figure 8). Owing to the studies of Sithara and Kiran (2018) and Simeon *et al.* (2017), who reported direct variation between biogas production and temperature, it was expected that highest biogas would be generated at highest temperatures, but reverse is the case for the 3 samples. However, it is clear that the condition of experiments in this study is mesophilic – temperatures range of 34-44 °C (Figure 5). As seen from Figure 8, there seems to be a definite convergence of daily temperatures, which is high, for the 3 samples on day 19. The band of temperatures after day 19 for the samples are also higher than before. From day 19, biogas production increases as the band of temperature increases for Sample A but reduces as the temperature band increases for Sample B.

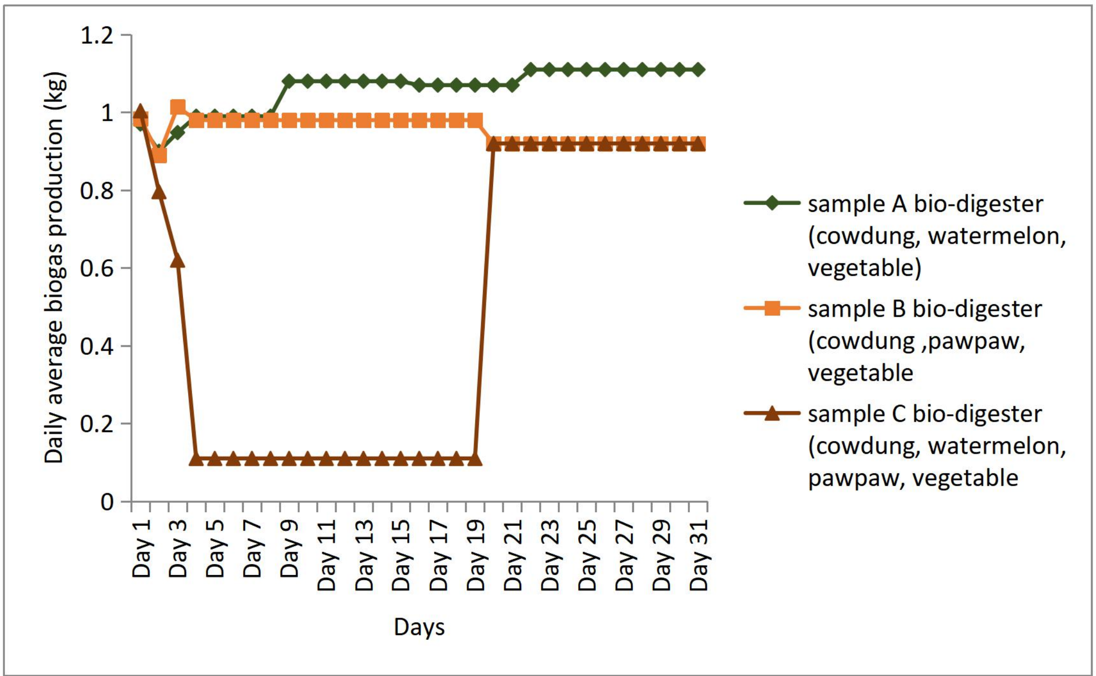

Figure 7: Daily average amount of biogas produced (kg)

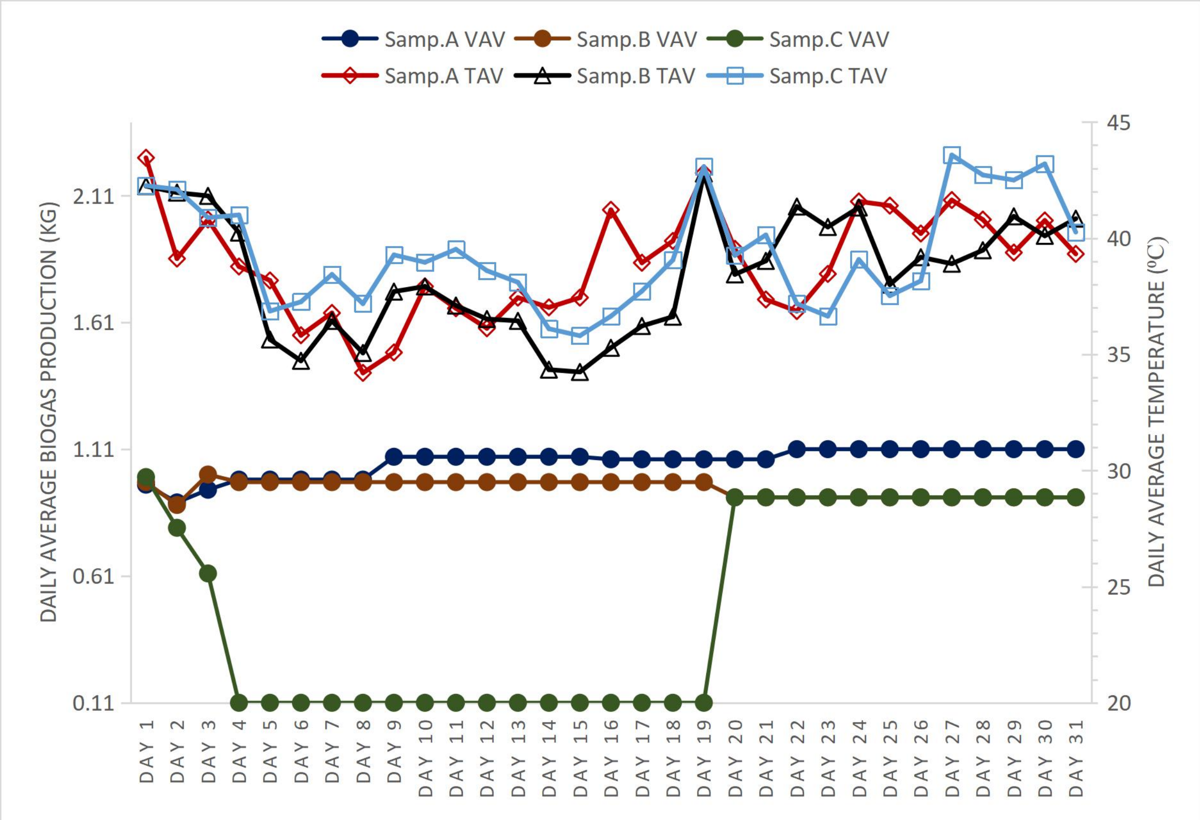

Figure 8: Juxtaposition of amount of daily biogas produced (V_{AV} in kg) and temperature (T_{AV} in ºC)

Table 5: Amount of biogas (kg) produced in Sample A bio-digester for 31 Days

Day	Date	V_1(kg)	V_2(kg)	V_3(kg)	V_4(kg)	V_5(kg)	V_{AV}(kg)
Day 1	3/11/2021	0.98	0.97	0.98	0.99	0.93	0.97
Day 2	3/12/2021	1.05	1.03	1.05	1.04	0.33	0.90
Day 3	3/13/2021	0.99	0.89	0.99	0.88	0.99	0.95
Day 4	3/14/2021	0.99	0.99	0.99	0.99	0.99	0.99
Day 5	3/15/2021	0.99	0.99	0.99	0.99	0.99	0.99
Day 6	3/16/2021	0.99	0.99	0.99	0.99	0.99	0.99
Day 7	3/17/2021	0.99	0.99	0.99	0.99	0.99	0.99
Day 8	3/18/2021	0.99	0.99	0.99	0.99	0.99	0.99
Day 9	3/19/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 10	3/20/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 11	3/21/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 12	3/22/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 13	3/23/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 14	3/24/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 15	3/25/2021	1.08	1.08	1.08	1.08	1.08	1.08
Day 16	3/26/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 17	3/27/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 18	3/28/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 19	3/29/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 20	3/30/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 21	3/31/2021	1.07	1.07	1.07	1.07	1.07	1.07
Day 22	4/1/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 23	4/2/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 24	4/3/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 25	4/4/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 26	4/5/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 27	4/6/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 28	4/7/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 29	4/8/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 30	4/9/2021	1.11	1.11	1.11	1.11	1.11	1.11
Day 31	4/10/2021	1.11	1.11	1.11	1.11	1.11	1.11
							Σ=32.85

Where: V_1 = Amount of biogas (8 am - 10 am), V_2 = Amount of biogas (10 am - 12 pm), V_3 = Amount of biogas (12 pm - 2 pm), V_4 = Amount of biogas (2 pm - 4 pm), V_5 = Amount of biogas (4 pm - 6 pm), V_{AV} = Average amount of biogas.

Table 6: Amount of biogas (kg) produced in Sample B bio-digester for 31 Days

Day	Date	V_1(kg)	V_2(kg)	V_3(kg)	V_4(kg)	V_5(kg)	V_{AV}(kg)
Day 1	3/11/2021	0.98	0.99	0.99	0.99	0.97	0.98
Day 2	3/12/2021	0.97	0.92	0.92	0.82	0.82	0.89
Day 3	3/13/2021	0.98	0.99	1.00	1.11	0.99	1.01
Day 4	3/14/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 5	3/15/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 6	3/16/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 7	3/17/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 8	3/18/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 9	3/19/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 10	3/20/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 11	3/21/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 12	3/22/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 13	3/23/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 14	3/24/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 15	3/25/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 16	3/26/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 17	3/27/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 18	3/28/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 19	3/29/2021	0.98	0.98	0.98	0.98	0.98	0.98
Day 20	3/30/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 21	3/31/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 22	4/1/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 23	4/2/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 24	4/3/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 25	4/4/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 26	4/5/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 27	4/6/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 28	4/7/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 29	4/8/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 30	4/9/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 31	4/10/2021	0.92	0.92	0.92	0.92	0.92	0.92
							Σ=29.60

Where: V_1 = Amount of biogas (8 am - 10 am), V_2 = Amount of biogas (10 am - 12 pm), V_3 = Amount of biogas (12 pm - 2 pm), V_4 = Amount of biogas (2pm - 4pm), V_5 = Amount of biogas (4 pm - 6 pm), V_{AV} = Average amount of biogas.

Table 7: Amount of biogas (kg) produced in Sample C bio-digester for 31 Days

Day	Date	V_1(kg)	V_2(kg)	V_3(kg)	V_4(kg)	V_5(kg)	V_{AV}(kg)
Day 1	3/11/2021	0.98	1.00	0.98	0.99	1.07	1.00
Day 2	3/12/2021	1.02	0.99	0.90	0.10	0.97	0.80
Day 3	3/13/2021	0.99	0.79	0.11	1.10	0.11	0.62
Day 4	3/14/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 5	3/15/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 6	3/16/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 7	3/17/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 8	3/18/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 9	3/19/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 10	3/20/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 11	3/21/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 12	3/22/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 13	3/23/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 14	3/24/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 15	3/25/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 16	3/26/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 17	3/27/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 18	3/28/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 19	3/29/2021	0.11	0.11	0.11	0.11	0.11	0.11
Day 20	3/30/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 21	3/31/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 22	4/1/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 23	4/2/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 24	4/3/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 25	4/4/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 26	4/5/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 27	4/6/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 28	4/7/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 29	4/8/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 30	4/9/2021	0.92	0.92	0.92	0.92	0.92	0.92
Day 31	4/10/2021	0.92	0.92	0.92	0.92	0.92	0.92
							Σ=15.22

Where: V_1 = Amount of biogas (8 am - 10 am), V_2 = Amount of biogas (10 am - 12 pm), V_3 = Amount of biogas (12 pm - 2 pm), V_4 = Amount of biogas (2 pm - 4 pm), V_5 = Amount of biogas (4 pm - 6 pm), V_{AV} = Average amount of biogas.

4. CONCLUSION

The results obtained from the study show that production of biogas from co-digestion of fruits and vegetable wastes mixed with cow dung is realistic under optimum mesophilic conditions. Therefore, it is concluded from the study that:

1. Agitation of slurry enhances biogas production – higher biogas yield was recorded in agitated bio-reactors than in reactors left unstirred.
2. The rate of biogas production was expected to be influenced by temperature, however, there was no distinct variation between biogas yield and temperature for this study.
3. Higher proportion of watermelon enhanced biogas yield – Biogas is better produced from the co-digestion of cow dung with WFW and VW as at all conditions of the research, the co-digestion of cow dung with WFW and VW produced the highest biogas yield than from the co-digestion of cow dung with PFW and VW.

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