Performance of selected organic wastes for available technologies for biogas, Kisumu City, Kenya

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Abstract: Inadequate solid wastes disposal exists in Kenya, for unsightliness and health problems. This study determined that available digesters performance differed for size and bio-material. Larger fixed dome, flexible tubing and ordinary drum (0.1 m^3, 2.4 m^3) sizes were thus tested within Kisumu County. Despite fixed dome having known design parameters, these technologies are not embraced for use. Market wastes were chopped to size while food and faecal wastes needed own or little water content, though all were mixed to porridge consistency. The 0.1 m^3 drum produced high CO_2 gas in small quantities as match box lighting test was positive only for market wastes (0.1 m^3) tube. The larger dome and 2.4 m^3 tube respectively produced gas for market (65%) and faecal (56%) wastes. A natural co-generation was observed in market waste and need for determining key digester size design parameters. The manual preparation best informs design automation and bio-digester management.

Keywords: design parameters; market wastes; technologies; performance; biogas; Kenya.

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1 Introduction

Biogas production was introduced in developing countries as a low-cost alternative source of energy for rural households and to partially contribute in forest conservation (Garfí et al., 2012). However, there has been poor adoption of this technology in Kenya, mostly associated with high cost of best performing digesters, lack of knowledge in design, installation, operation, maintenance and frequent microbial failures (Bui et al., 1991). In Kenya, foreign developed biogas systems have hampered local innovativeness and scientific advancement in the field of renewable energy with local resources (Webber et al., 2008). Kisumu County/City is not an exception as there is no particular widespread adopted technology in size and form.

The common wastes available from communities especially within the city, townships and market centre's are mostly mixed in nature and may need identification, characterisation, ways of preparation and specific digester designs (Aleluia and Ferrão, 2016). The low adoption of the wastes energy conversion technologies adds to their none-use as a form of renewable energy. Hence, waste collection has mostly been geared for disposal with inadequate and inefficient management system within Kisumu County (the Kisumu City, townships, market centres and even the villages). The city, townships and markets like Kibuye in Kisumu are worst affected. Wastes disposal within the city hence lacks appropriate scientific, technical and socio-economic approaches and thus, observable problems as in Aguko et al. (2020).

The processes/technologies practiced around the county/city are akin to firefighting like: *land filling*, where waste is dumped in a pits, open areas and low lands; *incineration*, wastes are subjected to uncontrolled combustion; *composting*, the aerobic fermentation process is mainly implemented with a view of fertiliser production though limited. These processes may result in bad odour that breeds growth of mosquito's, flies, insects and bacteria. The possibility of air pollution by poisonous gases such as HF, SOx, NOx and incombustible residue may not be avoided. The leachates may also pollute the surface and ground water air (Sakar et al., 2009). Other known improved techniques for example *pyrolysis*, are absent.

Last is the *anaerobic digestion*: which is an emerging technology practiced by very few but has potential. Here, the organic matter is fermented in a digester, in absence of air to produce fuel gas (biogas) and a digestate rich in nitrogen, phosphorous and potassium (Chen and Neibling, 2014). Biogas could be obtained by fermentation of the abundantly available organic matter such as agricultural (manure), municipal (food, sewage sludge), industrial (rice husks) and market wastes (vegetables, fruits and cereals) under anaerobic conditions or digestion (AD), through appropriate technologies. These are largely available in the city/county and are the subject of disposal problems and especially faecal matter and market wastes.

In principle, the origin of all these is from plant photosynthesis created by the sun's energy as a sustainable technique that recycles the nutrients (such as nitrogen and phosphorus). The performance of AD process is dependent on characteristics of feedstock, technology, as well as microorganisms involved in different degradation steps (Abbasi et al., 2012). The relative percentages of methane and carbon dioxide expected is 60% to 40% (Ismail and Adewole, 2014) for biogas but depends on the ratio of carbohydrates, proteins and fats in feedstock and dilution factor in the digester (CO_2 can be absorbed by water). It is also a determinant for burning capability of biogas. The uses of biogas for the city/county situation today can mostly be adopted for heating in schools and some institutions. Home use may still be limited by feed availability, technology choice and initial funds for installation.

The composition of biogas expected is dependent on type of feedstock but range within limits as in Table 1. Chemical properties of methane are that; it has a specific gravity of 0.554, only slightly soluble in water, burns readily in air, the flame is pale, slightly luminous and very hot. The boiling and melting points are respectively –162°C (–259.6°F) and –182.5°C (–296.5°F). It is a stable gas, but mixtures of methane and air, with methane content between 5% and 14% by volume, are explosive (Korres et al., 2013). The other components (CO_2, H_2S) can also be easily tested.

Table 1 Components of gas produced after fermentation

Component	*Symbol*	*% content*
Methane	CH_4	50–75
Carbon dioxide	CO_2	25–40
Nitrogen	N_2	< 5
Hydrogen	H_2	< 1
Oxygen	O_2	< 1
Water vapour	H_2O	0.3
Hydrogen sulphide	H_2S	50–5,000 ppm

Source: Adapted from Karki (2009)

When biogas and digestate are formed, the degradation process is in four phases (Novotny et al., 2010; Pawlowska and Pawlowski, 2014) that comprises hydrolysis, acidogenesis and methanogenesis. The small molecular weight organic matters are decomposed into volatile fatty acids and by-products (carbon dioxide, ammonia and hydrogen sulphide) which are further digested by acidogenesis process. The configurations can be either continuous or a batch process with advantages and disadvantages. The main product biogas is a combustible, sustainable renewable energy resource which can be harnessed with a digestate being utilised as fertiliser and soil improver (Abbasi et al., 2012; Turco et al., 2016). It may also have contaminants (impurities) that include sulphur or siloxanes, mainly from soaps and detergents. If properly handled within the city/county, it has potential for hygienic and sanitary conditions as bad door may be controlled.

In a continuous digestion processes, organic matter is constantly mixed and added in stages to the digester (first in-first out). The end-products are periodically removed, resulting in constant production of biogas. *Co-digestion plants or* simultaneous digestion of two or more substrates may also enhance the performance of the AD process, owing to a positive synergy in the digestion medium by providing a balanced nutrient supply and sometimes by suitably increasing the moisture content required in the digester (Horan et al., 2018). The digesters thrive in two main conventional operational temperature levels for anaerobic digesters (Yadvika et al., 2004; Tufaner and Avsar, 2016) which are: mesophilic which is optimal around 30–38°C or at ambient temperatures between 20–45°C. The thermophilic temperatures is optimal around 49–57°C to elevated temperatures of up to 70°C. Advanced waste treatment technologies can produce biogas with 55%–75% methane, which can be increased to 80%–90% methane by using purification techniques (Caruana and Olsen, 2012). The county conditions and practice will favour mesophilic temperatures, but available greenhouse technology may be used to improve or maintain the conditions.

It was therefore necessary to determine the performance of biogas technologies available within Kisumu with selected and available organic materials. The designs or technologies available in Kisumu County/City are:

1 the simple ordinary drums
2 fixed dome
3 the flexible structure apart from
4 floating drum bio-digester model.

This should enhance selection, adoption and redesign to suite users.

Bio-gas plant(s) are therefore good candidates that could finally help in city, township, market and village waste management and provide; benefits as an alternative source of energy to fulfil the immediate cooking energy demand where there is no option other than firewood (Bryan et al., 2010). Such can reduce; dependence on import of LPG, burning fire wood for cooking/heating to relieve mostly women of various health problems (cough, severe headaches, respiratory and eye-related effects) for a healthy life. Other advantages are relief from washing dirty utensils blackened by firewood and many direct/indirect employment opportunities to people (Bryan et al., 2010).

2 Methodology

2.1 Available digesters

The fixed dome bio-digester (FDBD) and flexible structure bio-digester (FSBD) models are easily designed to the need of biogas production and availability of particular organic materials. The process can be repeatable for simple ordinary drum bio-digesters (SODBD) but values for some bio-materials are not documented as they also need detailed laboratory tests that could also be affected by locality. Thus, the approach of testing the available technologies for their performance with different organic materials. Four FDBD plants were then already implemented in Kisumu City in the name of bio-towers (Figure 1) but only one at Obunga peri-urban area was/is operational to date. The FSBD were also respectively implemented in Nyamasaria and Dunga to use cow dung from the nearby community and hyacinth or any other bio-material. However, three FSBD of 1 m^3 each were purchased for batch biogas production and installed at Kibuye for KIWAN community-based organisation (CBO). Two 2.4 m^3 FSBD type were sited at Nyamasaria. The SODBD were located at Jaramogi Oginga Odinga University at a designated area for ease of monitoring. Subsequently, the SODBD were also repeated at KIWAN CBO site in Kibuye.

A CBO called KIWAN was however struggling at Kibuye market with composting technology, with a desire to produce biogas for their local use within the market. This motivated the study as KIWAN was also driven by operational failure of the large fixed domes that were also difficult to repair as was constructed for the market. The biogas performance tests were in this process carried out at Jaramogi Oginga Odinga University of Science and Technology (JOOUST), Nyamasaria, Obunga and at Kibuye.

Figure 1 Bio-tower (see online version for colours)

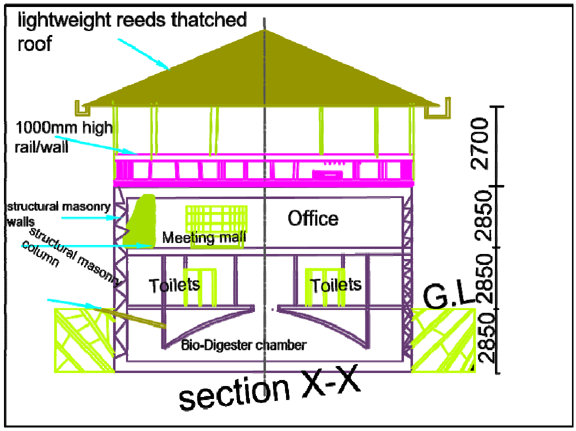


Table 2 Sizing of household biogas digester

$$Amount\ of\ gas\ needed\ per\ day = \frac{Gas\ demand}{Gas\ caloric\ value}\frac{\text{m}^3}{\text{day}} \quad (1)$$

$$Volume\ of\ gasholder\ needed = Amount\ of\ gas\ needed \times 50\%\ \text{(Nyaanga, 2015)} \quad (2)$$

$$Amount\ of\ gas\ needed\ per\ day\left(\frac{\text{m}^3}{\text{day}}\right) = Amount\ of\ organic\ material\ per\ day \times rate\ of\ gas\ production\ \frac{\text{m}^3}{\text{kg}}\ \text{(Nyaanga, 2015)} \quad (3)$$

$$Amount\ of\ organic\ material\ per\ day = \frac{Amount\ of\ gas\ needed\ per\ day}{Rate\ of\ gas\ production\ per\ kg\ of\ material} \quad (4)$$

$$Amount\ of\ water\ needed = Constant(Derived\ from\ ratio\ of\ material\ to\ water\ required) \times Volume\ of\ slurry \quad (5)$$

$$Example: Mix\ ratio\ of\ 1:1 = 2 \times Mass\ of\ slurry\left(\frac{\text{kg}}{\text{day}}\right) \quad (6)$$

$$Daily\ slurry\ input, V_d = \frac{Retention\ time \times Mass\ of\ slurry}{Density\ of\ slurry}\ \text{m}^3 \quad (7)$$

$$Volume\ flow\ rate\ of\ slurry = \frac{Mass\ of\ slurry}{Density \times 24\ hrs \times Seconds\ in\ an\ hour} \quad (8)$$

$$But; Q = AV = \frac{\pi D^2}{4}V\ \text{where}\ V = Mean\ velocity\ through\ pipe\ (d)\ diameter \quad (9)$$

$$D = \sqrt{\frac{4Q}{\pi v}} = \frac{4 Slurry\ mass}{\pi Flow\ velocity} \quad (10)$$

Source: Adopted from Nyaanga (2019)

Sizing of a bio-digester would then be the start for the process and necessarily needed knowledge of prior determined parameters which include: gas demand, gas caloric value and rate of production per kilogram of the bio-material, water to bio-material ratio, density of the slurry and retention time (Table 2). Such values for some bio-materials are not documented as they require detailed laboratory tests that could also be affected by locality. The rest of design parameters in Table 2 are easily calculated. *Market wastes* (fruits, vegetables, tubers, maize and cobs) is one kind of bio-material, that was thought of a as potential for cogeneration due to the nature of the mixture. This could be a unique situation of design in terms of mixture parameters determination and locality for sizing the digester (Table 2). Cow dung though already has known determined parameters, save for those at site for example energy demand. Performance tests were thus done for the technologies in their situation status.

2.2 Simple ordinary drum digester

A 100 litre plastic cylindrical container (SODBD) was assembled from locally available resources (local hardware) which included: digester tank, gas collector (such as balloons), slurry outlet pipe, gas outlet pipe, slurry inlet pipe, gas valves, gas gauge, adhesives and were used as bio-digester tank.

This means the volume was pre-decided without considerations of design preliminary requirements (volume, material, density, caloric value, retention time and management – Table 2). But, a 0.30 m ruler was used in marking 50 mm from the top and bottom of the tank on opposite sides (inlet and outlet) and marked for 50 mm slurry inlet and 75 mm outlet diameter holes. A 40 mm (inlet and outlet) and a 20 mm (gas outlet) red hot iron rods were used in making the holes. A 25 mm diameter gas outlet hole was marked at the top centre of the tank for connecting a gas gauge. *Glue was placed on* gas outlet (Figure 2), slurry inlet and outlet pipes and left to dry for about two minutes. Thereafter, each pipe was attached to their positions and waterproof adhesive applied at the joints and left to dry for five minutes. At the end of each pipe, the specific valves were threaded and fixed appropriately. The pressure gauge was fixed just before the gas outlet valve. The layout of the SODBD is as shown in Figure 9.

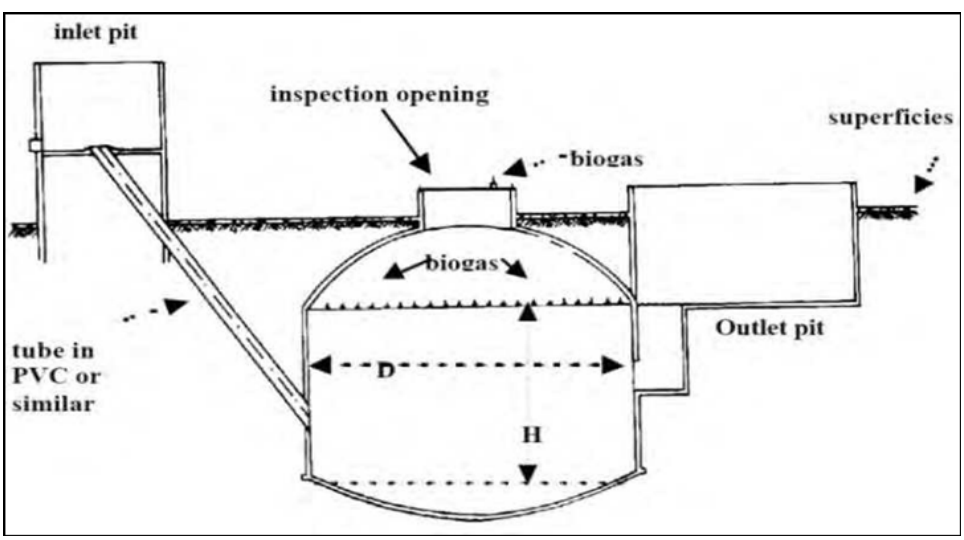
Figure 2 Gas outlet (see online version for colours)

2.3 Flexible structure and fixed dome bi -digesters

The two Nyamasaria FSBD are as shown in Figure 3 and is buttressed on the sides to help contain pressure each with a slurry inlet and outlet. The FDBD as were already installed at Obunga, Kibuye market and Manyatta (Figure 4), comprises a cylindrical body, two spherical domes, inlet pit, outlet pit and an inspection opening (Florentino, 2003). The digester is a permanent structure made of cement and bricks. Thus, the two digesters (FDBD, FSBD) may have been predesigned, not necessarily for a particular bio-material and only testing was required unlike the SODBD/FSBD. The Obunga bio-tower digester (Figure 4) is still operational and others were not for various reasons.

Figure 3 FSBD (see online version for colours)

Figure 4 FDBD



2.4 Materials collection and preparation (FDBD, FSBD and SODBD)

Waste material and preparation concerned mostly the FSBD and SODBD as dome equipment waste were directly from the bio-tower toilets. The FSBD/SODBD activities mainly comprised waste identification/survey, assemblage of equipment's, chopping/shredding, mixing and last was placement of the slurry through the inlet pipes or chambers. Waste survey/identification is an activity that should preceded purchase and design/installation of the biogas plant (Aguko et al., 2018). It involved both observation and actual characterisation by weight and frequency of the output.

The key waste types that were observed to be significant in Kisumu City were market wastes, faecal matter and food wastes materials. A record of their periodic availability is essential with consideration of their location, quantity, types and sources. In addition, the plant waste preparation site (PWPS) with reference to source of the materials (distances) is also essential. Foremost, the food wastes were brought to the PWPS (Kibuye market) as and when they were needed. They were collected by a 100 litre plastic tank placed nearby a school at a strategic point for students and teaching staff for the disposal of the food leftovers. Another 100 litre plastic tank was at nearby hotels (temporary eating places or houses – TEH) within Kibuye market. These were collected daily to when they were not required.

Market waste materials information (Aguko et al., 2018) were gathered from Kibuye market by eight casual workers of the Kibuye market waste management (CBO) and assisted by two research assistants. This was undertaken for a period of three months. The market waste brought to PWPS were separated based on types; fruits, spices, vegetables and cereals like maize cobs and leftovers. The non-biodegradable types such as stones, strings, tissue papers, and dippers were removed from the fresh bio-solids. The equipment's/tools used in handling market wastes included wheelbarrows for transportation of sack loads or buckets from source to PWPS. The buckets were also used for handling of water, preparation of waste mixtures and for feeding the digesters. Rakes and spades were for gathering, spreading on tarpaulin and scooping at source and the PWPS. This saved time and eased work during sorting, cutting/chopping of wastes for ease of digester feeding and bacterial digestion.

Chopping/shredding was done by ordinary sharpened machetes after weighing by a non-digital weighing scale to increase surface area for bacterial action. The size reduced wastes were once more weighed for any loss due to previous processes. The market wastes (tomatoes, oranges, avocado, cabbage, etc.) were weighed with regard to type, for determining the quantities (kg) most available, the recovered weight before and after chopping, loss after size reduction of juice/water spillage from fruits and spices, mixing ratio weights achieved with water and final mix weight of all market wastes put together. All the sorted wastes were kept in plastic tanks and tightened to avoid odour and flies attraction. Initial processed stock that was feed into the 1 m^3 FSBD with market wastes produced no gas when water was added. This informed the next stock feeding preparation that only used as much moisture from market wastes for the 1 m^3 and 2.4 m^3.

Food waste and faecal slurry were neither separated nor sorted due to their nature and content. Food wastes incorporated items like porridge, cooked rice, beans and were from St. Teresa's girls' secondary school, about 500 m from Kibuye market. Human waste was from nearby Kibuye city council toilets, done by blocking a sewer line manhole in the morning and wastes collected in the evening by buckets. Food waste and faecal matter slurry were thus also mixed to porridge consistency.

Mixing of food and market wastes (fruits, spices, vegetables, maize, etc.) were handled in tanks of 100 litres (mixing chambers) and water added as appropriate. The prepared and mixed feedstock/waste was stored in lid tightened 100 litre plastic tanks in readiness for the initial digester input feeding. Faecal slurry was mixed by their own water content from sewer lines and approximately 50% by weight water added.

The 1 m^3 FSBD portable biogas plant/digesters (at PWPS in Kibuye) were fed by buckets through the inlets raised to about 900 above own ground levels. The same was done to the 2.4 m^3 FSBD, with market wastes at Nyamasaria, transported by a pickup in 100 litre tank loads that were prepared at the PWPS (about 5 km away). Feeding required push force to displace the already fed materials to occupy the digester space to capacity.

Piping tubes were connected to all the digester types (SODBD, FSBD and FDBD) for gas delivery to the burning point (biogas stove). The stove (Figure 5) was specifically made for burning biogas (methane); the burner was a modified normal LPG gas burner whose gas nozzle was widened to 3 mm due low pressures in the digesters. In the case of the 1 m^3 FSBD, lit match sticks from a match box were pointed directly to the 25 mm gas outlet tubing for burning test.

Figure 5 Valve modified stove for biogas use (see online version for colours)

An electronic gas-board analyser machine which draws the gas from digester was used to determine gas constituents in all the digesters to ascertain composition by percentages, at approximately 40-day digestion period. A de-sulphuriser which had iron pellets was used to remove/absorb sulphur gases during biogas testing in the case of FDBD and FSBD at Nyamasaria. This was not done to the smaller 1 m^3 FSBD at Kibuye in the first or initial feeding that yielded no gas. Their gas pressure during formation was determined at collection point by a manometer.

2.5 Monitoring (FSBD)

Monitoring was done for temperature, pH, pressure, slurry depth at outlet and the quantities especially for FSBD. The measurements were taken for a period, over two-hour interval, between 8 am to 4 pm (weekdays) and on Saturdays between 8 am to 2 pm. Sundays were prayer days. The FDBD and SODBD were however not monitored due to the inherent design difficulties. These specifically were due to placement/absence of the parameter monitoring equipment. Thus parameter monitoring equipment's should always be considered as part of the digester design requirements.

Foremost, it was not easy to measure the amount of gas produced within the flexible tube. Pressure was however measured by inserting a gauge at gas outlet pipe and opening gas valves for the gas to push the pressure gauge. Temperature (using a digital thermometer) and pH were both measured at slurry inlet and outlet. That is, the market waste solution was picked in small sized crucible mortars, the digital pH meter was then removed from its neutral storage solution, base cleaned, dipped in the crucible mortar samples for the respective measurements of pH. In case of the gas, a rubber was pushed to cover the stem of pH meter and inserted into gas pipe for air tightness. The valves were then opened for gas to flow to pH meter and values recorded.

The slurry depth (in about 45° exit) in waste pipe was determined daily as it exited the pipe to discharge at a concrete collection point. This was by using 100 cm flexible wooden ruler hinged at 10 cm along its length for easy of usage. The unfilled length of exit pipe if any, was calculated from the total length or volumes by taking note of the filled length. This was particularly to take care of over flows. The volume (depth, width and length) occupied by slurry discharged to the rectangular concrete collection point was calculated after measuring the inner dimensions by a ruler and final volume figures were rounded upwards, to take care of irregular surface of concrete collection point.

2.6 Slurry addition and gas collection (FSBD, FDBD and SODBD)

2.6.1 FSBD and FDBD

The FSBD (1 m^3) at Kibuye were fed with initial 600 litres of market wastes slurry while those at Nyamasaria (Figure 3), with an initial 1,500 litres. Respectively, this left a space of 400 (33%) and 900 litres (37.5%) for gas but every week 100 and 300 litres were added. The Obunga bio-tower (FDBD) was continuously fed from the toilets that were being used by the peri-urban community within the vicinity of the facility, with an output as in Table 3.

Table 3 Obunga gas production values

Month	*Av. no long calls*	*Av. mass daily faecal matter (kg)*	*Monthly mass of faecal matter (kg)*	*Av. biogas produced (m^3)*	*Av. biogas produced (m^3/kg)*
1	1,302	0.12	156	3.1248	0.02
2	1,170	0.12	140	2.808	0.02
3	1,457	0.12	175	3.4968	0.02

The Obunga bio-tower faecal matter input was estimated from cash income as in Table 3. In the first month of the three months (31, 30 and 31 days for the months) examined, the bio-tower generated an income of Kshs.18,600, with an average number of 42 long calls per day, according to the bio-tower caretaker's. The second and the third month were respectively; Kshs.17,450 and Kshs.25,420 at 39 and 47 long calls per day. It was then assumed that every person produced 123.6 grams of faecal per long call or 0.12 kg. The amount of gas produced therefore averaged to 0.02 m^3.

2.6.2 SODBD

75 litres of slurry was poured through the inlet valve and closed leaving 25% space for the gas. The digestion process was estimated to take between 20–30 days for the gas to be realised. Close monitoring was then undertaken during the period and especially for checking leaks. The first and second volume of gas was collected by a balloon (Figure 6) every after 14 days. Burning test of the gas was then carried out by opening the gas valve, lighting a match stick and pointing to the 25 mm gas outlet tube.

Figure 6 Preparation of the slurry (see online version for colours)

3 Results

3.1 Gas testing

The *SODBD* gas testing was only by pointing a lit match stick (match box stick test – MBST) directly to the 25 mm gas outlet tubing. The gas burned with a blue non-luminous flame which could be seen by human eye and also felt by briefly placing a palm or finger at the gas outlet tubing. This necessitated use of balloons to collect the gas and volume determined in the laboratory (Table 4 and Figure 7). The 1 m^3 FSBD were foremost also subjected to MBST. Market waste material (FSBD) produced the luminous flame, while the 1 m^3 faecal matter and food wastes did not respond.

The SODD laboratory tests were done twice with the first test producing zero results (Tables 3 and 4) based on a ratio of 1:1 waste and water. Faecal matter was 25:25:0, food waste was 25:25:0 and while the three put together; water, faecal matter and food waste were in the ratio 25:12.5:12.5. The second attempt yielded gas from ratios of 40:35, 40:35 and 40:17.5:17.5. It is observed from this that slightly less water than 1:1 was required, that is about 88% by weight and this prompted the change in ratio of the blends (Table 5).

Table 4 Blending 1, for SODBD

Blends setting Mix ratios	*Methane yield*	*CO_2 yield*
Faecal matter (25:25:00)		
Inside G/hse	0.00	0.00
Outside G/hse	0.00	0.00
Food waste (25:25:00)		
Inside G/hse	0.00	0.00
Outside G/hse	0.00	0.0022
Food waste + faecal matter (25:12.5:12.5)		
Inside G/hse	0.00	0.00
Outside G/hse	0.00	0.00

Figure 7 Gas collection (see online version for colours)

Table 5 Blending 2, for SODBD

Blends setting Mix ratios	*Methane yield*	*CO_2 yield*
Faecal matter (40:35:00)		
Inside G/hse	0.0054	0.0036
Outside G/hse	0.0042	0.0028
Food waste (40:35:00)		
Inside G/hse	0.0039	0.0026
Outside G/hse	0.0033	0.0022
Food waste + faecal matter (40:17.5:17.5)		
Inside G/hse	0.0075	0.0050
Outside G/hse	0.006	0.0040

Inside the greenhouse, higher and constant temperature, close to optimum was maintained compared to outside (Table 5). The mass ratio of 40:35 kilograms of faecal matter showed an increase of 0.00012 m^3 from 0.0054 m^3 to 0.0042 m^3 of methane produced for a retention period of 28 days. Compared to known approaches in a controlled and uncontrolled environment, 1 kg of faecal matter at 25°C–35°C, produces 0.478 m^3 and 0.430 m^3 of biogas in a retention period of 60 days. The difference could arise due to the retention period.

3.2 FSBD

The FSBD and SODBD need elaborate waste material preparation. Weight loss was determined in between collection and after chopping and shredding (Table 6). In the case of FSBD at Nyamasaria, a further monitoring of digestion process was done that involved measuring pH, pressure, etc. (Table 7). All the digesters were however subjected to the electronic gas-board analyser machine (Table 8).

Table 6 Market wastes weight loss before and after shredding

Items	*Before chopping*	*After chopping*	*Weight loss*	*Avg. weight loss*
Fruits	196	193	3	3.17
	225	222.5	2.5	
	345	341	4	
Vegetables	100	99	1	1.67
	50	48	2	
	55	53	2	
Spices	141	138.5	3.5	1.83
	110	109.5	0.5	
	98	96.3	1.5	
Maize cobs	340	338	2	2.67
	200	197	3	
	105	102	3	

Note: Percent loss are 1.22, 2.44 and 1.24, respectively.

Figure 8 and Tables 4 and 5 show that the 1 m^3 FSBD did not yield the gases expected to within standards. CO_2 was high in percentage and this contributed to no flame in the MBST. Market waste alone, produced a flame but through the 25 mm hose tube. This could be seen by naked eye and felt on the fingers or palms, but could not burn in the 3 mm valve stove (Figure 7) that was modified for the purpose.

As in Table 8, the FDBD digester produced the best percentage of methane paralleled by the 2.4 m^3 FSBD at Nyamasaria. The materials were faecal matter and market wastes. Though CH_4 produced by the FSBD was higher, market waste output was significant with respect to size of the FSBD which was smaller. The result could be attributed to inherent market material mixtures which can be considered to have *co-generation attributes*. This suggest that when different substrates are used the digesting bacteria then have a variety of nutrients for nourishment hence more gas production compared to when one substrate is used.

Table 7 Monitoring flexible bio-digester structure

Day	*Inlet/input litres*	*Time*	*Temp., °C*			*pH*			*DP Kpa*	*DDE (m)*	*D (Lt)*
			Gas	*Inlet*	*Exit*	*Gas*	*Inlet*	*Exit*			
		12 pm–2 pm	32.5	31	30.6	5.9	5	7.4	0	0.39	0
		2 pm–4 pm	32.3	31	30.6	5.7	5.6	7.5	0	0.37	0
T	300	8 am–10 am	35.7	31	30.6	5.8	5.6	7.7	1	0.36	0
		10 am–12 pm	37	31	30.6	5.19	5.7	7.6	1	0.36	0
		12 pm–2 pm		31	30.6	5.8	5.6	7.6	1	0.36	0
		2 pm–4 pm		30	30.6	5.6	5.6	7.6	1	0.36	0
W	300	8 am–10 am		31	30.6	5.9	5.8	7.9	1	0.3	0
		10 am–12 pm		31	30.6	6	5.8	7.9	1	0.3	0
		12 pm–2 pm		31	30.6	5.9	5.7	7.8	1	0.3	0
		2 pm–4 pm		31	30.6	5.6	5.8	7.6	1.5	0.3	0
T		8 am–10 am	31	30.6	5.9	5.8	7.6	1.5	0.27	0	
		10 am–12 pm		31	30.6	5.8	5.6	7.6	2	0.27	0
		12 pm–2 pm		31	30.6	5.8	5.6	7.6	2	0.27	0
		2 pm–4 pm		30	30.6	5.7	5.6	7.6	2	0.27	0
F		8 am–10 am		31	30.6	6.2	5.5	7.5	2.5	0.21	0
		10 am–12 pm		31	30.6	5.9	5.7	7.5	3	0.21	0
		12 pm–2 pm		31	30.6	5.8	5.7	7.7	3	0.21	0
		2 pm–4 pm		30	30.6	5.9	5.6	7.6	3	0.21	0
S		8 am–10 am		31	30.6	6.1	5.6	7.6	4	0	21
		10 am–12 pm		31	30.6	5.9	5.6	7.4	4	0.4	0
		12 pm–2 pm		31	30.6	5.9	5.5	7.6	4	0.4	0
M		8 am–10 am	31	30.6	6.2	5.7	7.8	2	0.38	0	
		10 am–12 pm		31	30.6	6.2	5.6	7.7	2	0.38	0
		12 pm–2 pm		31	30.6	6.2	5.7	7.6	2	0.38	0
		2 pm–4 pm		31	30.6	6.2	5.7	7.6	2	0.38	0
T		8 am–10 am	31	30.6	5.8	5.6	7.6	2.5	0.35	0	
		10 am–12 pm		31	30.6	5.9	5.5	7.7	2.5	0.35	0
		12 pm–2 pm		31	30.6	6	5.6	7.7	2.5	0.34	0
		2 pm–4 pm		31	30.6	6.2	5.7	7.5	2.5	0.34	0
W		8 am–10 am	31	30.6	5.9	5.7	7.8	2.5	0.3	0	
		10 am–12 pm		31	30.6	5.9	5.8	7.9	3	0.29	0
		12 pm–2 pm		31	30.6	6.2	5.6	7.9	3.75	0.29	0
		2 pm–4 pm		31	30.6	6.3	5.7	7.8	3.75	0.27	0

Notes: DDE – discharge distance to exit, D – discharge, DP – digester pressure and pH – acidity/alkalinity.
NB: the parameters in the table were fairly stable.

Table 7 Monitoring flexible bio-digester structure (continued)

Day	*Inlet/input litres*	*Time*	*Temp., °C*			*pH*			*DP Kpa*	*DDE (m)*	*D (Lt)*
			Gas	*Inlet*	*Exit*	*Gas*	*Inlet*	*Exit*			
T		8 am–10 am	30	30.6	5.8	5.6	7.7	4	0.27m	0	
		10 am–12 pm		31	30.6	5.9	5.6	7.6	4	0.27m	0
		12 pm–2 pm		30	30.6	5.9	5.4	7.5	4.5	0.25m	0
		2 pm–4 pm		30	30.6	5.9	5.6	7.7	4.5	0.21m	0
F		8 am–10 am		31	30.6	6.2	5.5	7.8	3	0.21m	0
		10 am–12 pm		31	30.6	6.2	5.6	7.8	3	0.20m	0
		12 pm–2 pm		31	30.6	5.9	5.8	7.8	3	0.20m	0
		2 pm–4 pm		31	30.6	5.7	5.8	7.7	3	0.19m	0
S		8 am–10 am		31	30.6	5.8	5.6	7.7	3	0.19m	0
		8 am–10 am		31	30.6	5.9	5.7	7.6	3.5	0.18m	0
		8 am–10 am		30	30.6	5.9	5.5	7.7	3.5	0.18m	0
M		8 am–10 am	31	30.6	6.2	5.5	7.5	3	0.15m	0	
		10 am–12 pm		31	30.6	6.2	5.6	7.8	3	0.13m	0
		12 pm–2 pm		31	30.6	6.3	5.7	7.7	2	0.13m	0
		2 pm–4 pm		31	30.6	5.9	5.6	7.7	2	0.10m	0
T		8 am–10 am	31	30.6	5.8	5.7	7.6	1	0.09m	0	
		10 am–12 pm		30	30.6	5.8	5.7	7.8	2	0.09m	0
		12 pm–2 pm		30	30.6	5.8	5.7	7.7	2	0.07m	0
		2 pm–4 pm		30	30.6	5.8	5.6	7.6	2	0.07m	0
W		8 am–10 pm	31	30.6	6.1	5.6	7.4	3	0.05m	0	
		10 am–12 pm		31	30.6	6.2	5.7	7.5	3	0.03m	0
		12 pm–2 pm		31	30.6	6.2	5.5	7.7	3	0.03m	0
		2 pm–4 pm		30	30.6	6.2	5.4	7.6	4	0.02m	0
T		8 am–10 am	31	30.6	6.2	5.7	7.8	4	0.0m	27	
		10 am–12 pm		31	30.6	5.9	5.6	7.7	0	0.12m	0
		12 pm–2 pm		31	30.6	5.7	5.7	7.5	0	0.12m	0
		2 pm–4 pm		30	30.6	5.7	5.8	7.4	0	0.12m	0
F	400	8 am–10 am		31	30.6	6.2	5.7	7.6	2	0.08m	0
		10 am–12 pm		31	30.6	6.1	5.8	7.6	2	0.08m	0
		12 pm–2 pm		31	30.6	6.3	5.8	7.7	3	0.07m	0
		2 pm–4 pm		31	30.6	5.9	5.6	7.6	2.5	0.06m	0
S		8 am–10 am		31	30.6	5.8	5.8	7.8	2	0.05m	0
		10 am–12 pm		31	30.6	5.6	5.7	7.7	2	0.05m	0
		12 pm–1 pm		31	30.6	5.6	5.7	7.7	2	0.03m	0

Notes: DDE – discharge distance to exit, D – discharge, DP – digester pressure and pH – acidity/alkalinity.
NB: the parameters in the table were fairly stable.

Table 8 Digester, machine gas analysed

Parameter	*MW 1 m³*	*FW 1 m³*	*FM 1 m³*		*FSBD 1 2.4 m³*	*FSBD 2 2.4 m³*
CH_4	0.02	0.17	37.21	65.8	56.97	56.44
O_2	0.025	0.25	0.234	0.23	0.234	0.24
CO_2	82.57	74.35	52.57	31.13	38.68	38.37
H_2S	617	1157	0.515	1937	0.005	0.016

Note: NB: MW = market wastes, FW = food wastes and FM = faecal matter.

Figure 8 Volume of methane and carbon dioxide produced from blends of bio-wastes (see online version for colours)

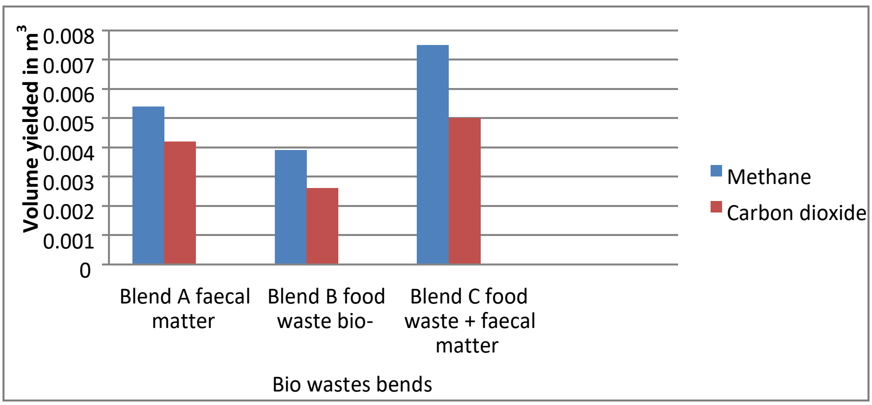
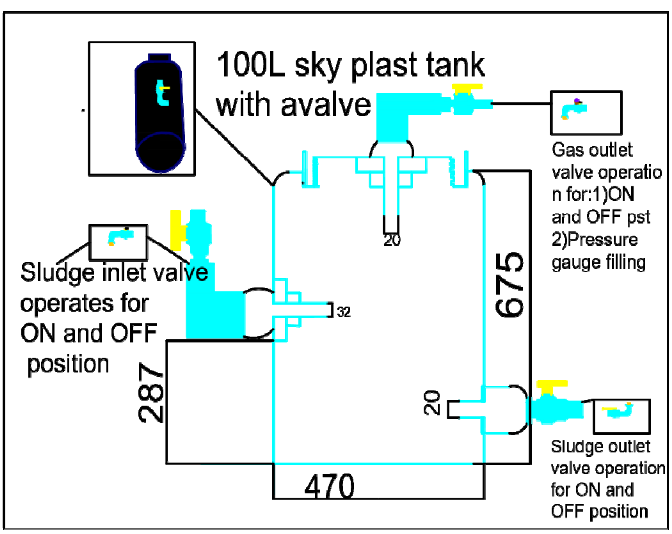


Figure 9 Layout drawing of biogas project (see online version for colours)



4 Conclusions

The methane production and quality improved by size of the digester (1 m^3, 2.4 m^3 to the larger FDBD) and bio-materials were a contributing factor. The 1 m^3 FSBDs were monitored for their performance at PWPS for the days installed and operated. Market waste, faecal matter and food waste digesters, respectively, formed a swollen canopy at day 10. The gas could light (directly from the outlet 25 mm valve) after 20 days for market waste but not for faecal and food waste. The digesters used were small and pressure kept fluctuating during the day. The market waste could not light continuously and efficiently due to the suspected high content of carbon dioxide and water. Out of no expectation, the digester feeding regime averaged 20% of the volume of the digester per week for SODBD and FSBD.

The slurry from faecal matter digester was emptied and re-fed with a new mixing ratio. All the digesters however could not light through the 3 mm valve stove. It was suspected faecal matter may have had detergents such as soaps. Collected food waste from schools had un-cooked food staffs and could take time to form gas and even burn. It thus may have required introduction of bacterial agents. Other aspects that could have affected the 1 m^3 digesters (faecal matter, food waste and market wastes) included low pressure which ranged from 1 to 2.6 Kpa and carbon dioxide.

An electronic gas-board analyser machine was further used to measure the constituents of both the 1 m^3 and 2.4 m^3 FSBD. The 1 m^3 bio-digesters had high content of CO_2 (Table 8) and other gases respectively for bio-wastes faecal matter, food and market wastes. Gas from faecal matter 1 m^3 FSBD could however not burn despite change of mixture ratio and methane content of 37.21% (Table 8).

When market waste was fed into the 2.4 m^3 FSBD at Nyamasaria, the gas was produced after 5 days and could light at day 20. After re-feeding, some parameters were monitored (Table 7). Pressure ranged from 1 to 5 Kpa. It could light effectively and for longer period. Methane production ranged at 56% and carbon-dioxide was 37.21%, which was within the range expected of methane production constituents. It boiled 1 litre of water within one minute when the valve was fully open; and within two minutes when it was at least half open.

The faecal matter FDBD at Obunga produced gas after 14 days that burnt well. After 30 days, methane production was 65%, which burnt efficiently and effectively. Market waste with use of 3 mm modified stove valve also burnt well. Both market and faecal matter wastes (2.4 m^3 FSBD and the Obunga FDBD bio-tower) produced gas that could be utilised and adopted in kitchens.

When setups were first done, the initial gas formed was released as it could have a high percentage of ammonia. This was to allow formation of other gases such as carbon-dioxide, methane, hydrogen and sulphur. These may react with water or air for example, hydrogen reacts very quickly with oxygen to form water (Schön, 2010). Ammonia gas in the system or digester could prevent growth of methanogens and assist condensates which clog pipes.

5 Recommendation

Market waste should be adopted as a cooking energy source through biogas production with equipment designed based on bio-material parameters. This would also be an approach towards waste management by reducing quantities taken to dumpsite. When using faecal matter, screening should be done not to allow detergents that prevent gas formation. Water ratio should be determined and water from showers that contain anti-bacterial soap or detergents in general should strictly be avoided from entering the digester. They affect bacterial formation and subsequently, gas formation. Food waste should be mixed with other bio-materials for adequate gas production but carefully.

Methane production technology equipment or digesters need to be designed based on parameters (client energy demand, retention time, caloric value of bio-materials, densities, etc.) as these have a bearing on gas production performance. There are design conflicts that relate to size, retention time, material types and gas constituents. The size affects pressure development and as such the digester gas constituents. In this case, the 1 m^3 digesters had more CO_2 than methane and hence lighting was difficult. The investments cost also is a factor that has not been smooth with the users leave a lone the inputs.

The FSBD *market wastes* performance is proven and this paper suggests an output that is comparable to that of cow dung. It may not need seeding. The FDBD and FSBD can be used with market waste and faecal matter as bio-materials for institutions and at market centres for biogas production. The gas may be compressed and packed into gas storage bags and sold to households at low cost price for sustainability of the systems.

Pre-treatment (lime water, de-sulphuriser and steel) of gas should be done to remove other gas traces apart from methane gas. pH meter probe should be part of the digester design to help ascertain the nature of feedstock in the digester; that is, determining either the low/high acidity or alkalinity of feed stock as pH value can be improved.

Early indicators of process imbalance include carbon dioxide and methane (Chen et al., 2017). Therefore, there is need to monitor some parameters (pH values, temperature variations, processing of inputs) even if the design was based on organic material parameter characteristics. That is, to identify some instabilities during the anaerobic digestion (Sieburg et al., 2018; Mudhoo, 2012). Security of the setups is also a necessity.

The digestion of human faecal matter requires about 50% of water to make the system moist enough for proper digestion to occur. The ratios for the substrates being 1:1 as for cow dung were not optimal. This is an indicator that different bio-materials may require different amount of water added and different design sizes of digesters for optimality. That is the bio-digester design should be based on bio-material characteristics such as density, etc. Also that, continuous feeding has advantages of continuous fermentation process in the bio-digester and hence the gas.

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