Sizing of an Anaerobic Biodigester for the Organic Fraction of Municipal Solid Waste

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***Abstract*—The anaerobic digestion (AD) of the organic fraction of municipal solid waste (OFMSW) for biogas production is a potential solution to the growing challenges associated with municipal solid waste (MSW) management while simultaneously providing an alternative clean energy source. Biogas is produced by the anaerobic digestion (AD) of biomass using microorganisms in specifically designed plants called biogas digesters under controlled conditions or naturally in marshes and landfills. It is a rather clean and versatile fuel as opposed to fossil fuels. To design an efficient AD system, a proper understanding of the quality and quantity of available feedstock must be made as well as prevailing operating conditions. This paper represents steps that were taken to come up with an optimal size of biodigester to treat OFMSW produced at the University of Johannesburg's Doornfontein Campus in downtown Johannesburg. The campus generates 232.2kg of OFMSW per day which required 30m^3 of biodigester capacity.**

***Index Terms*— Anaerobic Digestion, Biogas Digesters, Clean Energy, OFMSW**

I. Introduction

ANAEROBIC digestion (AD) of biomass is a collection of processes by which microbes breakdown biomass in the absence of oxygen to produce biogas with an approximate composition of 50-70% methane (a combustible gas), 30-50% carbon dioxide and other trace gases depending on the nature of the biomass. The process can be achieved most commonly in specifically designed plants called biogas digesters under controlled conditions or naturally in marshes and landfills [1]. To produce an optimum yield of biogas from a given substrate, a number of operating parameters have to be optimised such as temperature which should lie between 30-400C for mesophilic digestion and 50-60°C for thermophilic. Other factors for AD optimisation are; concentration of feedstock, feed material composition, hydraulic retention time, pH value, carbon-nitrogen ratio, toxicity, agitation, air tightness and moisture content [2, 3].

Biogas can be economically manufactured at both small and large scales therefore can be tailored to supply rural and urban gas needs as well as meet regional and nationwide energy demands. It has been used as an alternative and renewable source of energy for wide spread range of applications including among others cooking, lighting, heating in households and most recently in the developed world, biogas technology is in advanced stages and being used as a vehicular fuel and to produce clean electricity in the Mega Watt range [2, 4].

There have been sustained concerns about the increased municipal waste generation in urban centres worldwide and constantly reducing space due to rapid population growths coupled with continuous infrastructure development. In most cases, the waste generated is commonly sorted for recycling and the non-recyclables which are usually the large portion are taken to landfills. However, the space for landfilling is quickly dwindling and the landfilled waste is leading to uncontrolled continuous emissions of landfill gas containing mostly methane which is a potential greenhouse gas with a global warming potential (GWP) of 21 [5]. Energy recovery from the organic fraction of municipal solid waste (OFMSW) represents a three-in-one potential solution to energy and environmental conservation whereby an alternative source of clean energy is obtained, GHG emissions are reduced and at the same time minimising the nuisance of solid waste [6]. This can be achieved through modern waste to energy techniques such as; incineration, pyrolysis/gasification and anaerobic digestion (AD) [5]. However, anaerobic digestion, in addition to energy recovery, it conserves the original water content of the feedstock and produces a nutrient rich organic agricultural fertilizer in the form of a digestate, unlike the other methods which burn off the water and produce toxic carbon and heavy metal rich by-products making AD the most environmentally friendly technology of all [7]. A report by FAO in 2011 showed that at least 33% of the global food supply goes to waste annually totalling to 1.3 billion tonnes of food waste worldwide [8]. If this waste is used for biogas production, it can yield up to 367m^3 of biogas per dry tonne at approximate 65% methane with energy content 6.25kWh/m^3 yielding 894TWh annually which is about 5% of the world's electricity needs [5]. In 2011, South Africa generated 59 million tons of municipal waste of which 13% was classified as organic waste and another 35% classified as non-recyclable waste [9].

For optimal performance of an AD system, the designer

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has to establish the most suited model and size of biogas plant to treat the substrate type at hand. Hence, as a first step to design a biogas digester, the quality and quantity of available feedstock has to be ascertained. Among the substrate parameters that should be ascertained are: generation rate, total solids (TS) content, total volatile solids (VS) content, moisture content, elemental composition, hydraulic retention time and optimum organic loading rate among others [10]. The choice of OFMSW for biogas production presents a substrate with its own set of unique properties that set it aside from other available substrates such as its ability to give higher biogas yields per unit weight with high methane content (up to 65%) than most available substrates [5]. However, there are several challenges associated with the choice of OFMSW as a substrate for production of biogas such as its heterogeneous nature that calls for extra sorting of the substrate as well as big particle sizes all of which increase its pre-treatment costs. Hence special care must be taken in the design of a biogas digester to handle OFMSW [2].

As part of a larger waste-to-energy project, the University of Johannesburg (UJ) in South Africa is planning a pilot scale biogas plant at the UJ Doornfontein Campus (DFC) based on OFMSW feedstock generated within the campus. This paper presents steps that were taken to come up with a suitable size of biodigester to treat the OFMSW produced at the University Campus in downtown Johannesburg, South Africa.

II. Materials and Methods

The sizing of the biodigester was achieved through a series of procedures involving feedstock quantification and characterisation, plant sizing, digester model selection and dimensioning.

A. Feedstock Quantification

1) Definition of waste stream categories

According to existing information and previous studies, the solid waste stream at UJ DFC was divided into general waste (residential) and garden waste. The garden waste was farther broken into compostable and none-compostable. The general waste was divided into recyclable (usable glass, metals, tins etc.) and non-recyclable. Then non-recyclables were divided into biodegradable and non-biodegradable. The target component for the waste-to-energy project was the biodegradable portion of the non-recyclable general waste as well as the compostable portion of the garden waste.

2) Weighing for Category Quantification

Following the existing waste sorting criteria at the waste transfer station for the general waste, the waste was weighed fresh from source before sorting to obtain the total amount of waste. The recyclable component of the waste from the collection bags was sorted out first. These would then be re-weighed to obtain the total non-recyclables and then sorted further into the biodegradable and the uncategorised whose weights were also obtained accordingly.

At the garden waste station, the total weight of the garden waste was also obtained first and then the compostable garden waste was sorted from the non-compostable and their weights obtained accordingly.

From step 1 and 2, the total of the biodegradable fraction of the waste were computed from the total of the biodegradable non-recyclable general waste and the compostable portion of garden waste.

3) Timing

The exercises were conducted at randomly selected week days during which waste sorting takes place at the respective transfer stations for 5 consecutive weeks both during the spring and autumn seasons. The data obtained was averaged out to obtain the daily generation rates. To carter for seasonal variation, the studies were carried out during the spring and the autumn seasons.

4) Sampling and Statistical Analysis

All generated waste ends up at the two earlier mentioned points. That is; the waste transfer station for general waste and the garden waste storage site for garden waste. The exercises were conducted such that all the available waste generated from the previous day was weighed and sorted. To test the reliability of the obtained data, analysis for obtained means was undertaken to ascertain whether they are at least within 90% confidence interval as specified by UNEP standards for sampling of municipal solid waste [11].

B. Feedstock Characterisation

For evaluation of the OFMSW as a feedstock for energy recovery, the waste had to undergo various selected tests to obtain key parameters for plant sizing. The tests that were conducted were; Ultimate Element Analysis, In-situ Density Determination, Volatile Solids (VS) content, Moisture Content and Total Solids (TS) content.

The samples to be used in the laboratory analysis were obtained from the same source in a similar way from the waste quantification exercise. The samples were mechanically mixed and reduced to manageable sizes using the conning and quartering method of sample preparation in accordance to BS EN 14899:2005.

The sample was wrapped in air tight plastic bags. Instantly, a small portion of the freshly obtained samples was tested for moisture content before destabilisation and in-situ density measured. The balance of the sample was preserved in a fridge for further tests. Prior to all conducted tests, the samples were ground using a blender to achieve homogeneity.

A number of tests were carried out on the feedstock samples and these are:

1) In-situ density

The wet density of the feedstock was determined in the field using containers of known volume and the weighing scale. From the fresh sample, the waste was loosely packed in a 250ml container of known mass (m_c) and then the mass of the container plus sample (m_{c+s}) was obtained on the scale from which the density would be computed as in (1);

Density of Sample (d_s) = ($m_{c+s} - m_c$)/250ml (1)

The procedure was carried out on four samples and the average value obtained as the density of the feedstock.

2) Total Solids and Moisture Content

Freshly ground samples were taken to the laboratory for moisture content determination. For each aliquot, 33g of sample was measured off the larger sample and oven dried at 105^0C for 24 hours. The dishes and watch glasses to be used in the experiment were first oven heated at 105^0C for 1 hour and later cooled in a desiccator to ensure that they are moisture free prior to use. The combined mass of the dish and watch glass (md) was obtained first after the desiccation procedure. Then the approximately 33g fresh sample was placed in the dishes, spread out and covered with watch glasses. Then the mass of the arrangement (m_s) obtained. The sample was then placed in the oven and dried for 24 hours at 105^0C after which it was cooled in a desiccator and reweighed to obtain the new mass of dry sample (m_{sd}). The final value of msd was obtained after repeated 1-hour heating, cooling and weighing process that yielded negligible change in mass. From these, the total solids and moisture content were computed as in (2) and (3);

% total solids (TS) = $(m_{sd}- m_d)/(m_s- m_d) * 100$ (2)

% moisture content (MC) = $(m_s- m_{sd})/(m_s- m_d) * 100$ (3)

3) Volatile and Fixed Solids Content

The residue obtained from the total solids and moisture content determination was then heated in a furnace at 550^0C for 2 hours and the new weight of the sample with the dish was obtained as the mass of residue without volatile solids (m_r). Necessary precautions were taken to ensure a moisture free furnace. From these, volatile and fixed Solids content were computed as in (4) and (5);

% volatile solids content (VS) = $(m_{sd}- m_r)/(m_{sd}- m_d) * 100$ (4)

% fixed solids (FS) = (mr - md)/(msd- md) * 100 (5)

4) Ultimate Analysis

To obtain the elemental (CHNOS) composition of the feedstock, the testing was outsourced to a specialist laboratory as the department lacked an elemental analyser. Part of the earlier prepared sample was delivered to the laboratory and the test was carried out at an agreed cost.

C. Plant Sizing

Using the obtained values from the waste quantification and characterization exercises, appropriate input parameters like the feedstock volumetric flow rate were ascertained that aided the bioreactor design using the formulae as in (6) to (8);

Volume of reactor (V_r) = Volumetric Flow rate (Q) x HRT (6)

Where;

HRT is the hydraulic retention time of the feedstock in days.

Taking the volume of the gas holder to be half the reactor volume;

Volume of the gas holder $(V_g) = V_r/2$ (7)

Total biodigester volume (V_d) is the sum of the reactor and the gasholder volumes.

$$V_d = V_r + V_g \quad (8)$$

D. Digester Model Selection and Dimensioning

In a separate study, multiple-criteria decision analysis (MCDA) techniques were employed to select the most suitable biogas digester technology from a list of identified alternatives based on their attributes and how well they satisfied the intended purpose [12].

After selection of a suitable model, appropriate dimensions of the digester were determined from geometric formulae as in (9) to (13) basing on the standard sizes of the selected digester model.

The reactor is a cylindrical tank of volume (V_r) given as;

$$V_r = \frac{\pi D^2 H}{4} \quad (9)$$

Where; D is the diameter of the tank and H is the height

Assuming the height of the reactor is equal to its diameter; $D \approx H$

$$V_r = \frac{\pi D^3}{4} \quad (10)$$

Hence the diameter D can be given as;

$$D = \sqrt[3]{\frac{4V_r}{\pi}} \quad (11)$$

Taking the gas holder/digester radial clearance to be 20 mm, gives a diameter (d) of the gas holder as:

$$d = (D - 0.04) = \left(\sqrt[3]{\frac{4V_r}{\pi}}\right) - 0.04 \quad (12)$$

Given a gas holder volume (V_g), the height (h) of the gas holder is therefore be given by:

$$h = \frac{4V_g}{\pi d^2} = \frac{4V_g}{\pi} * \left(\left(\sqrt[3]{\frac{4V_r}{\pi} - 0.04}\right) - 0.04\right)^{-2} \quad (13)$$

III. Results and Discussions

A. Feedstock Quantification

The data obtained from waste quantification exercise was processed to produce statistical data as in Tables I, II and III;

TABLE I
AVERAGE DAILY WASTE GENERATION IN SPRING

Parameter	GENERAL WASTE (kg)					GARDEN WASTE (kg)	
	Recyclables	Paper bags	Food	Polystyrene	Uncategorised	Compostable	None Compostable
Mean	44.292	22.260	134.487	3.628	35.782	98.799	7.803
Standard Deviation	5.213	19.857	21.767	0.842	5.979	14.841	1.835

TABLE II
AVERAGE DAILY WASTE GENERATION IN AUTUMN

Parameter	GENERAL WASTE					GARDEN WASTE	
	Recyclables	Paper bags	Food	Polystyrene	Uncategorised	Compostable	None Compostable
Mean	82.297	3.064	95.603	6.788	60.014	133.560	27.876
Standard Deviation	42.444	0.830	17.897	2.947	19.696	34.917	9.908

TABLE III
COMBINED AVERAGE DAILY WASTE GENERATION

GENERAL WASTE (kg)					GARDEN WASTE (kg)		TOTAL (kg)
Recyclables	Paper bags	Food	Polystyrene	Uncategorised	Compostable	None	
63.295	12.662	115.045	5.208	47.898	116.179	17.839	378

An approximated 378 kg of municipal solid waste is generated daily at the campus of which 231.22kg (61.2%) is the OFMSW portion made up of food waste and compostable garden waste. Hence 231.22 kg of solid waste per day will be the design mass flow rate for the proposed biodigester.

Of the total waste generated, 64.6% and 35.4% are the general waste and the garden waste respectively. 47% of the general waste generated is food waste whereas 26%, 5.2% and 2.1% are recyclables, paper bags and polystyrene respectively. And the remaining 19.7% is made up of a complex mixture of substances that were referred to as un-categorised in this study. 86.7% of the garden waste is biodegradable and the balance is non-biodegradable.

More garden waste is generated during the autumn season than spring due the massive loss of leaves by trees during autumn. However, only 82.7% of the total garden waste during autumn is biodegradable as opposed to the 93% during spring because most of the garden waste produced in autumn is not fresh green waste.

B. *Feedstock Characterisation*

The results obtained from the characterisation analyses are as summarised in Table IV;

TABLE IV
FEEDSTOCK CHARACTERISTICS

Parameter	**Value**
Average daily generation rate	231.22 kg/day
Total Solids (TS)	27.14%
Moisture Content (MC)	72.86%
Volatile Solids (VS) (% of TS)	94.90%
Fixed Solids (FS) (% of TS)	5.1%
Density	775.0 kg/m^3
C,H,O,N	52.80%, 6.02%, 38.42%, 2.1%
C:N ratio	25:1

From Table IV, UJ DFC generates an average of 231.22kg of biodegradable waste per day of which 27.14% is solid content and the remaining 72.86% is all water content. In addition, of the solids, 94.9% is the digestible component and the remaining 5.1% is ash content.

Generally the OFMSW characteristics obtained were in agreement with most of the reviewed literature which indicate that typical OFMSW has TS and VS ranges of 20-30% and 90-95% respectively. And the C:N ratio of 25:1 obtained is within the optimum range of 20-30:1 which means the substrate doesn't require co-digestion to improve its properties [3], [13]-[15].

C. *Plant Size*

1. Bioreactor size

From (6), volume of reactor (V_r) is given by;
Volumetric Flow rate (Q) x HRT
Feedstock Flow Rate (Q) = 231.22 kg/day
Using Density as 775.0 kg/m^3;
Q = (231.22 /775.0)m^3/day
=0.298m^3/day

To achieve substrate fluidity, the feedstock is mixed with water at a ratio of 1:1. Hence, an additional 0.298m^3 of water is to be added giving a total feedstock flow rate of approximately 0.6 m^3 per day.

From literature, values for optimum HRT for OFMSW range between 21-30days [5], [13], [16].
Taking the upper limit HRT of 30 days,
V_r = 0.6x30= 18m^3

Organic loading rate (OLR) Check;

The optimum Organic loading rate for OFMSW ranges between 5-10 kgVS/m^3 [13, 14, 16].
Organic Loading Rate = (Q x S)/Vr;
Where:

S: Concentration of Volatile Solids in the input (kg/m^3)
S=0.2714x0.949x775.0 = 199.6 kg/m^3
OLR= (0.6x199.6)/18
OLR = 6.65kgVS/m^3 (This is within the range between 5-10
Therefore, the 18m^3 reactor size is Ok)

2. Gas holder Size

From (7);

$$V_g = V_r/2$$

$$V_g = \frac{18}{2} = 9m^3$$

3. Biodigester Volume

From (8), the total digester volume (V_d) is the sum of the reactor and the gasholder volumes.

$$V_d = (18 + 9) = 27m^3$$

Therefore the total volume of the digester will be 27.0m^3. Say **30**m^3

D. *Digester Model Selection and Dimensioning*

From the technology selection, the best digester model selected for the project was the Puxin digester which is available in $10m^3$ and $6m^3$ capacities. Therefore, the project would require three (3) $10m^3$ plants.

Using the geometric formulae, the respective key dimensions of the digesters were obtained. Substituting into the (10) to (14) gives digesters with possible dimensions as in Table V;

TABLE V
BIODIGESTER DIMENSIONS

V_c (m^3)	D (m)	H (m)	V_g (m^3)	d (m)	h (m)	V_d (m^3)
6. 7	2.04	2.04	3.3	2.00	1.06	10.0

IV. CONCLUSIONS

The study presents methods and results from a case study to size a suitable anaerobic biodigester to handle OFMSW generated at the University of Johannesburg's Doornfontein Campus. The plant was scaled based on reliable estimates of waste quantification and characterisation studies conducted at the study area. Of the 378kg of solid waste generated daily at the school campus, 231.22kg is the biodegradable portion which will be handled by the proposed biogas digester consisting of food waste and compostable garden waste. This this will require $30m^3$ of biodigester capacity.

A Puxin digester model a Chinese technology supplied locally by BiogasSA will be the preferred model which is present in standard sizes of 10 and $6m^3$. Therefore, the project will require three (3) $10m^3$ plants.

V. RECOMMENDATIONS

The study was carried out through the spring and autumn seasons. To achieve a more reliable estimate of the OFMSW quantities, more studies should be carried out over the other two seasons of the year that is summer and winter so as get a more accurate picture on seasonal variation.

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