Integrative Municipal Sewage Sludge Management through Biogas Production: A Case Study of Municipal Plants in Harare, Zimbabwe

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Abstract

In this study, the potential to generate electricity from sewage sludge biogas harnessed from municipal sewage plants was investigated. Two sewage plants Crow borough and Marlborough were investigated as the potential raw material suppliers for the biogas generation. Sewage sludge samples were collected sand analyses for the total solids (TS), volatile solids (VS) and chemical oxygen demand (COD) among other parameters. Biogas generation was quantified in 250 mL flasks conducted under anaerobic conditions at mesophilic temperatures of 37 °C and thermophilic temperatures of 55 °C and agitation rates of 200 rpm. Optimum biogas production was achieved at 37 °C and 200 rpm with a methane composition of 72% before upgrading. The sewage sludge digestion to biogas was confirmed by the decrease in both TS and VS by 25.4% and 14.5% respectively. The average biogas generation rate was 0.015 m^3/L with a Wobbe index of 24.78 indicating the high calorific value of the biogas and its potential to be generated to electricity.

Keywords: Biogas, digestate, municipal plants, resource recovery, sewage sludge

1. Introduction

Municipal sewage plants generate huge amounts of sewage sludge during sewage treatment, which if not properly managed can be an environmental nuisance and also result in land filling problems (Mustafa et al., 2016). Sewage sludge on the other hand has potential to be generated to biogas through anaerobic digestion through processes such as hydrolysis, acidogenesis, acetogenesis and methanogenesis (Savari et al., 2016). Biogas, is a renewable and alternative source of energy that can be used for cooking and heating purposes and sewage sludge biogas has composition ranging from 60-70% (Appels et al., 2008). The production of biogas from municipal sewage is actually an attraction in developing countries where the energy deficit is on the increase. Figure 1 gives a summary of the biogas production processes.

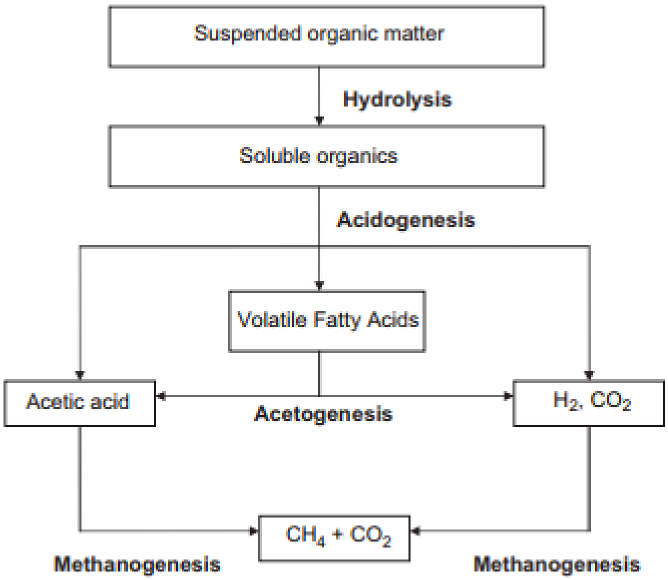

Figure 1. Biogas production processes (Appels et al., 2008)

This study looked at integrative resource recovery from municipal sewage sludge in a bid to recover biogas, a resource that can be used for electricity generation with a particular emphasis to effect of anaerobic digestion temperature and agitation effects.

2. Materials and Methods

2.1 Materials

Samples of municipal waste were collected from the bio-nutrient reactor (BNR) sections of the various plant, eight 250 mL volumetric flasks from Jambo Enterprise, Harare, Zimbabwe, balloons from Nappa Reid, Harare, Zimbabwe, water bath, distilled water, Osert gas analyzer from Sellathe Scientists, gloves from Lahama Tradings, thermometer from Deree Electrical Instruments, stirrer from Lovanni Impex Ltd, TPS WP-80D dual pH-mV meter. The reagents that were used for biogas purification were ferrous material, gas column container (imitating the scrubber and absorption column), water, potassium hydroxide, lime, and iodine solution and these were obtained from BARCO chemicals, Harare, Zimbabwe.

2.2 Methods

2.2.1 Physicochemical characteristics of the sewage

Sewage sludge samples were collected from the bio nutrient removal section at the sludge blending tank of the Crow borough and Marlborough sewage plants in Harare, Zimbabwe which was used as the basis of this study. Special care was taken during the extraction process to ensure that a sample representative of the sludge in the tank was removed. The samples were collected in 5L clean polyethylene containers and brought back to the laboratory within 30 minutes and immediately stored at 4 ºC in a refrigerator. The samples were allowed to equilibrate to laboratory temperature before it was used for the experiment.

The sewage sludge biological oxygen demand (BOD), chemical oxygen demand (COD), total phosphate (TP), total suspended solids (TSS), total dissolved solids (TDS) and total volatile solids were quantified over a 5 day period. The physicochemical parameters were measured in accordance to APHA (2005).

The determinations of total solids (TS), volatile solids (VS) and fixed solids (FS) were carried out as proposed by Standard Methods for the Examination of Water and Wastewater (APHA, 2005). TS indicated the mass that remained after drying the sludge sample at 105 °C for 48 hours, and were expressed as a percentage of the total wet mass. The VS content was obtained by measuring the mass loss after heating the TS fraction at 550 °C for 1 hour. The mass remaining was the fixed solids (FS). VS and FS were expressed as a percentage that can be referred to the wet mass or to the TS. All samples were weighed on AND ER-180A electronic balance (± 0.2 mg). The pH level of the samples was taken using TPS WP-80D dual pH-mV meter.

2.2.2 Biogas production from sewage sludge

A batch system was set up to monitor biogas generation from the samples. A 1L glass vacuum filtering flask was used as an anaerobic reactor for sludge incubation in a water bath set at a constant mesophilic temperature of 37 ºC and sealed with a thick, black rubber stopper. The side arm was connected with a 50 cm rubber tubing hose of diameter 7.9 mm for gas movement to an inverted graduated gas collector i.e. 500 mL plastic container. The collector acted as a sampling port used to sample and release biogas. Samples of 600 mL of sewage sludge were used in each reactor. All the experiments were carried out in triplicate. The system was inspected for any gas leakages before commencement of the experiment.

2.2.3 Biogas composition determination

A sampling port was created by drilling a hole and sealing it with a rubber membrane at the bottom of the graduated gas collector. Gas samples, extracted using a 50 mL air locked syringe, were transferred and stored in 1L CEL scientific gas sampling gas. Gas measurements were monitored daily by recording the downwards displacement of water. The incubation time was approximately 15 days and collected gas samples were analyzed using the Orset gas analyzer.

2.2.4 Effect of temperature on biogas production

Four 250 mL samples of sewage sludge were set in 250 mL volumetric flasks. Each sample represented every stage in anaerobic process namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. This was done by placing each flask in a water bath respective with temperature that would give optimum methane production. A balloon to collect the biogas was placed at each opening. The volume of gas obtained in each balloon was measured as an indication to the amount of biogas produced. The agitation rate was fixed at 200 rpm and the amount of gas generated was compared to a system

2.2.5 Biogas scrubbing

250 mL sample of sewage sludge was poured in a 500 mL volumetric flask. This was connected via a tube to a flask containing 200 mL of water which acted as a carbon dioxide solvent. This was also connected to another flask containing a 200 mL of 2M iron solution which acted as an absorbent for hydrogen sulphide this was also connected to a flask containing potassium hydroxide for absorbing ammonia and other trace elements. Since hydrogen sulfide is the major element compared to other trace element present besides methane its presence was tested using iodine solution to ensure that only methane gas was being produced. Methane gas was collected in a balloon.

2.2.6 Methane gas quality tests

There was need to test the gas being produced that it was methane. This was done by lighting a match after releasing the gas to test if it ignites. Secondly the methane gas was changed into a halocarbon compound chloromethane which produces ether like smell and a halide test was performed by adding silver nitrate and nitric solution to the solution for a white precipitate to form.

2.2.7 Effect of agitation on methane production from sewage sludge

Three pairs, each of samples of sewage sludge were placed in 250 mL volumetric flasks and covered with balloons at each end. One flask was not to be stirred as a control measure the other one was stirred at 200 rpm for 3 minutes on an hourly basis. The volume of gas produced was measured after ten days.

3. Results and Discussion

3.1 Potential to harness biogas from the local municipal plants

The Harare sewer plants` daily inflow rates for Crow borough and Marlborough are shown in Table 1 which reveal a total of 61 000 m^3/ day flows of waste water per day showing the availability of the raw material that can be used for biogas generation which can ultimately be used for electricity generation. Zimbabwe's electricity sector comprises of five power stations with a total installed capacity of 1 961 MW (megawatts). The five power stations are only capable of meeting a maximum demand of 1 600 MW given Zimbabwe's current maximum demand of around 2 034 MW.

Table 1. Waste water treatment plants in Harare July 2012 (Harare Water Works)

Name of plant	Location	Design capacity (m^3/day)	Flows (m^3/day)
Crow borough	West Mufakose, Zimbabwe	54 000	110 000
Marlborough	North west Marlborough, Zimbabwe	7000	10 000

3.2 Raw sewage sludge water characteristics

The parameters analyzed included BOD, COD, TP, TS, TSS, TDS, TVSS were indicative of the organic matter of the sewage that would affect the anaerobic digestion of sewage sludge (Bartakke and Deshmukh, 2015). Of importance was the level of COD which was between 500-1000 mg/L and as shown above on average it was 600 mg/L in both sewage plants (Table 2 and Table 3). The COD revealed the strength of the sewage sludge which should not be high as it would affect the energy used in the bio digester. The amount of total volatile solids (TVSS) was low as was less than 5% (as obtained in some cases in this study) which showed that the sewage sludge had sufficient solids for anaerobic digestion. This is also shown by the amounts in total solids and total dissolved solids.

Table 2. Marlborough raw sewage parameters

Parameter	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	17.2	18.0	15.0	20.5	22.0
BOD (mg/L)	210.0	310.0	132.5	194.6	420.0
COD (mg/L)	270	404.9	513.8	595	2843.8
TS (mg/L)	55.8.	553.5	507	884	3075.1
TDS (mg/L)	330.5	185.4	369.5	169	1063.2
TVSS (%)	5.6	8.9	1.3	1.8	5.0
TP^- (mg/L)	18.8	15.5	12.5	16.8	23.8
pH	6.95	7.04	6.82	7.07	6.72

Table 3. Crow borough raw sewage parameters

Parameter	Day 1	Day 2	Day 3	Day 4	Day 5
Temperature (°C)	19.5	19.0	21.2	21.0	22.5
BOD (mg/L)	150.0	390.0	121.3	188.3	230.6
COD (mg/L)	384.2	425	414.4	663	635.4
TS (mg/L)	401.8	264.4	411.5	320	344.8
TDS (mg/L)	210.0	335.6	184.0	256.9	371.3
TVSS (%)	4.5	4.0	1.8	2.6	3.0
TP (mg/L)	14.25	13.0	9.5	18.5	24.5
pH	7.16	7.07	7.08	6.96	6.72

3.3 Biogas production and monitoring

The rate in which biogas was produced was equal to the rate the sewage sludge was decomposed. This helped in ascertaining that the process can be continuous. The amount of biogas produced 3.78L in comparison to the mass 0.25kg showed that a great amount of gas could be generated from minimal amount of sludge. However, the retention time of 15 days as shown in Figure 2 initiated the need of optimizing in the design for an efficient production of methane to produce sustainable amount of electricity.

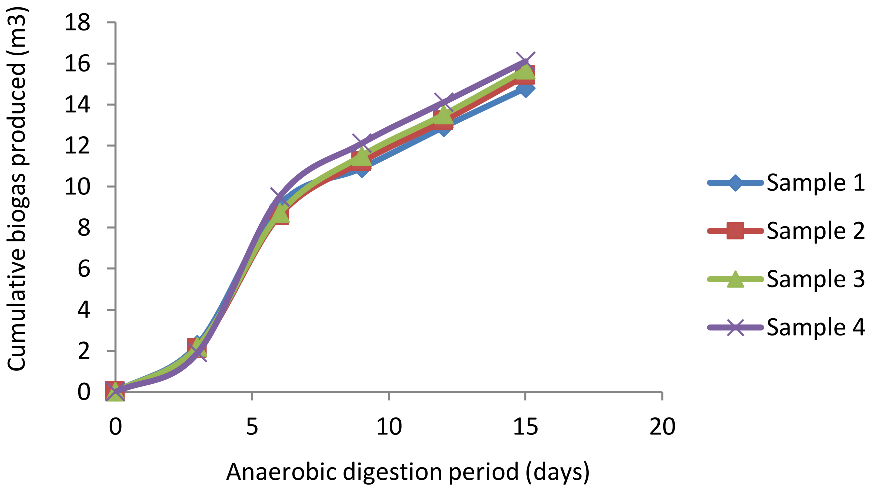

Figure 2. Cumulative biogas production from sewage sludge over 15 days

Table 4 shows a summary of results obtained by anaerobic digestion of a sample of sewage sludge over a period of 15 days. Biogas with 72% of methane was obtained from the process which was within the stated range of 55%- 75% (Peterson et al., 2007; Kosh et al., 2010; Roati et al., 2012). The peak volume of biogas produced was 0.48 L/hr and the Ph of the digestate was 6.68 with a biogas production rate of 0.015 m^3/L.

Table 4. Biogas from municipal sludge physiochemical properties

Parameter	Value
Total volume of gas generated (L/hr)	3.78
Peak volume of gas (L/hr)	0.48
TS (%)	2.62
VS (%)	2.36
(VS/TS %)	78.63
Ph	6.68
Biogas production (m^3kg^{-1} VS added)	0.53
Biogas production (m^3kg^{-1} VS destroyed)	0.60
Biogas production(m^3L^{-1}) sludge	0.015

3.4 Biogas composition

The biogas composition of the sludge samples is shown in Figure 3, with methane having a composition of 72%, carbon dioxide 20, hydrogen sulphide 4% and other trace gases like ammonia and siloxanes had 6%. The biogas composition obtained correlated with that reported in litearature (Peterson et al., 2007; Kosh et al., 2010; Roati et al., 2012). From the biogas composition analysis, the impurities of concern are carbon dioxide and hydrogen sulfide which must be removed. The removal of these impurities was carried out in the experiment on the scrubbing effect in methane generation.

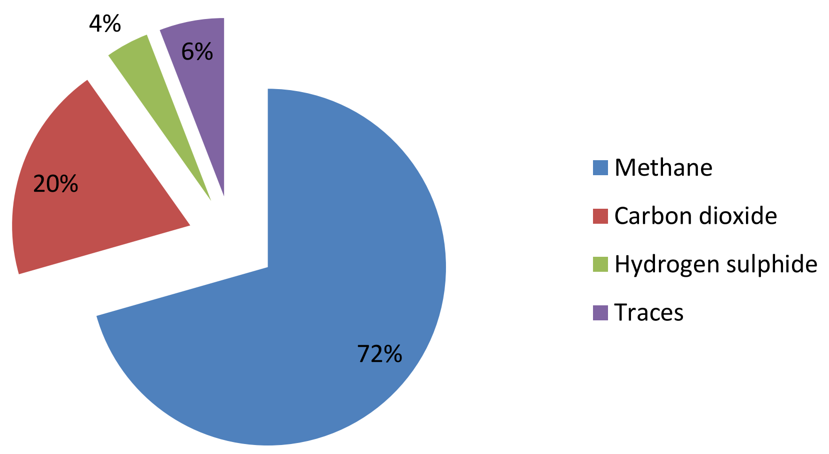

Figure 3. Biogas composition from sewage sludge

3.5. Effect of temperature on biogas production

It was observed that anaerobic digestion takes place faster at mesophilic conditions as compared to thermophilic conditions with biogas quantities higher by around 50% (Figure 4). These results aided in choosing the ideal heating system for the digesters to maintain the temperatures at 37 °C. The same results were reported by Kardos et al. (2011), who reported that sewage sludge digested under mesophilic conditions had higher biogas quantities produced in comparison to thermophilic conditions.

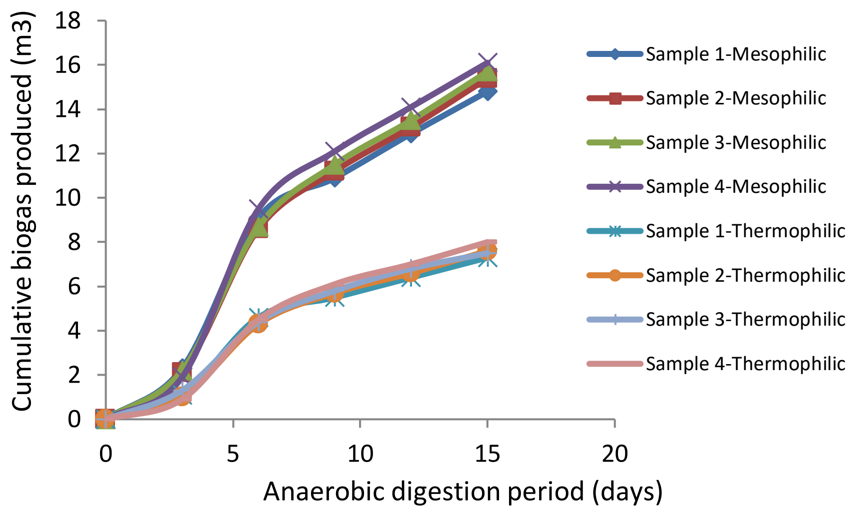

Figure 4. Effect of temperature on biogas production

3.6 Biogas scrubbing

From the experiment on scrubbing effect in methane generation process it was observed that iron pellets could remove hydrogen sulfide as shown by the iodine test carried out which showed absence of hydrogen sulfide and trace siloxanes. The methane composition increased from 72% to 90%. Biogas scrubbing is essential to increase the calorific value of the biogas (Lien et al., 2014). The carbon dioxide was removed from the biogas by water and for precision scrubbing potassium hydroxide solution was used for removal of trace impurities. Methane gas was produced as indicated by the halide test whereby it was first converted to halo carbide.

3.7 Methane quality test analysis

Upon lighting a match, the biogas ignited which showed that methane was present. Moreover, methane was converted to a halocarbon namely chloromethane which was reacted with silver nitrate and nitric acid which formed a white precipitate which showed that methane gas was produced.

3.8 Effect of agitation

Employing agitation rates of 200 rpm during anaerobic digestion of the sewage sludge enhanced the biogas quantity produced under mesophilic conditions by more than 75% (Figure 5). The effect of stirring showed the need to keep a uniform distribution within the digester. Moreover, it provided all of the substrate to be exposed to the bacteria for digestion over a short period of time enabling maximum methane production. Keanoi et al. (2014) also reported a 64% increase in biogas amount generation in a system where there was high agitation unlike in an agitation free system.

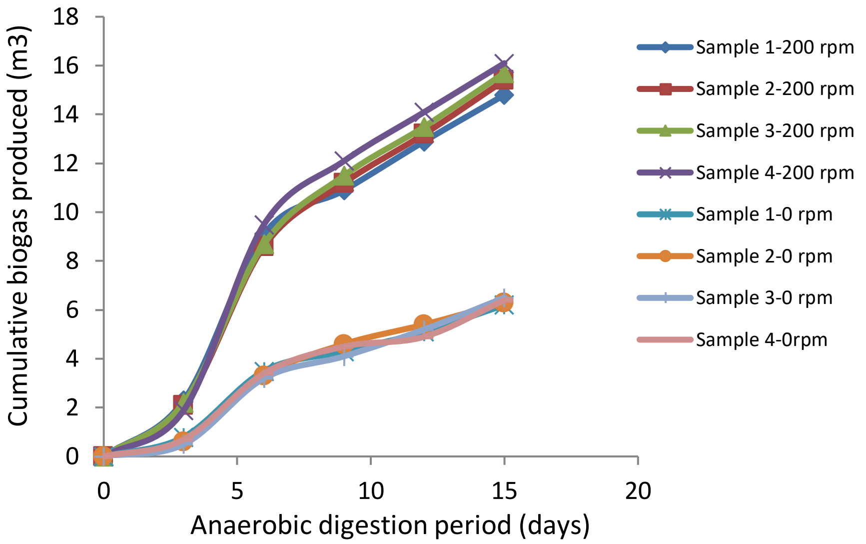

Figure 5. Effect of agitation on biogas production

3.9 Changes in total solids and volatile solids

The efficiency of the anaerobic digestion of the sludge samples was evaluated in terms of TS and VS reduction. The results of total solids content of the sludge sample before and after digestion are presented in Table 5. A 25.4% reduction in TS and a 14.5% reduction in VS were observed in this study. This noticeable drop in total solids content between pre and post digestion demonstrated the effectiveness of solid reduction in anaerobic digestion. The reduction of organic matter was measured by the volatile solid reduction, indicating the completeness of digestion, it is important to note that the TS reduction was dependent on the amount of moisture content in the samples, which in turn influences the fixed solids content. Sajeena et al. (2013) reported a decrease of more than 60% in the TS and VS during biogas production from municipal waste.

Table 5. Reduced solids during anaerobic digestion

Parameter	Pre digestion sludge (%)	Post digestion sludge (%)	Difference (%)
Total solids (TS)	3.5	2.6	25.4
Volatile solids (VS)	2.8	2.4	14.5
Fixed solids (FS)	0.4	0.3	25
pH	6.9	6.7	-

3.9 Wobbe index

The Wobbe index is used as an indicator on the interchange ability of fuel gases and is particularly useful for evaluating fuels in a combustion engine. A 65% methane (CH_4) content has a lower heating value of 20.2 MJ/kg and a density of 1.2 kg/ Nm^3. The Wobbe index of biogas can be calculated using Equation 1

$$Wobbe\ index = \frac{LHV\ (CH4)}{RD} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (1)$$

Where: LHV (CH_4) is the Lower heating value of biogas and RD is the relative density which is dimensionless. The relative density can be calculated using Equation 2

$$Relative\ density = \frac{Density\ of\ biogas}{Density\ of\ air\ at\ standard\ temerature\ and\ pressure} \ldots\ldots\ldots. (2)$$

Using Equation 2; relative density was equal to 1.2 kg/Nm^3/1.293 kg/Nm^3 = 0.928. The Wobbe index is therefore calculates as 20.2 MJ/kg/0.928 which equals 2177 MJ/kg. The biogas produced from sewage sludge physiochemical properties is shown in Table 6.

Table 6. Summary of biogas production from sewage samples

Biogas parameter	Quantity
Methane composition (%)	72
Carbon dioxide composition (%)	20
Hydrogen sulphide composition	2.5
Biogas production per day (m^3/d)	6222
Calorific value, lower (MJ/ Nm^3)	23
Calorific value, lower (MJ/ kg)	20.2
Density of biogas (kg/Nm^3)	1.2
Density of methane (kg/Nm^3)	0.66
Relative density	0.928
Wobbe index (MJ/Nm^3)	21.77-24.78

4. Conclusion

Municipal sewage plants provide an alternative and source of raw material for biogas generation promoting resource recovery from sewage plants. Biogas generation from sewage plants does not only provide biogas which is rich in methane with an average composition of around 72% but also provide a waste management strategy for municipal plants.

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