Bio-methane Potential of the Organic Fraction of Municipal Solid Waste

N. Mojapelo, E Muzenda, R. Kigozi and A. O. Aboyade

***Abstract*—** Biogas is a gas formed from the breakdown of biomass by microorganisms in an anaerobic environment composed of methane (50%–70%) and carbon dioxide (30%–50%). The upgrading of biogas by the removal of carbon dioxide to increase the percentage of methane to over 92% produces bio-methane which is a potent versatile clean fuel. This paper represents a study that was carried out at the University of Johannesburg's Doornfontein Campus (UJ DFC) to ascertain the potential of bio-methane recovery from the organic fraction of municipal solid waste (OFMSW) collected at the campus' cafeteria and student residences. The campus produced 231.22 kg of OFMSW per day with a density of 775 kg/m^3, 27.14% total solids, 94.89% volatile solids, C:N ratio of 25:1 and a bio-methane potential of 386.46 ml/g at 62% methane composition.

***Keywords*—**Biogas, bio-methane potential, organic fraction of municipal solid waste

I. Introduction

DUE to population growth, industrialisation, urbanization and economic growth, a trend of significant increase in municipal solid waste (MSW) generation has been recorded worldwide [1]. The urban population is increasing due to rapid industrial growth and migration of people from rural to urban centres. Municipal solid wastes (MSW) are generated in increasing amounts in proportion to the rise in population and urbanisation and large percentage are taken to landfills. As more land is required for the ultimate disposal of these solid wastes, issues related to disposal have become highly challenging [2] and require innovative solutions to minimize their impact on environmental quality and public health. For instance, in 2006, the United States generated 251 million tons of MSW, an increase of 5% over 2000 level and 22% over 1990 level [3]. About 67% of the MSW was disposed in landfill and 33% was recycled and composted. The landfilled MSW contains a large fraction (more than 60%) of biodegradable materials [3] and presents increasing management challenges. This has led to increasing quantities of domestic solid waste while space for disposal decreases. In this case, landfilling is no longer an option for waste management because of its environmental drawbacks. The continuous increment of MSW has a negative impact on the environment because the present methods of disposal like landfilling are not suitable in areas where space is a constraint and valuable land that can be used for diverse purposes is wasted. Collection and transportation of MSW to the landfill represents a major challenge as it is costly and the wastes at the sites continuously emit methane which is a potential greenhouse gas (GHG) [2].

Solutions to these problems have been developed around the world to address waste management challenges. These include gasification, pyrolysis and plasma technologies (incineration) of solid wastes. These technologies are waste treatment processes that involve the combustion of organic substances contained in waste materials at elevated temperatures in the absence of oxygen [4]. Waste materials are heated to high temperatures, creating gas, solid and liquid residues. The gases are then combusted, releasing hazardous pollutants [4]. These technologies require a great deal of energy to operate, and some facilities have consumed more energy to operate than could be produced [4]. Among the other waste-to-energy options, Anaerobic Digestion (AD) of organic matter is an attractive option. AD of biomass is a well-known natural process of biodegradation of organic matter performed by microorganisms that transform a biodegradable substrate into biogas and produce a stabilized solid residue defined as a digestate [5].

The exhaustion of fossil fuels and the global warming situation are strongly motivating research in alternative energies [6]. Many countries are interested in sustainable renewable energy sources such as; geothermal power, wind power, small-scale hydropower, solar energy, biomass energy, tidal power, and wave power [6]. Zheng et al., (2012) [7], reported that biomass energy is gaining increasing importance because of its environmentally sound and energy-saving production methods. Various biomasses derived from the carbonaceous waste of human and natural activities could be utilised as renewable energy resources [8].

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Anaerobic digestion (AD) plays an important role in the waste management by converting waste into useful gas. The use of the anaerobic digestion as a process to treat organic solid wastes has increased significantly [9]. The reason of this new tendency in the treatment of solid wastes can be explained considering mainly three factors: i) the need to apply a process to dispose of organic solid wastes in a more environmentally friendly manner than landfilling as required by the latest regulations concerning environmental protection in many countries in the world; ii) the opportunity to obtain from this process a renewable fuel called biogas as an alternative to fossil fuels; iii) the advantage of relatively low costs in starting up and managing this process. Anaerobic digestion technology is attractive because of its role in organic waste management and climate change mitigating potential as well as bioenergy production.

The University of Johannesburg, Doornfontein, together with the Process, Energy and Environmental Technology Station (PEETS) aims to champion the energy, waste, environment, and water issues using the sustainable innovations. PEETS is undertaking a study to generate biogas from solid waste generated at the University of Johannesburg's Doornfontein Campus (UJ DFC). The study forms part of the South African National Energy Development Institute (SANEDI) funded project to investigate the feasibility of converting MSW to fuel in the form of compressed biogas (CBG). As part of this project, waste studies were carried out at the UJ DFC and this involved waste quantification, waste characterisation and Bio-methane Potential studies. The results obtained were used to estimate the energy recovery from the MSW.

II. Materials and Methods

The study was divided into 3 stages, namely quantification, characterisation and bio-methane potential (BMP) of the OFMSW using the UJ DFC as a case study.

A. Waste Quantification

Waste generated at the study area was quantified during the autumn and spring seasons which run from March to May and September to November respectively. This involved measurement of the waste at the point of generation. The waste was categorised, weighed and the data was recorded. All the waste considered in this study was collected from the University of Johannesburg (UJ) student centre and the residences within and outside the campus; it was then taken to the recycling station where waste was hand-sorted thrice a week. The canteen food waste consisted of mixed cooked and uncooked food such as pasta, rice, meat, fruit and vegetable peelings. From these, samples were prepared for further tests. Prior to testing, the samples were homogenised using a blender to reduce the particle sizes and achieve proper workability. A small portion of the uniform sample was constantly taken to perform the necessary tests in order to determine the physical and chemical composition of the OFMSW.

B. Waste Characterisation

Waste characterisation is the process by which the composition of different waste was analysed. This includes laboratory tests which helps in determining and understanding the physical and chemical properties of a sample.

The OFMSW samples obtained from the quantification exercises were wrapped in air-tight plastic bags and preserved in a fridge at 4 ˚C. The Total Solids (TS) and Volatile Solids (VS) content were measured according to the standard method 2540 G [10]. The pH was determined using a pH meter (Jenway 3510) calibrated with buffers at pH 4, 7 and 10. Elemental composition (C, H, N, S, and O) of the sample was attained by ultimate analysis using element analyser. The density of the wet feedstock was determined in the field using containers of known volume (250 ml) and the weighing scale. The GC was calibrated using a standard gas containing 35% CO_2 and 65% CH_4.

C. Bio-methane Potential (BMP)

In order to determine the biogas production rates of the OFMSW, 4 bench-scale anaerobic batch digesters were pre-set at operating conditions of temperature, and pH. Literature reports that optimum operating pH range for anaerobic digestion is 7 to 7.5 and the mesophilic temperature range is 20 to 45°C [11], therefore the temperature was constantly set at 35°C in an automatic water bath.

The inoculum was prepared by digesting 50 g of cow dung in a separate set up for 14 days until little or no biogas was produced. The inoculum was passed through a 2 mm sieve to remove any large particles and then incubated at 35°C for a week to allow for any residual carbon source to be depleted prior to feeding with new substrate [12]. The waste water from this set up was then used to inoculate the feedstock.

From the homogenised sample prepared at the waste quantification stage, 150 g were fed into the digesters. Each BMP test was performed under controlled conditions in a 5 L plastic bottle where each bottle was partially filled with inoculum and a substrate with a ratio of 2:1; tap water was added up to 4 litres total volume. The digesters were then immersed in a water bath filled with tap water kept at a constant temperature of 35˚C.

The pH level was neutralised by a solution of 8 g NaOH in 100 ml water which was prepared and fed in the digester at small quantities to increase the pH to 7. Daily volume of the biogas produced was measured by using the downward water displacement in the 2-littre measuring cylinders. The digesters were agitated regularly to ensure uniform mixing of the substrate and to avoid temperature gradients within the digester.

The gas was sampled by extracting it from the digester using a gas syringe and was analysed using Gas Chromatography (GC) instrument. The methane content of the biogas was measured using a GC with flame-ionization and thermal-conductivity detectors. Operating conditions were: oven temperature 70˚C, detector 150˚C and injection port 80˚C. Helium was used as the carrier gas (20 ml/min). The energy content of the daily biogas generation was determined by using the energy value of pure methane of 9.81 kWh/Nm^3 [13].

III. Results and Discussion

A. Waste Quantification

Prior to the waste quantification exercise, the waste was broken down into waste stream categories as showed in Table I. Table I further shows the summary of the results obtained from the waste quantification exercises over the spring season that runs from September to November as well as the autumn from March to May. Figs 1 and 2 give the average composition of the daily generation from general and garden waste respectively.

TABLE I
AVERAGE WASTE GENERATION RATES PER DAY AT UJ DFC

Waste Stream		Spring	Autumn	
		Mean (kg)	Mean (kg)	Combined mean (kg)
General waste	Recyclables	44.292	82.297	63.295
	Paper bags	22.260	3.064	12.662
	Food	134.487	95.603	115.045
	Polystyrene	3.628	6.788	5.208
	Uncategorised	35.782	60.014	47.898
Garden Waste	Compostable garden waste	98.799	133.560	116.179
	None Compostable garden waste	7.803	27.876	17.839
TOTAL				378

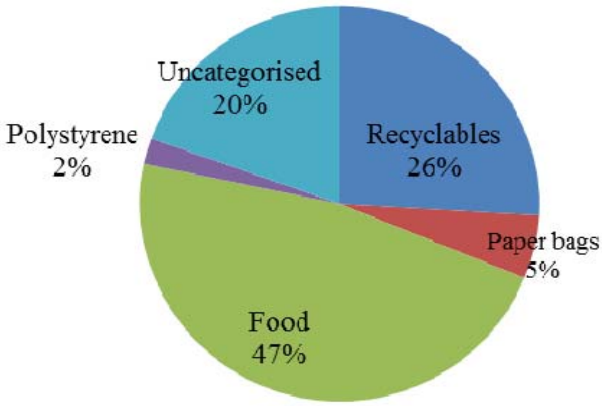

Fig. 1 UJ DFC daily general waste per category

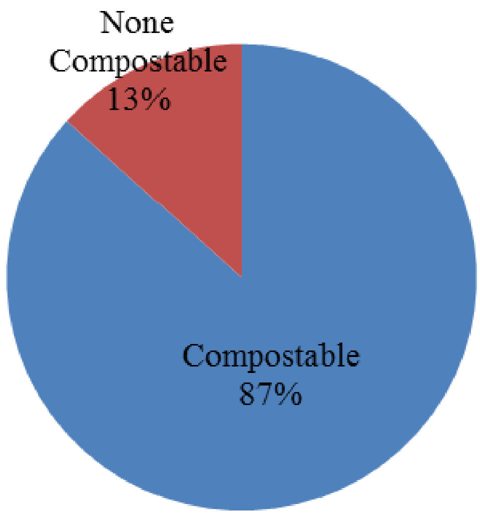

Fig. 2 UJ DFC daily garden waste composition

An approximated 378 kg of MSW was generated daily at the campus of which 231.22 kg (61.2%) was the OFMSW portion made up of food waste and compostable garden waste. Of the total waste generated, 64.6% and 35.4% were the general waste and the garden waste respectively. 47% of the general waste generated was food waste whereas 26%, 5.2% and 2.1% were recyclables, paper bags and polystyrene respectively. The balance of 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 was biodegradable and the balance was non-biodegradable. More garden waste was generated during the autumn season than spring due to leaves dropping from trees during autumn.

B. Waste Characterisation

The average moisture content (MC), volatile solids (VS), fixed solids (FS) and total solids (TS) of the MSW are shown in Table II. The average MC of MSW was found to be 72.86%. Zhu et al., (2010) [3] reported that the average MC of solid waste ranges from 63% to 73%. Substrates with MC of approximately 75%, such as food and yard waste, are suitable for digestion [3]. Also, the wetter the material, the more volume and area it takes up relative to the levels of gas produced [3]. The average TS were determined to be 27.14%, VS 94.89% and FS was 5.11%. These results are in agreement with the studies of Zhu et al, (2010) [3] which reported the averages of MC, VS and VS/TS to be 74%, 23% and 87%, respectively.

It is necessary to maintain proper composition of the feedstock for efficient plant operation so that the C/N ratio in feed remains within desired range [14]. The C/N ratio for MSW was found to be 25:1; this had a significant effect on the pH of the slurry as it was dropping continuously. The increase in carbon content gave rise to more carbon dioxide formation and lower pH value, while high value of nitrogen enhanced production of ammonia gas that increased the pH to the detriment of the micro-organisms [15].

TABLE II
AVERAGE BIOMASS PROPERTIES

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)	94.89%
Fixed Solids (FS) (% of TS)	5.11%
Density	775kg/m^3
C:N ratio	25:1

C. Bio-methane Potential

Cumulative volumetric biogas yields and biogas production rates for the MSW under mesophilic conditions for the 4 digesters are shown in Fig. 3. In all the digesters, after 14 days biogas production became constant. This was due to the minimum amount of solid left in the digesters [9]. Potts and Martins, 2009 [16] reported that the waste must be held in the digester until stabilisation is complete. Also that the retention time of mesophilic digestion is 12-25 days. Fig. 3 shows the individual BMP results for the downward displacement while Fig. 4 shows the average specific yields from the 4 digesters expressed as volume of biogas per unit weight of substrate added. The biogas yield from OFMSW was 0.385 l/gVS which is comparable with the work of Kubaska et al, (2010) [17] which reported a biogas yield of 0.4 l/gVS for OFMSW.

As shown in Fig. 5, the methane production rate was relatively high during the first days of digestion, then slowly reduced. This was due to the fact that OFMSW is rich in fat and hence produces more methane at a faster rate. Gas production started quickly a day after seeding and agitation also played a role in the production of methane [11], by facilitating contact among the microorganisms, the substrate and nutrients and promotes a uniform temperature throughout the process. Maximum methane is achieved as agitation rate was increased, thus indicating the effective influence of the agitation rate on the overall conversion process [18]. Fatty materials are very energy-rich and can produce a lot of gas with a high content of methane [19]. Literature reports that anaerobic decomposition of pure fat produces larger quantities of biogas than both protein and carbohydrate substrates. In theory, fat produces biogas consisting of about 70% CH_4 and 30% CO_2, pure protein gives biogas composition of 60% CH_4 and 40% CO_2, whilst biogas obtained from pure carbohydrate has equal proportions of these gases [11].

From Table II, the feedstock was generated at 231.22 kg per day with TS and VS content values of 27.14% and 94.9% respectively which gives a VS generation rate of 59.6 kg VS per day. Therefore the OFMSW if treated via AD would be capable of producing 23 m^3 of biogas per day.

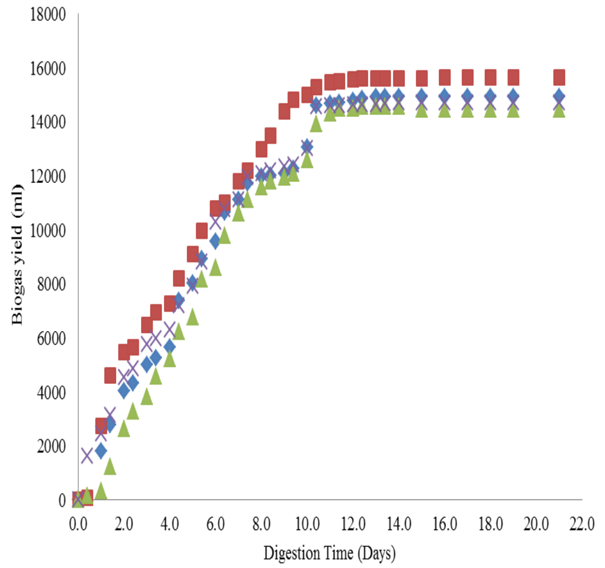

Fig. 3 Plot of biogas yield against time from the anaerobic digestion of OFMSW

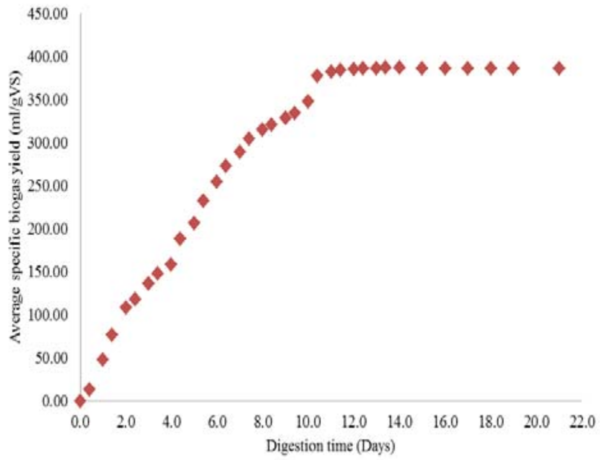

Fig. 4 Average specific biogas yield against digestion time

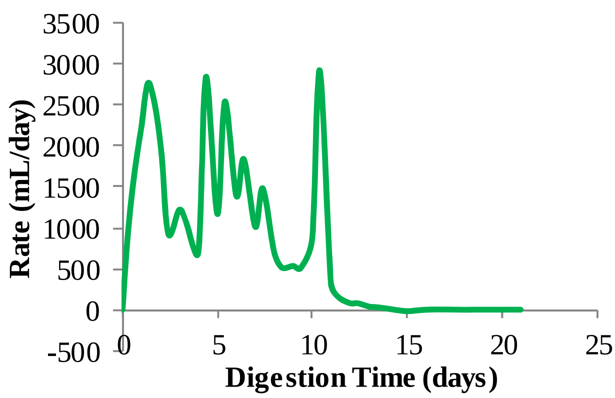

Fig. 5 Biogas rate per day

D. Gas Analysis

Methane and carbon dioxide are the main compositions of the biogas, there are also small amounts of hydrogen sulfide, nitrogen, ammonia, oxygen and hydrogen [20]. Biogas samples were collected periodically and analyzed for CH_4 and CO_2 using GC equipped with a thermal conductivity detector. The biogas composition during digestion of MSW had constant methane content. The methane content started at approximately 52% during the first 3 days and increased to 62% on the 8th day and remained constant throughout the whole period. The average CH_4 and CO_2 contents that were measured are 62% and 38%, respectively. OFMSW is able to produce biogas that has 58-70% methane. The biogas yield from the biowaste varies from 0, 3 to 1, 0 m^3/kg oDM [21] while that of OFMSW is approximately 0.35 m^3/kg oDM [22].

From the analysis using GC, it was observed that the biogas produced contained an average 62% CH_4. Literature reports that a typical normal cubic meter of methane has a calorific value of around 10 kWh, while carbon dioxide has zero [13]. The energy content of biogas is therefore directly related to the methane concentration [23]. In other words, with a biogas composition with 62% methane, then, the energy content would in this case be around 6.2 kWh per normal cubic meter. At 23 m^3 of biogas per day, the waste would therefore be capable of yielding 142.6 kWh worth of energy per day which is significant as it can be locally utilized at the university campus.

IV. CONCLUSION

Anaerobic Digestion of OFMSW can contribute towards organic waste management, climate change mitigation, green energy production and landfill diversion opportunities. Municipal solid waste (MSW) can be used as substrate for biogas production, however few plants utilize this substrate source due to difficulties in removing impurities and smell challenges. Although OFMSW is not uniform in character, it has relatively high stability in the fermentation process. OFMSW are able to produce biogas with high methane concentration.

BMP tests are a powerful tool to assess the methane yield from the digestion of organic solids. However the lack of a standard procedure to carry out these experiments is a challenge in the interpretation of the data limiting the application of such tests. This study evaluated biogas recovery potential of MSW at mesophilic conditions. Mesophilic AD of OFMSW produces a small increase in digester gas methane content from day one of methane production to the 8^{th} day of the tests.

378 kg of municipal solid waste per day of which 231.22 kg was the organic fraction composed of food waste and garden waste are produced at the UJ DFC. The feedstock had an in-situ density of 775 kg/m^3 with a total solids (TS) content of 27.14%, volatile solids (VS) content of 94.9% and C:N ratio was 1:25. BMP tests showed that the feedstock had a biogas generation potential of 386.46 ml/g VS with an average methane content of 62%.

If treated via anaerobic digestion, the OFMSW could produce an estimated 142.6 kWh of energy per day that can be utilized at student center food outlets, heating students' residences during winter resulting in significant reduction of DFC electricity bill. It can be concluded that a digester can be designed and built at the University of Johannesburg's Doornfontein campus UJ DFC for a large scale AD biogas production.

ACKNOWLEDGMENT

The authors are grateful to the interns Constance Maluleka Constance, Reynold Mtizi and Kgotsofatso Mphaphathe for assistance with site field work. Lebogang Mokgatle is acknowledged for her assistance with laboratory analysis. This work was funded by the South African National Energy Development Institute (SANEDI) and the Process Energy and Environmental Technology Station (PEETS) at the University of Johannesburg.

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