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Quantification of Biomethane Potential from Anaerobic Digestion of Food Waste at Vaal University of Technology

Kgomotso Matobole, Pascal Mwenge, Tumisang Seodigeng

***Abstract*—**The global urbanisation and worldwide economic growth have caused a high rate of food waste generation, resulting in environmental pollution. Food waste disposed on landfills decomposes to produce methane (CH_4), a greenhouse gas. Inadequate waste management practices contribute to food waste polluting the environment. Thus effective organic fraction of municipal solid waste (OFMSW) management and treatment are attracting widespread attention in many countries. This problem can be minimised by the employment of anaerobic digestion process, since food waste is rich in organic matter and highly biodegradable, resulting in energy generation and waste volume reduction. The current study investigated the Biomethane Potential (BMP) of the Vaal University of Technology canteen food waste using anaerobic digestion. Tests were performed on canteen food waste, as a substrate, with total solids (TS) of 22%, volatile solids (VS) of 21% and moisture content of 78%. The tests were performed in batch reactors, at a mesophilic temperature of 37 °C, with two different types of inoculum, primary and digested sludge. The resulting CH_4 yields for both food waste with digested sludge and primary sludge were equal, being 357 Nml/g VS. This indicated that food waste form this canteen is rich in organic and highly biodegradable. Hence it can be used as a substrate for the anaerobic digestion process. The food waste with digested sludge and primary sludge both fitted the first order kinetic model with k for primary sludge inoculated food waste being 0.278 day^{-1} with R^2 of 0.98, whereas k for digested sludge inoculated food waste being 0.034 day^{-1}, with R^2 of 0.847.

***Keywords*—**Anaerobic digestion, biogas, biomethane potential, food waste.

I. Introduction

FOOD waste (FW) contains materials which were initially intended for human consumption but ended up being discarded, degraded, or even contaminated. FW has high organic content and is rich in protein, starch, cellulose and fat, and contains about 80% of water on average [1]. Due to global urbanisation, population growth and economic development, FW from institutional (e.g., school canteens), industrial (e.g., food-processing factories) residential and commercial (e.g., restaurants) is being produced at an alarmingly high rate. FW decays easily and frequently food safety complications and environmental pollution commonly arise due to inadequate FW management systems. FW constituted the highest percentage of OFMSW, and when buried in landfills, it decomposes to produce CH_4. CH_4 is a greenhouse gas, and as compared to CO_2, its global warming potential is 25 times higher on a 100-years' timescale. Hence effective OFMSW management and treatment is attracting widespread attention in many countries. The high organic content and high biodegradability of FW make anaerobic digestion process the most attractive method of FW treatment to generate energy and for waste reduction [1]-[3].

During the anaerobic digestion (AD) process, complex organic materials are degraded into simpler compounds in the absence of oxygen. Several microbial consortia are involved in this process where they convert complex macromolecules into low molecular weight compounds. The AD is similar to the process in animals' stomachs, this natural biological process is used and monitored by engineers on industrial scale [4]. In landfills containing organic material, biogas can spontaneously occur, as well as naturally in swamps. Primarily, the constituents of biogas are CH_4 and carbon dioxide (CO_2) with variable amounts of hydrogen sulphide (H_2S), oxygen and water [2].

There are four biochemical steps in the AD process. The first step is called hydrolysis -hydrolytic bacteria remove polymers to monomers. This step depends on temperature, pH, initial composition of the feedstock and concentrations and compositions of the intermediate compounds. The second step is called acidogenesis - acidogenic bacteria convert hydrolysis products into a carboxylic acid, CO_2, hydrogen and alcohol. The third step is called acetogenesis, in which the acidogenesis products are converted into acetic acid, hydrogen and CO_2. Finally, the last step is called methanogenesis where bacteria called methanogens break down the acetic acid to produce CH_4 [5]- [8].

The main products of AD are biogas and the digestate. Biogas is composed of 55-70% CH_4 and 30-45% CO_2. A process of biogas upgrading is used to extract purified CH_4 from the biogas. The resulting gas is called biomethane which has similar uses as natural gas. Biomethane contains more than 97% CH_4 and can be compressed into gas cylinders or be used for the generation of electricity, heat production and transportation whereas the digestate can be processed further to manufacture organic fertiliser since it comprises of rich macro and micronutrients which do not have any detrimental effects on the environment [9]-[11]. Lastly, CO_2 can be isolated from biogas by a membrane or cryogenic distillation for the production commercial grade CO_2.

The use of AD for the production of biogas assists in the

K. Matobole is with the Vaal University of Technology, Andries Potgieter boulevard, Vanderbijlpark, South Africa (e-mail: kmatobole@gmail.com).

P. Mwenge and T. Seodigeng are with the Vaal University of Technology, Andries Potgieter boulevard, Vanderbijlpark, South Africa, (phone: +27 16 950 9655; e-mail: pascalmwenge@gmail.com, tumisangs@vut.ac.za).

reduction of our dependency on fossil fuels for energy generation since CH_4 can be used in the generation of renewable energy. This also positively affects the communities by making them more sustainable. AD projects provide a highly sustainable material management system reducing waste food disposed at the landfills. Finally, this process may also produce products that may be used as soil fertilisers or conditioners [12]. One of the distinct advantages of a biogas plant is its ability to be located anywhere, in the vicinity of the available waste feedstock.

FW composition varies depending on the location, cultural habits, season of the year, eating habits, etc. In order to be able to design the most efficient anaerobic digestion system, it is crucial to know the composition of the FW. FW is mostly disposed in dumping sites and causes a foul smell because its degradation is rather rapid. Generally FW contains about 80-90% of VS and moisture of 75-95%. The foul smell and great amount of leachates generated during waste collection, transportation and dumping are mainly caused by the high moisture and organic content of the waste. Due to these contents, AD can be employed to efficiently treat such a waste [13]..

Vaal University of Technology's canteen caters for all its students on campus and produces a significant quantity of FW. This is a concern since the FW collection site is only a few meters away from the kitchen, where food can be easily contaminated. This waste collection site is also highly untidy, hence the process of AD can be utilised to solve solid waste management problems. Furthermore FW can become valuable resource for renewable energy, and portable industrialised biogas unit can be designed and installed onsite. Although AD is a process known for many decades, it is still not fully understood due to the involvement of complex of bio-reactions. Hence this study aimed at quantifying the BMP of FW generated at VUT's canteen.

II. Materials and Methods

A. Sample Collection

FW utilised for the experimental studies was collected from Vaal University of Technology's canteen. The university's residences are all self-catering units. Therefore, the canteen caters for almost all the students on campus with their food. This results in high quantities of FW being generated on a daily basis. Generated FW comprised of scraps generated while food is being prepared in the kitchen, consumer's leftovers and unserved food. The FW was composition of vegetable peelings, cooked and uncooked rice, samp, pasta, pap, red meat and chicken.

B. Sample Preparation

To get a good representation of the food sample, a large quantity of FW sample was taken and then sorted to eliminate unwanted materials such as bones, cutlery, toothpicks, plastics and paper towels. The particle size of FW was reduced by firstly manually chopping bigger pieces. To ensure that the particle size is adequately reduced, an electrical blender was used as a grinder. This was a form of physical pre-treatments, which ensures that the feed to the bioreactor is of homogeneous nature. The homogenised FW was then stored into labelled plastic bags and refrigerated at 20 °C for subsequent experiments.

C. Preparation of Inoculum

Primary sludge and digested sludge were used as an inoculum in the experiments and were collected from a Waste Water Treatment Plant in Gauteng.

D. Analytical Methods

The laboratories in the Department of Chemical Engineering, Applied Chemistry and Process, Energy and Environmental Technology Station (PEETS) at University of Johannesburg were used for waste characterisation as well as analysis of biogas. The organic substrate characteristics are vital in the AD process. The samples were stored in the fridge at a temperature of 4 °C to stop further degradation. The proximate analysis included the moisture content and TS at a temperature of 105 °C using the oven. This was followed by the VS from the same sample at a temperature of 550 °C using the furnace [9]. All analytical determinations were conducted by Standard Methods of examination of water and wastewater as prescribed by [14]. Equations (1)-(3) were used to calculate TS, VS and MC, (4) was used to calculate the C/N ratio [15]-[16].

$$VS(\%) = \frac{M_{dried} - M_{burned}}{M_{wet}} * 100 \quad (1)$$

$$TS(\%) = \frac{M_{dried}}{M_{wet}} * 100 \quad (2)$$

$$MC(\%) = \frac{M_{wet} - M_{dried}}{M_{dried}} \times 100 \quad (3)$$

where MC = moisture content; M_{dried} = dried sample amount (mg); M_{burned} = burned sample amount (mg); M_{wet} = wet sample amount (mg).

$$\frac{C}{N} = \frac{(F \times C_f) + (S \times C_S)}{(F \times N_f) + (S \times N_S)} \quad (4)$$

where F = first substrate; S = second substrate; C_f = first substrate's carbon composition; C_s = second substrate's carbon composition; N_f = first substrate's nitrogen composition; N_s = second substrate's nitrogen composition.

E. CH4 Production Assays

BMP tests use a simple approach, where an anaerobic inoculum is mixed with a substrate of organic nature within specified operating conditions. The quantity of the bio-methane produced in the process is measured by a specified method. This test provides the maximum quantity of CH_4 produced per gram of VS; this is the indication of anaerobic

degradation potential [17]. Automatic CH_4 potential test system (AMPTS II), Fig. 1 (Bioprocess Control, Sweden, Ab) was used to conduct CH_4 tests.

The production rate of biogas was determined by using 500 ml batch bioreactors. Before starting the experiments, to make the environment conducive for AD, N_2 gas was flushed into the reactors to expel the oxygen. To maintain a constant mesophilic temperature for the experiment, hot water bath incubation unit was maintained at 37 °C. Gases, such as H_2S and CO_2, were trapped by the CO_2-fixing unit which uses hydroxides to absorb these gases. Alkaline solution is used to clean the biogas [18]. In order to ensure proper contact between nutrients and microbes, the BMP set-up was agitated on the 1 min on/off basis. The resulting bio-methane was measured by the gas volume measuring device, which measures the bio-methane via liquid displacement method. The results were recorded by an integrated data acquisition system. BMP tests were done in duplication.

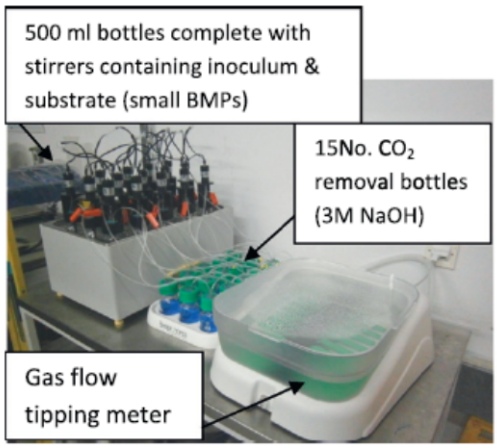

Fig. 1 Automatic CH_4 potential test system (AMPTSII)[19]

III. Results

A. Substrates Characterization

From Table I, the moisture content of the substrate was 78% which is an indication that the substrate contained enough moisture for the process of AD. Reference [20], reported % MC of 74%, which is comparable to the one used in this work. The substrate's TS was 22%, which is in the range of the TS for FW used in [21] which was between 15-30%. This indicated that the substrate was rich in organic matter which would be later biodegraded into biogas and hence FW is a desirable substrate for anaerobic digesters, as highlighted by [20].

TABLE I
Substrate Characterization Results

Substrate	% TS	% VS	% MC
FW	22.013	21.433	77.867
Primary sludge	3.339	4.480	96.661
Digested sludge	7.381	5.04	92.619
Cellulose	92.22	96.167	7.67

B. BMP Production Curves

During BMP assay, the resulting biogas production curves can produce different patterns, which have significant implications. The biogas production curve's shape and the kinetics of different steps involved in AD are primarily regulated by characteristics of the substrate's biodegradability as well as the production of inhibitory intermediates products [22].

In Fig. 2, the highest CH_4 yield is found to be 357 Nml/g VS, which was achieved with the use of digested sludge as an inoculum. This value is lower than the one reported by [20], which is 472 ml CH_4/g VS. Cho et al. [21] carried out BMP tests on Korean food with the TS of 15-30% and mesophilic temperature of 37 °C. The yield obtained in this study is however close to the yield reported by [19], 348 mL/gVS at the retention time of 10 days. At a retention time of 28 days and 50 °C [19] reported a yield of 435 mL/g VS. Dried substrate samples were fed to two different reactor sizes of 0.5 and 5 litres; this was also done for wet substrate samples. The resulting specific CH_4 yield for FW was between 467, and 529 L CH_4/kg VS added, respectively. These high results were due to acclimatised inoculum as well as the moisture within the wet samples of FW. Both these values are higher than the ones resulting from this experiment.

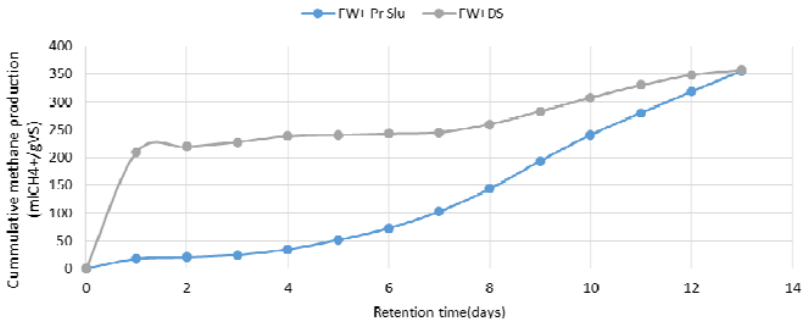

Fig. 2 Cumulative CH_4 production of FW with primary and digested sludge as an inoculum

It can also be seen that the digestion of primary sludge digestion and FW experienced a lag phase. This might be due

to the properties of the microbial community. However, ultimately both primary and digested sludge produced the same amount of CH_4, thus there might be difference in their kinetics.

Fig. 3 shows peaks during the production of CH_4; digested sludge shows the rapid CH_4 production which may be due to the availability of readily biodegradable organic matter within the substrate. Primary sludge is the deposit formed during mechanical treatment in wastewater treatment facility. The primary sludge is collected from the bottom of the primary clarifiers and contains much foreign material which may not be readily digested hence it is initially outperformed by the digested sludge, which results in further treatment of the sludge and might contain readily biodegradable materials.

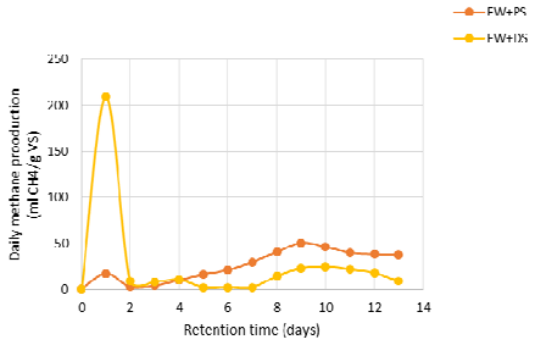

Fig. 3 Daily CH_4 production with two types of inoculum

C. Batch Kinetic Study

The first order model can be used to predict the hydrolysis constants

$$B = B_0\{1 - \exp(-kt)\} \tag{5}$$

where B_o= Ultimate CH_4 yield (mL/g VS); B= Cumulative CH_4 production at digestion time t (mL/g VS); k_1 = hydrolysis rate constant (day^{-1}); t = time in days.

Equation (5) is the description of the exponential profile of substrate growth [2]. When rearranged and taking natural logarithms, it leads to:

$$\ln\left(\frac{B}{B_0}\right) = -k_1 t \tag{6}$$

Equation (6) is the first order reaction kinetics which will be used for verification of process kinetics. A plot of $-\ln\left(\frac{B}{B_0}\right)$ versus time provides a straight line. If the process produces a straight line with appropriate regression constant coefficient is said to have followed a first order kinetic model. The slope of the straight line gives the 1st order activation constant (day^{-1})

For this experiment, the first order activation constant, *k* was found to be 0.2779 day^{-1} with R^2 to be 0.983 for the primary sludge inoculated FW whereas for digested sludge inoculated FW *k* was found to be 0.037 day^{-1} and R^2 to be 0.847. Even though primary and digested sludge inoculated FW experiments both resulted in the equal amounts of CH_4 yields, their first order kinetic constants are not similar. This shows that the characteristics of both their composition are totally different, hence the difference in kinetics.

IV. Conclusion

It is concluded that initial and digested sludge inoculated for FW experiments both resulted in the equal amounts of CH_4 yields and both fitted first-order kinetic model. It is recommended that further kinetic studies be performed on the results of this work in order to determine advanced kinetics modes.

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