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Design and Development of Food Waste to Biogas Converter System

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The valorisation of food waste via anaerobic digestion has shown to be a promising option for tackling waste accumulation and achieve energy security. In this study, a lab scale and a pilot scale anaerobic digester, with food waste as the feedstock and palm oil mill effluent (POME) as the microbial inoculant, were evaluated for their biogas production. For the lab scale study, the effect of different food waste to POME ratio, ranging from 1:1, 1:2 and 2:1, on the biogas production were investigated for a period of 7 d. From the experimental work, the ratio of food waste to POME at 2:1 gave the highest biogas yield of 0.14 L. For the pilot scale study, a digester was designed based on a daily electricity demand of 9.5 kW of an eco-park. With the use of the Pro Engineer Software, it is estimated that a digester with a volume of 4.27 m^3, handling capacity of 200 L of food waste daily, and a hydraulic retention time of 15 d, can generate sufficient biogas to meet the electricity demand for the eco-park.

1. Introduction

The increasing in urbanisation and population growth has led to the concern of waste accumulation globally. In Malaysia, food waste accounts for 55 % of the waste disposed to the landfill, with a daily food waste production of 16.888 t (Sharif, 2018). The organic fraction of municipal solid waste (OFMSW) is usually disposed through landfill in many countries, leading to several environmental problems, such as the release of greenhouse gas (GHG), groundwater pollution and land contamination (Nghiem et al., 2017). In addition, Malaysia produces a significant amount of wastewater from the oil palm industry, known as the palm oil mill effluent (POME). POME is a high strength wastewater with chemical oxygen demand (COD) of 15,000-100,000 mg/L that can cause severe water pollution if not properly treated (Khadaroo et al., 2020). POME is commonly treated with open ponding system, which is inefficient due to ineffective residual oil removal and high GHG emission (Mansor et al., 2017). The use of alternative technology to valorise such organic wastes for delinearising the current waste scenario is of high interest.

Anaerobic digestion (AD) is the biological degradation of organic waste under the absence of oxygen by microorganisms which produces energy-rich biogas and nutrient-rich digestate. The anaerobic digestion is characterised by four distinct phases, which can be in sequential and parallel (Pontoni et al., 2015), namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is the first process that occurs in AD. Organic substrates are hydrolysed by fermentative bacteria to produce a mixture of organic acids, H_2 and CO_2. Next, small molecular materials and soluble organic substrates are degraded into volatile fatty acids (VFA) along with the generation of by-products during acidogenesis. Then, hydrogen-producing acetogenic bacteria convert the VFA into acetate, H_2, and CO_2. In the last stage, methanogenesis can occur by two different pathways, namely hydrogenotrophic methanogenesis that utilise H_2 and CO_2 to produce CH_4, and the acetotrophic methanogenesis that utilises acetate to produce CH_4 and CO_2 (Li et al., 2018).

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AD has been used for treating a wide spectrum of feedstock, including food waste (Zhang et al., 2020), food waste with chicken manure (Chuenchart et al., 2020), food waste with garden waste (Perin et al., 2020), POME (Khadaroo et al., 2020) and animal manure (Flores-Orozco et al., 2020). Due to the high biodegradability of food waste, process inhibition due to acidification associated with the rapid organic matter degradation is a major limiting factor for large scale AD. Co-digestion, the selection of microbial inoculant and the ratio of food to microbial loading (F/M) ratio are critical determinants for a stable and efficient AD process (Bong et al., 2017).

In this study, anaerobically treated POME is chosen as the microbial inoculant for the AD of food waste. The main objective of the lab work is to determine the biogas potential and the optimum condition for maximum biogas and CH_4 production. The obtained experimental data and secondary data are then used in a stimulation software for the design of a pilot-scale digester. The main objective for the work is to determine the size of digester and the quantity of feedstock needed to achieve a target of electricity demand of 9.5 kW of an eco-park located in Universiti Teknologi Malaysia. The execution of such waste characterisation study on a specific area can ensure a consistent supply of waste to the AD in order to generate a certain level of electricity. This will help to improve recycling programs and conduct managing plan to reduce waste and eventually, to conserve money and resources.

2. Materials and Methods

2.1 **Experimental setup for lab-scale AD**

Fruit and vegetable waste (FVW) a local wet market had been collected as feedstock in this experiment. The feedstock was prepared by mixing and blending the FVW consisting of orange, banana, honeydew, chili pepper, cabbage, starfruit, mustard green, carrot and mustard green to obtain homogenous sample. Then, the homogenous FW was frozen and stored in freezer at -10 °C before used as feed material. The inoculum that was used in this experiment was anaerobic digester outlet palm oil mill effluent (POME) which was taken from Kim Loong Palm Oil Sdn. Bhd., Kota Tinggi, Johor. POME was specifically chosen from the anaerobic digester outlet, which had high biogas content, indicating a rich and abundance culture of methanogenic microbial community. The obtained POME was fed with brown sugar to maintain their activity prior to the experiment.

The anaerobic digestion in lab scale was carried out with total working volume of 90 mL and 60 mL at room temperature for 7 d. The three samples with different FVW to POME ratios of 1:1, 1:2 and 2:1 was prepared according to Table 1. The daily production of biogas was determined by water displacement method as shown in Figure 1.

Table 1: Sample preparation for the lab-scale AD

Sample	Ratio of Feed to Microbial loading (volume basis)	FVW (mL)	POME (mL)
S1	FVW : POME = 1:1	30	30
S2	FVW : POME = 2:1	60	30
S3	FVW : POME = 1: 1	30	60

Figure 1: Experimental setup for lab-scale AD

The analysis of pH, total solids (TS) content and chemical oxygen demand (COD) of each sample were determined before and after the experiment according to the standard methods of APHA (1998). Oven was used at the temperature of 105 °C to determine the TS while COD reagent was used to determine the COD of each sample.

2.2 Design of pilot-scale AD

The scaling up of the pilot-scale AD was designed by using the Pro Engineer Software. The design was constructed based on the electricity demand of the Eco Park located in UTM, which is 9.5 kWh daily. The calculation of the electricity demand is shown in Table 2.

Table 2: Electricity demand at Eco Park UTM

Site	Equipment	Number of units	Operation time (h/d)	Power needed (kWh/d)
Fertigation	2 kW pump	1	1	2.00
Aquaponic	30 W pump	3	24	2.16
Biogas	1.5 kW grinder	1	1	1.50
Others	40 W lamp	8	12	3.84
Total				9.50

Since the range of CH_4 composition in biogas was in range of 40 – 65 %, the lowest CH_4 composition was chosen in determining the amount of biogas needed to generate 9.5 kWh/d. The average volatile solid (VS) in FVW is in the range of 5 – 13 % on a wet weight basis. The value of the VS content in the FVW collected from Pasar Taman Universiti was chosen to be 10.13 %. Then, the amount of daily feedstock is determined based on the volatile solid required for the process as shown in Figure 2.

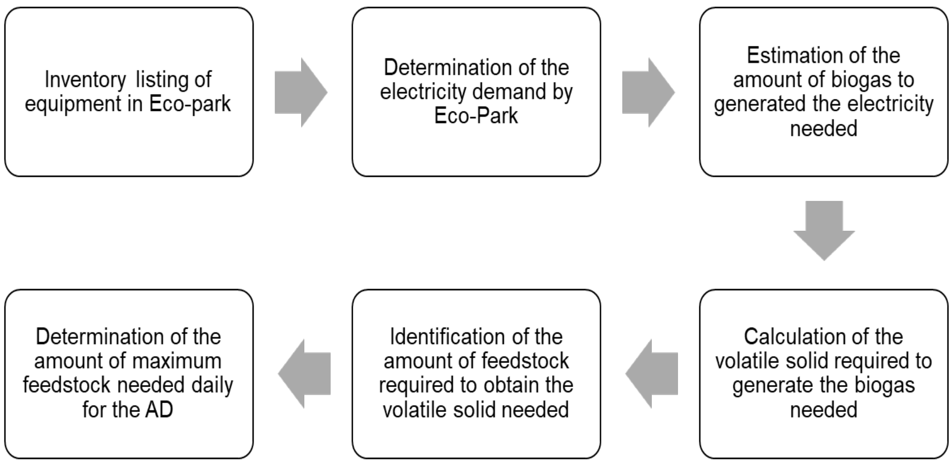

Figure 2: Process flow in designing the pilot-scale AD for Eco-park UTM

Once the daily amount of the feedstock needed to meet the electricity demand in the Eco park was determined, the total volume of the reactor (V) is calculated based on Eq(1):

$$V_{reactor} = \frac{4}{3}\,(HRT \times amount\ of\ daily\ feedstock) \quad (1)$$

3. Results and Discussions

3.1 Biogas production from lab-scale AD

The use of FVW as feedstock and POME as the microbial inoculant for AD and the effect of their respective ratio were evaluated by the quality of biogas produced and the reduction of COD and TS. The biogas production for the three samples were recorded daily as shown in Figure 3. The COD and TS were measured for the initial and final values for the calculation of the removal efficiency as shown in Figure 4.

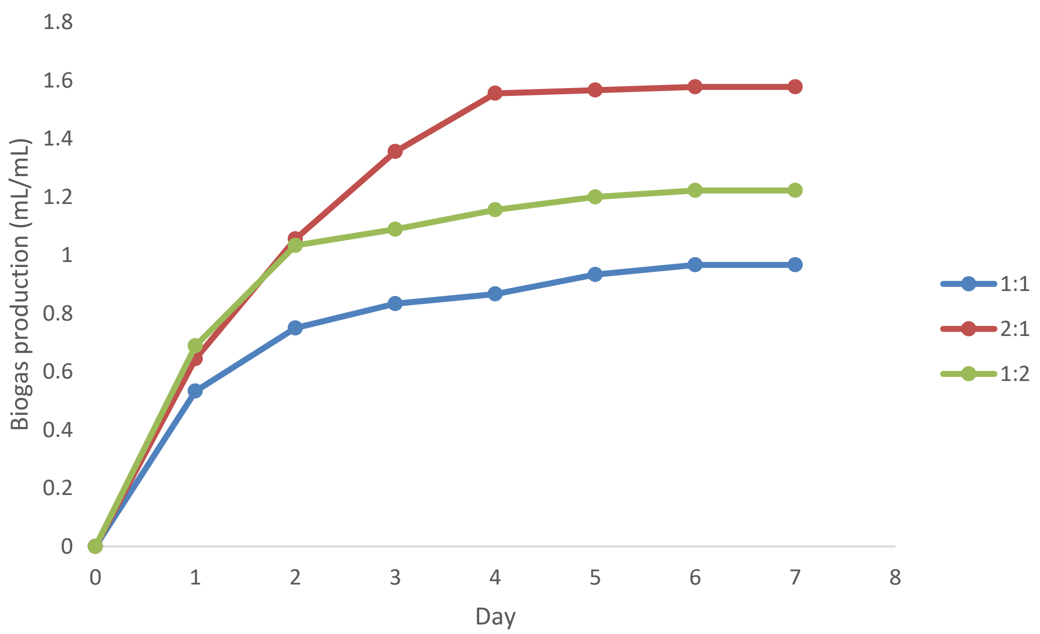

Figure 3: Daily biogas production(mL of biogas/mL of feed) for three samples with different ratios of FVW and POME

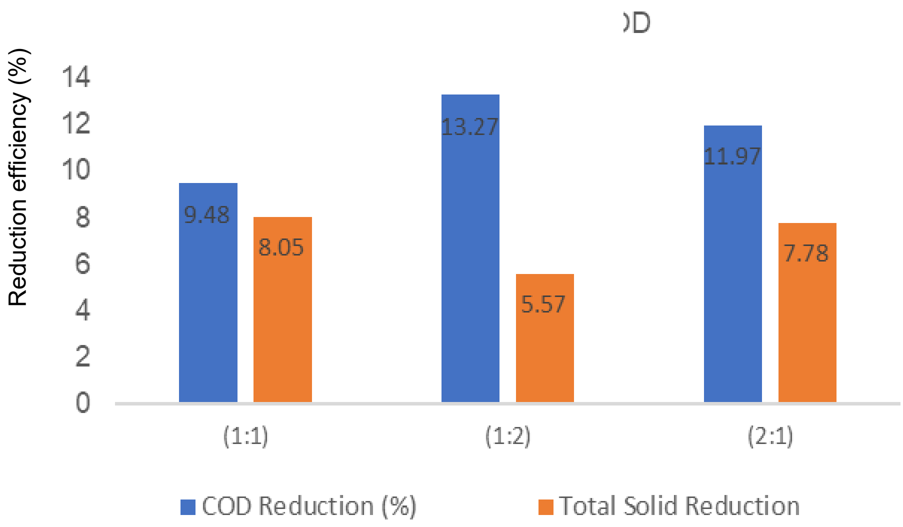

Figure 4: COD and TS reduction efficiency for three samples with different ratios of FVW and POME

Figure 3 recorded the daily biogas production of each sample in 7 d. The initial biogas production for each sample was high during first two days and the biogas production started to become slower on the third day onwards. The rapid increment of the biogas production indicated a successful initiation of the AD process and no significant lag phase was observed. Food waste is rich in labile organic matter such as carbohydrates, protein and lipid with higher degradation constant of 0.005-2.0/d and lignocellulosic biomass had a lower degradation constant of 0.009-0.094/d (Vavilin et al., 2008).

The highest production of biogas was recorded when a ratio of FVW:POME of 2:1 was used. A higher loading of microbial inoculant could lead to a fast depletion of available organic matter that hindered the continual growth of the microbial biomass. Higher microbial inoculant loading with F/M of 0.5 allows a rapid start-up of the process but is prone to acidification from fast degradation of organic matter (Hidalgo et al., 2018). Nevertheless, lower microbial inoculant loading with F/M 1-2 is less susceptible to acidification but can exhibit

lower biogas production due to insufficient microorganisms (Pellera and Gidarakos, 2016). In this context, a ratio of FVW and POME of 2:1 was the optimum ratio.
Based on the result from Figure 4, it was found that the COD reduction efficiency was in the range of 9.48 - 13.27 % for all three samples. The digestion of FVW and POME with a ratio of 1:2 gave the highest COD reduction efficiency, which was 13.27 %. The lowest COD reduction efficiency was achieved with the ratio of 1:1, which was at 9.48 %. For TS, the reduction efficiency was observed to be in the range from 5.57-8.05 %. The highest TS reduction was achieved at 8.05 % when the AD of FW and POME was performed at a ratio of 1:1. The lowest TS reduction was achieved at 5.57 % when the ratio of 1:2 for FVW and POME was used.

3.2 Development of pilot-scale AD from stimulation software

The volume of the pilot-scale digester was determined by calculating the amount of electricity to be generated after the consideration of heat loss and process efficiency. The conversion efficiency of energy to electricity was set at 35 %. A total of 27.143 kWh must be generated daily from the gas engine in order to achieve the electricity demand. This amount of electricity can be generated with 7.436 m^3 of biogas with 40 % CH_4 content. Biogas must be generated more than the requirement since the process was not 100 % efficient. By assuming the process is only 90 % efficient, 8.263 m^3 of biogas with 40 % CH_4 is needed to satisfy the electricity demand. Based on the experimental analysis, the FVW collected from the local wet market contains 10.13 % volatile solid (VS) on a wet weight basis. It was estimated that an amount of 25.04 kg VS must be fed daily into the AD. This is equivalent to a quantity of food waste of approximately 200 L. Based on a hydraulic retention time (HRT) of 15 d, the minimum capacity of the AD is estimated to be 4 m^3 in in order to generate sufficient amount of electricity. Figure below shows the design of the pilot-scale AD by using the Pro Engineer software.

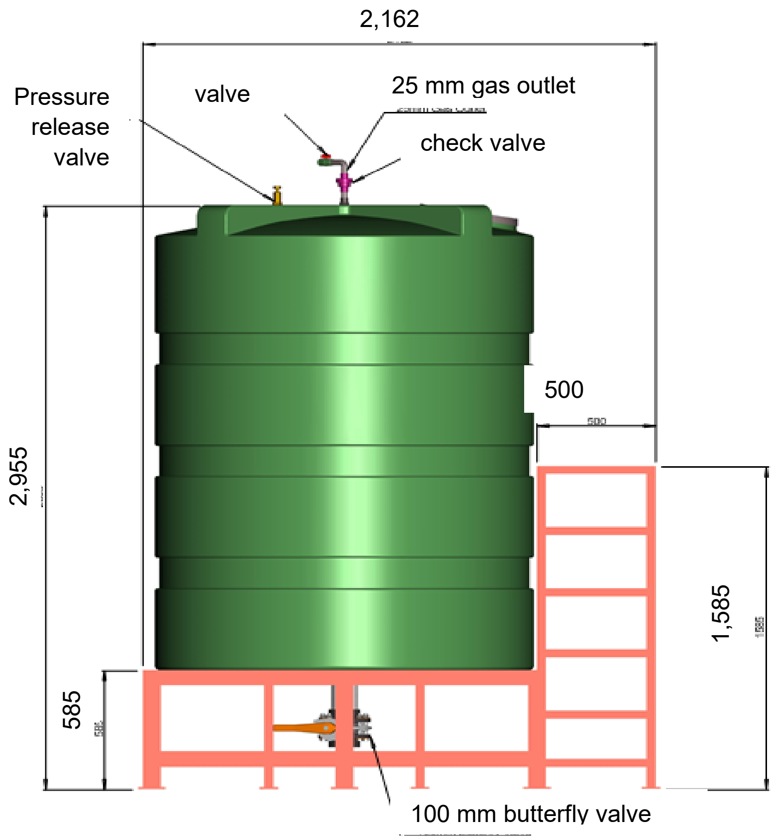

Figure 5: The design of the pilot-scale AD for Eco-park UTM

4. Conclusions

In this study, the optimum ratio of food waste to POME was investigated using three ratios. In terms of biogas production, the optimum food waste to POME ratio was 2:1. For COD reduction efficiency, the highest achieved was 13.27 % when a food waste to POME ratio of 1:2 was used. Over a digestion course of 7 d, the total biogas yield was 0.04 – 0.14 L, corresponding to a maximum daily biogas yield of 0.02 L/d. The electricity demand of Eco-park was estimated to be 9.5 kW/d. The capacity of the pilot-scale AD to satisfy the estimated electricity demand was calculated to be at least 4 m^3. On such basis, the amount of food waste to be supplied from the nearby local wet market is estimated to be 200 L/d. This study provides a preliminary insight into the potential use of food waste and POME to produce biogas that can be scaled up to secure on-site electricity supply. The main limitation of the work is the short digestion period where the organic matter might not be fully degraded and lead to an underestimation of the biogas production potential. For future work, the AD of food waste and POME using reactor with higher working volume and longer digestion time, as well as the possible inhibition from the accumulation of acids and NH_3 at high loadings, are considered to provide more accurate information for the design of pilot-scale digester and logistic design.

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