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OPTIMUM ORGANIC LOADING RATES (OLR) FOR FOOD WASTE ANAEROBIC DIGESTION: STUDY CASE UNIVERSITAS INDONESIA

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ABSTRACT

Indonesia currently has a waste generation problem arising from the fact that sixty percent of the waste it produces is organic waste (OW). The scope for anaerobic digestion (AD) of OW has not yet been optimized, with many reactors not functioning properly. The purpose of this study is to determine the suitability of food waste with an organic loading rate (OLR) of 8–14 kgVS/m^{3}day to produce the highest volatile solids destruction (VSD) and methane. A semi-continuous pilot-scale dry AD of 0.5 m^3 was run for 134 days in mesophilic conditions. The results showed that the feedstock was suitable for dry AD due to the high total solids (TS) (23.2–27.1%) and organic content (volatile solids of 90–95% TS). Meanwhile, the optimum OLR was 10 kgVS/m^{3}day with a VSD of 92.2% and a methane yield of 127 LCH$_4$/grVSday. In addition, OLR 10 kgVS/m^{3}day had the highest stability, as shown by the pH value of 6.52 and ammonia concentration of 848 mg/l. The VSD values fell with respect to the OLRs of 12 kgVS/m^{3}day and OLR 14 kgVS/m^{3}day, to 90.42% and 86.73%, respectively.

Keywords: Biogas; Inhibitor; Municipal waste; Renewable energy

1. INTRODUCTION

The amount of municipal solid waste (MSW) generated in Indonesia is approximately 175,000 tons/day, where 60–74% is organic waste (OW). OW is generally generated by domestic, commercial, and institutional premises (Dong et al., 2010). The incorrect treatment of OW can lead to serious cases of environmental contamination, including *Escherichia coli* outbreaks and contaminated ground and surface water. Having organic solids that account for 61% of the waste, a moisture content of 78%, and volatile solids (VS) of 81% TS (Wang et al., 2014) means there is potential for treatment by anaerobic digestion (AD). Based on ecosystem sustainability, AD is the most efficient method of OW treatment. AD offers the ability to reduce a high quantity of OW in a small area and is a relatively faster method than composting. Additionally, AD is considered a source of renewable energy due to the production of methane, which can be utilized as biogas, and it is suitable for sustainable social-economic development (Tetteh et al., 2018). It comprises the four stages of hydrolysis, acetogenesis, acidogenesis, and methanogenesis.

Indonesia has very little experience in the field of AD for MSW. From a previous survey, the very few facilities that are in operation mostly do not produce methane (Priadi et al., 2015). One of the indicators of AD processing is based on the efficiency with which organic matter is decomposed, which is usually measured by volatile solids destruction (VSD). Generally, a higher VSD value indicates higher production of methane as biogas (Nagao et al., 2012). However, VSD

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has an upper limit, where methane production declines due to the value of VSD exceeds the limit. The decline happens due to inhibitor accumulation caused instability of AD. Fluctuating feedstock and low COD in recirculated leachate may also result in very low biological activity and then lead to low biogas production. These conditions can be overcome by operating AD with the optimum organic loading rate (OLR). Thus, to improve AD performance, the OLR should be adjusted according to the MSW specific to Indonesia so that the waste degradation process can be streamlined and made more efficient.

OLR represents the daily quantity of OW used as feedstock in a continuous system. The optimum value indicates the total nutrients needed for microorganism growth and metabolism (Dong et al., 2015). Excess OLR can induce accumulation of volatile fatty acids (VFA), shock loading on the reactor, and a low pH (Lin et al., 2011; Dai et al., 2013). A low OLR, however, can lead to the microorganisms lacking the required nutrients, unstable growth, death, and the production of inhibitors to generation such as ammonia (Dai et al., 2013; Dong et al., 2015). The value of OLR depends on the type of AD reactor, such as a one- or two-stage and a wet or dry AD. The OLR in wet AD using household OW has been found to either vary within the range of 2–10 kgVS/m^{3}day (Aslanzadeh et al., 2014) or to be below 7 kgVS/m^{3}day (Kothari et al., 2014). Meanwhile, dry AD has a higher OLR than wet AD, with a range of 7–15 kgVS/m^{3}day (Fagbohungbe et al., 2015) or 12–15 kgVS/m^{3}day (Kothari et al., 2014). Dry AD has the ability to attain a higher OLR and process a greater volume of OW by up to > 60% (Mattheeuws & Baere, 2011). There are several advantages of implementing dry AD, such as the small volume, thus making it suitable for hydrophobic substrate (Fagbohungbe et al., 2015), VSD at 40–75%, low hydraulic retention time (HRT), high and consistent biogas production (Kothari et al., 2014), and good tolerance to shock loading. Nevertheless, the optimum OLR for dry AD is needed in order to produce a good level of VSD and methane, specifically in the context of using OW in Indonesia. Accordingly, this study aims to determine the optimum OLR needed to produce VSD using a semi-continuous pilot-scale dry AD.

2. MATERIALS AND METHODS

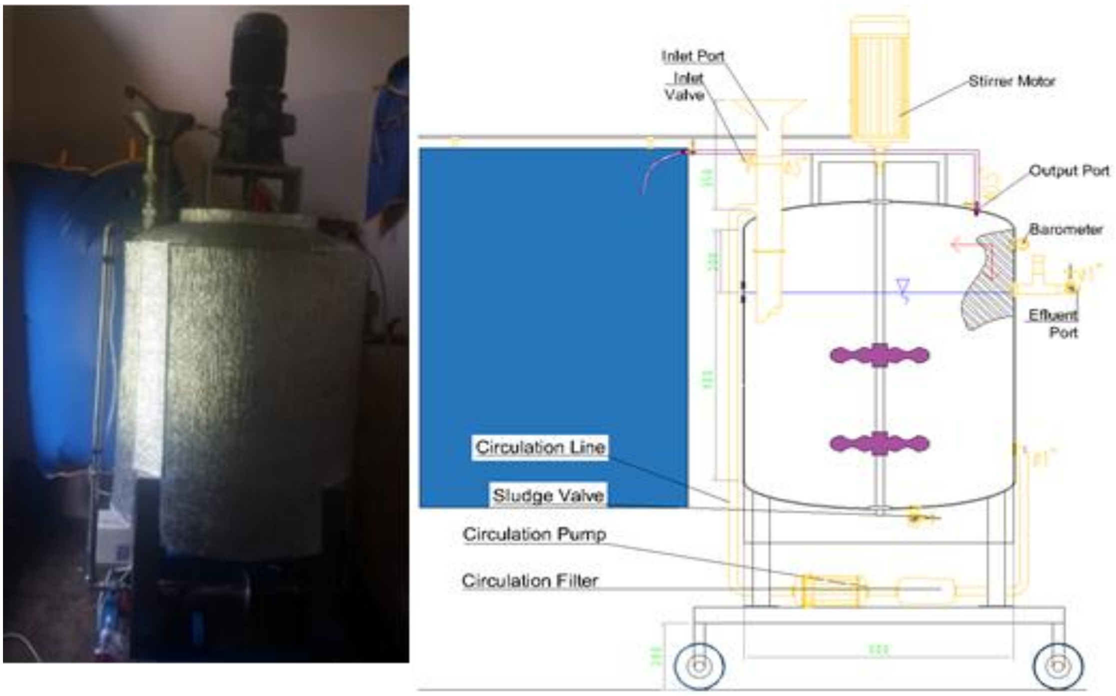
2.1. Experimental Set-Up

The main substrate (i.e., OW) was collected from the canteen of Universitas Indonesia in Depok, Indonesia. It consisted of food residues, rice, noodles, fish, vegetables, fruits, crop residues, etc. The inert materials in the OW were manually separated (e.g., plastics, papers and cardboards, metals, shells, bones, and inorganic matter) to avoid any obstruction during the process. Then, the OW was mechanically shredded into 3–5 mm-sized particles. Particle size is likely to have an influence by facilitating the process of waste degradation, hydrolysis, and acidification, as well as increasing the contact surface area between the microorganisms and the waste as feedstock (Basaria & Priadi, 2016; Wijayanti et al., 2018). The chopped feedstock was stored in a freezer at -25^{o}C to avoid its degradation for subsequent use and was then liquefied at room temperature prior to usage. Most of the OW from food waste has low carbon-to-nitrogen (C/N) ratio. So, the co-digester used, such as cow manure (CM), was added to enhance C/N ratio by up to 20–30. The combination of OW and CM can result higher methane production rather than only use OW as the substrate.

The pilot-scale reactor comprised a continuous stirred tank reactor (CSTR) in order to improve the efficiency of the contact between the microorganisms and feedstock. The reactor was entirely made up of stainless steel with a volume of 500 L, comprising of substrate volume of 400 L and headspace volume of 100 L (Figure 1) (Zeshan, 2012). The height-to-diameter ratio of the reactor was 0.60–1.00, which was set based on Jain et al. (2015). Stainless steel was chosen due to its resistance to high pressure, corrosion, low leakage rate, and aggressive substances such as

H_2S, ammonia, acid, and microbes. Influent channel was made of PVC pipe with diameter of 3”. The biogas generated was collected in PVC gas bag with the capacity of 0.85 m^3.

As the feedstock in AD must be homogeneous, the reactor was equipped with mechanical stirring, where the rotation speed was set at 30 rpm intermittently for 4 hours per day (2 hours each for before and after the substrate addition). The temperature inside the system was maintained passively at the mesophilic condition of 25–45^{o}C, by an insulator jacket surrounding the reactor. The temperature must be specifically in mesophilic condition to maintain the stability and consistency of the operational reactor with the most optimum metabolism rate and growth of microorganisms to produce methane. This was also intended to suppress the inhibitor in the form of ammonia, to prevent pathogen, and to minimize energy consumption. Temperature must be strictly controlled as it can affect the biogas production. The experiment itself was carried out for 134 days.



(a) (b)

Figure 1 The pilot-scale dry anaerobic digestion: (a) actual photo; (b) simplified drawing

Before daily feeding with a mixture of OW and inoculum 1:2 (w:w) was firstly used as acclimatization process. The inoculum was obtained from an effluent of AD plant at Kopro Grogol Petamburan Market, Jakarta, Indonesia. After the mixture was added to the reactor, degasifying process was performed by injecting N_2 for 5 minutes to remove oxygen inside the reactor. The acclimatization was a greater help for the microorganism adaptation with the new substrate, such as OW. The acclimatization process took 53 days. The parameter of temperature and pH was monitored in order to maintain the mesophilic condition and pH remains above 6. Sodium bicarbonate ($NaHCO_3$) as a buffer solution was also intermittently added at the concentration of 3 mg/l when the pH dropped below 6.

Daily feeding was carried out with a mixture of OW and CM in the ratio of 9:1 (w:w) (Theresia & Priadi, 2017). The OLR was gradually increased from 8 kgVS/m^3day to 14 kgVS/m^3day (Fagbohungbe et al., 2015). OLR calculation was determined using Equation 1, where M corresponds to the mass of substrate (kg/day), TS corresponds to total solid (TS) percentage of substrate (%), VS corresponds to VS percentage of substrate (%TS), and V corresponds to effective volume of reactor (m^3). Each OLR was operated for a period of 2–4 weeks based on steady-state values of biogas production of less than 10 % after 3 instances of feeding (Wang et al., 2014). The volume of biogas was measured directly using a high-precision gas flow meter.

$$OLR = \frac{M \times TS \times VS}{V} \tag{1}$$

2.2. Analytical Methods

Biogas and feedstock samples were taken from the reactor five times a week and analyzed for their pH (SNI 06-6989.23-2005), temperature (SNI 06-6989.23-2005), total ammonia nitrogen (TAN) (Nessler Method, HACH Company), carbon (spectrophotometry method), TS (SNI 06-6989.28-2005), and VS (SNI 06-6989.26-2005). To further analyze the AD performance in removing organic matter, VSD was calculated using Equation 2, where VS_{ef} corresponds to VS percentage in effluent (%) and VS_{in} corresponds to VS percentage in influent (%). The biogas volumes were measured using a high-precision gas flow meter by Keyence FDA100. The biogas composition was measured using a gas chromatography (GC) application (Bruker, USA). The interpretation was then statistically analyzed to validate the results using a correlation test and t-test.

$$VSD = 1 - \frac{VS_{ef} \times (1 - VS_{in})}{VS_{in} \times (1 - VS_{ef})} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1. Feedstock Characteristics

The feedstock used in this study had a TS content in the range of 23.2%–7.1%, which falls within the optimal range of 20–50% (Kothari et al., 2014). The feedstock also had high organic content, represented as VS, with a value of 89.7–94.9%TS. This value was the highest obtained out of several studies that reported a range of 61.6–93.8%TS (Dong et al., 2010; Zhang et al., 2012; Browne et al., 2014; Wang et al., 2014). Due to these high values for TS and VS, a mixture of OW and CM is suitable for use in dry AD. The C/N ratio of the feedstock is 18.5–27.3, which fell within the ideal range of 10–30 (Lin et al., 2011). The feedstock also had a temperature of 27.6–28.0^{o}C and a density of 0.862–0.887 kg/l.

3.2. VSD and Biogas Production

The OLR of 8 kgVS/m^3day had the lowest VSD at an average of 81.6% (Figure 3a). The high fluctuation of VSD indicates that the reactor was still adjusting to the loading rate. In the early phase, the pH was considered to be low (5.5–5.7) and outside the optimum range of 6.5–8.2. Buffer was therefore added until the average pH reached 6.3 (Figure 2b) (Lee et al., 2009; Kothari et al., 2014). At this feeding phase, ammonia had the lowest concentration at 452 mg/l (Figure 2c). In the next OLR phase of 10 kgVS/m^3day, the reactor demonstrated the highest VSD ($p < 0.05$, Figure 3a) with VSD at 92.2%, or equal to a VS reduction of 197 g/l. The results obtained in this study are similar to those of a previous study where the optimum OLR was reached at 8.8–12.5 kgVS/m^3day (Fernández-Rodríguez et al., 2008). The average pH was relatively constant at 6.5 and was thus considered to be optimum for AD (Lee et al., 2009). The increase in VSD was followed by an increase in biogas production. However, the amount of ammonia increased by an average of 848 mg/l due to the high concentration of total nitrogen in the substrate at 3.1% compared to other studies (Dong et al., 2010; Browne et al., 2014). A high concentration of total nitrogen in the feedstock can lead to an accumulation of ammonia resulting from the disintegration of amino acids and protein during the hydrolysis stage (Dong et al., 2010).

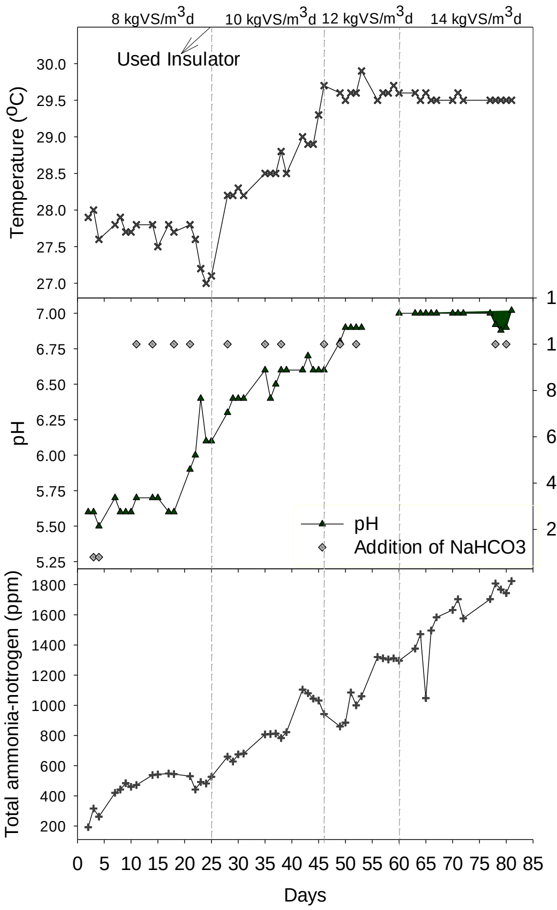


Figure 2 Reactor stability: (a) Temperature; (b) pH; (c) TAN

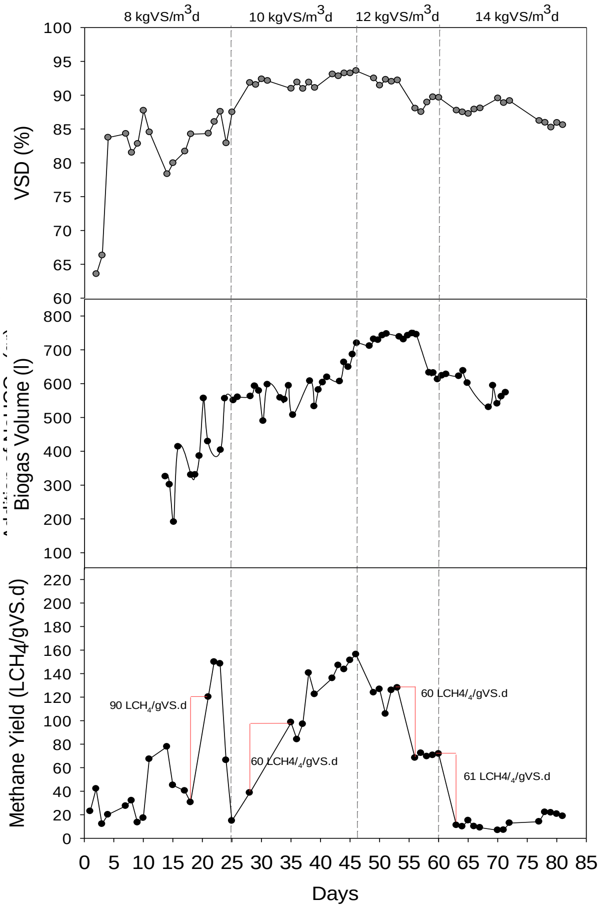


Figure 3 Reactor Performance: (a) VSD; (b) Biogas volume; (c) Methane yield

When OLR was increased to 12 and eventually to 14 kgVS/m^{3}day, VSD decreased to 90.4% and 86.7%, respectively. A decline in VSD can be caused by an excess of organic content (Babae & Shayegan, 2011). Ammonia buildup was also observed during the 2 feeding phases, increasing to 1,145 mg/l and 1,595 mg/l, respectively, which has the potential to disrupt the metabolic processes of microorganisms. Compared to other studies, the amount of ammonia in this study was below the inhibiting threshold limit of 3,000–3,300 mg/l (Appels et al., 2008; Westerholm et al., 2011). However, another study reported a maximum ammonia concentration of approximately 570 mg/l (Appels et al., 2008). Excess ammonia can inhibit the methanogenesis process by up to 50% (Appels et al., 2008) and alter the intracellular pH, leading to greater energy consumption and enzyme inhibition (Zeshan, 2012).

During the AD process, methane production is a key indicator of reactor performance (Nagao et al., 2012) and depends on the metabolism of the methanogenesis bacteria. During the first phase (OLR 8 kgVS/m^{3}day), methane production continued to fluctuate and was relatively low, with an average of 52.7 LCH$_4$/grVSday. This could be due to the low pH and VSD. The results statistically demonstrated that a higher VSD will lead to higher methane or biogas production (r^2=+71%). Methane production increased drastically when the pH was in the optimum range for the methanogenesis process and also fell in line with the decrease of pH. In the next stage, there was an increase in average methane production, especially in the period OLR10 of 127 LCH$_4$/kgVSday compared to the OLR of 12 kgVS/m^{3}day, which is 96.3 LCH$_4$/grVSday (Figure 3c).

4. CONCLUSION

With a high TS and organic content, a mixture of OW and CM is suitable for use in dry AD. The optimum OLR in this experiment was 10 kgVS/m^3day, which gave a VSD of 92.2% or 179 g/l and a methane yield of 127 LCH_4/kgVSday. The operation is likely to be more stable with temperature, pH, and ammonia values of 28.7^{o}C, 6.52, and 848 mg/l, respectively. Thus, the optimum OLR obtained for AD can produce high VSD and serve as a solution to the problem of OW in Indonesia.

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