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Kinetics on anaerobic co-digestion of bagasse and digested cow manure with short hydraulic retention time

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Abstract

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The anaerobic co-digestion of bagasse with digested cow manure was operated in 3 l semi-continuous reactor under mesophlic temperature at 34 ± 1°C. Short hydraulic retention time and high organic loading rate applied were 10 days and 3.465 kg volatile solids (VS)/m^3.day, respectively. Anaerobic co-digestion of bagasse with digested cow manure obtained higher biogas yield (69 ml/g VS) compared with the anaerobic digestion of digested cow manure alone (20.42 ml/g.VS). Kinetic assessment revealed that the maximum specific growth rate, the maximum rate of substrate consumption, half-velocity constant, endogenous decay constant and microbial growth yield obtained were 3.917 day^{-1}, 870.309 mg/mg, 15.09 mg/l , 8.1518 day^{-1} and 0.0193 mg/mg, respectively. This result indicated that a longer retention time was required to allow the bacterial growth.

Keywords: kinetic parameters; high organic loading rate; single stage anaerobic digestion

Anaerobic digestion may be considered as a proper approach to handle the problems of organic wastes generated in each region. It occurs since anaerobic digestion is an effective method to degrade and remove organic pollutants by mineralizing organic compounds into simpler useful chemicals (Lier et al. 2008).

Some studies had revealed that there are several operational parameters that significantly affect the performance of anaerobic digestion process including pH, temperature, hydraulic retention time (HRT), organic loading rate, solid concentration and reactor configuration (Rincón et al. 2008; Mariakakis et al. 2011; Bayr et al. 2012; Nasir et al. 2012; Darwin et al. 2016). The HRT is considered as the most crucial parameter that extremely affects the performance of anaerobic digestion process, particularly microbial activities involved in the different stages of the process (Fang et al. 2000; Kim et al. 2006).

Since anaerobic digestion is a complex process involving different types of microorganisms, comprehensive studies are required to optimize and enhance the performance of anaerobic digestion process based on some approaches in engineering as well as biotechnology. Kinetic study of anaerobic digestion is a worthwhile approach that can be utilized for understanding and optimizing anaerobic digestion process as it has been widely used for investigating different microbial activities and biochemical pathways during anaerobic digestion process through simplified kinetic approaches (Chen 2010). Two typical methods that can be utilized for describing the kinetics of biogas production of lignocellulosic biomass are to determine the rate-limiting substrate for the kinetic evaluation; another method is by using volatile solids or chemical oxygen demand concentration as an indicator of the substrate concentration (Chen, Hashimoto 1978; Hill 1983).

In this current study, the effects of short hydraulic retention time and high organic loading rate in the conventional single stage system were investigated through the evaluation of anaerobic diges-

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tion kinetics of digested cow manure with bagasse as a co-substrate under mesophilic conditions. Substrates assessed contained a significant amount of total solid content, and were typically utilized for enhancing biogas production.

MATERIALS AND METHODS

Substrate preparation. Bagasse used for this experiment was collected from several sugarcane juice vendors located in Banda Aceh, Indonesia, and dried to reach the moisture content of ± 7% (wet basis). The dried bagasse was milled using a laboratory grinder to an average particle size of 20 mesh. The percentage of total solids of bagasse used as a co-substrate was about 93.32 ± 0.39%. Wastewater as well as sludge was taken from the cow unit farm at Sibreh, Aceh Besar; before using this manure, it was stored in a refrigerator at the temperature of ± 5°C. For characterization of substrates, bagasse as well as digested cow manure were analysed for solid concentration. For total solids measurement, samples of bagasse and cow manure were dried at the temperature of 105°C, and followed with burning the samples at the temperature of 550°C in the furnace. The analysis of total solids (TS) as well as volatile solids (VS) was determined in accordance with the Standard Methods (APHA 2012).

Experimental procedure. Experiments were carried out in the Laboratory of Bioprocess and Postharvest Technology, Department of Agricultural Engineering, Syiah Kuala University. Some sample analysis measurements were conducted at the Institute for Research and Standardization of Industry, Banda Aceh. An anaerobic semi-continuous reactor was run at steady state conditions where the temperature was maintained under mesophilic condition at 34 ± 1°C by using thermostatic heater. The working volume of the digester was 3,000 ml. The short hydraulic retention time applied in this experiment was 10 days. The loading rate applied in this experiment was 300 ml/day. High organic loading rate was also applied in this experiment by adding 30 g of bagasse into 300 ml of cow manure where bagasse as a co-substrate was loaded at 10% of the total volume of daily cow manure loaded.

Before running anaerobic digestion process, the measurement of organic loading rate was conducted. The measurement of organic loading rate was based on the percentage of total solids and volatile solids of the culture. Based on the initial analysis, total solids and volatile solids of the culture obtained were 4.295% and 80.684%, respectively. Some parameters including the working volume of digester (3 l) and loading rate (300 ml/day) had been known; thus, organic loading rate applied in this experiment was 3.465 kg VS/m^3·day.

The effluent and influent ports were located on the top of the digester. The gas outlet located on the top of the reactor was connected to tubing to the port of the gas meter. The effluent samples were taken from the port for further analysis. To ensure the semi-continuous process system run properly, pH of the culture including influent and effluent was measured periodically during the feeding period; and there was no pH control applied in this system. Biogas production was measured using a gas meter based on water displacement (Fig. 1).

Analytical methods. The parameters of influent as well as effluent were analysed for total solids (TS), moisture content (MC), volatile solids (VS), total

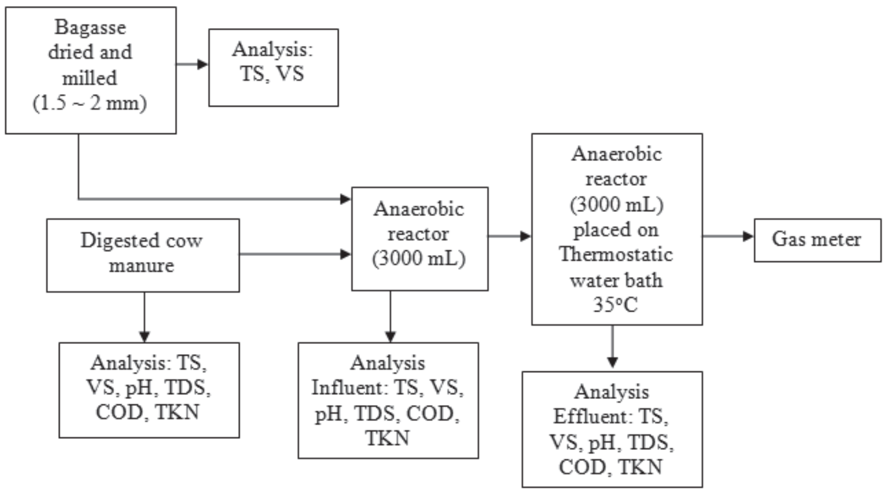

Fig. 1. Process flow diagram of anaerobic co-digestion experiment

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dissolved solids (TDS), chemical oxygen demand (COD) and total Kjeldahl nitrogen (TKN). All parameters measured were carried out based on the Standard Methods (APHA 2012). The tudy revealed that assessing the amount of solid mixed and organic compounds was required to determine the strength of the wastewater (Joanne 1991). Volatile solids reduction and chemical oxygen demand removal were analysed in order to know the efficiency of biodegradation during anaerobic digestion process based on the formula used by previous studies (Joanne 1991; Darwin et al. 2014). Biogas production rates were measured as the volume of biogas generated per dayand the biogas yield were measured according to the total biogas produced per gram volatile solids added (Lo et al. 1984; Parawira et al. 2008; Gontupil et al. 2012; Darwin et al. 2016).

RESULTS AND DISCUSSIONS

Table 1 summarizes the characteristics of the culture influent loaded into the anaerobic semi-continuous reactor. The initial parameters of each culture were pretty good; the initial pH of both cultures was still in the range of optimum pH to perform anaerobic digestion (Cheng 2010). The influent of digested cow manure had a slightly lower pH (6.79) than the optimum pH (7); once the cow manure was added with bagasse, pH of the culture increased to 7.09 which was considered as the optimum pH for operating anaerobic digestion. The culture of bagasse co-digested with cow manure contained a significant amount of organic matters compared with the culture consisting of solely digested cow manure as a substrate. The COD influent of digested cow manure co-digested with bagasse was 9654.48 mg/l, which was 80.36% higher than the COD influent of cow manure (1,896 mg/l). Volatile solids of cow manure co-digested with bagasse was 80.68%, which was 17.79% higher compared with the volatile solids of cow manure culture (66.33%).

Anaerobic co-digestion of bagasse with digested cow manure generated a considerable amount of biogas per day, and the maximum biogas production was at days 4 and 6 of the digestion process, which had an average daily production of 396.67 ml/day (Fig. 2). A significant increase of biogas production occurred from the first day to the second day of the process where it increased tenfold, which was from 35 ml to 350 ml. At this period, pH was still in the range of the optimum pH for biogas production between 7.15 and 6.92. Although pH of the culture decreased steadily from 7.15 to 4.69, it did not suddenly affect the production of biogas (Fig. 2).

Unstable conditions in the anaerobic co-digestion of bagasse with digested cow manure led to a significant decrease of biogas production as pH culture declined considerably from 6.9 to 4.9 during a period of time. This condition may affect methane production as metabolic pathway of bacteria can shift when pH alters in the digester. This result was in agreement with a previous study revealing that unstable conditions occurred during the anaerobic acidogenesis process at pH 5 (Ren et al. 2007). Anaerobic co-digestion of cow manure with bagasse produced higher biogas compared with anaerobic digestion of digested cow manure as a single substrate where the total biogas generated from the anaerobic co-digestion was 6,855 ml, which was about 92.41% higher than the anaerobic digestion of cow manure (520 ml). This condition allowed the digester of anaerobic co-digestion of bagasse with digested cow manure to reach higher biogas yield (69 ml/g VS) compared with the anaerobic digestion of cow manure (20.42 ml/g VS). Biogas yield obtained in this

Table 1. Influent and effluent data

Analysis	Unit	Cow manure		Bagasse co-digested with cow manure	
		influent data	effluent data	influent data	effluent data
COD	mg/l	1,896	1,896	9,654.48	9,654.48
TS	%	1.28	1.28	4.29	4.29
VS	%	66.33	66.33	80.68	80.68
pH	–	6.79	6.79	7.09	7.09
TKN	mg/l	320.18	320.18	396.83	396.83
TDS	mg/l	1,560	1,560	1,540	1,540

COD – chemical oxygen demand; TS – total solids; VS – volatile solids; TKN – total Kjeldahl nitrogen; TDS – total dissolved solids

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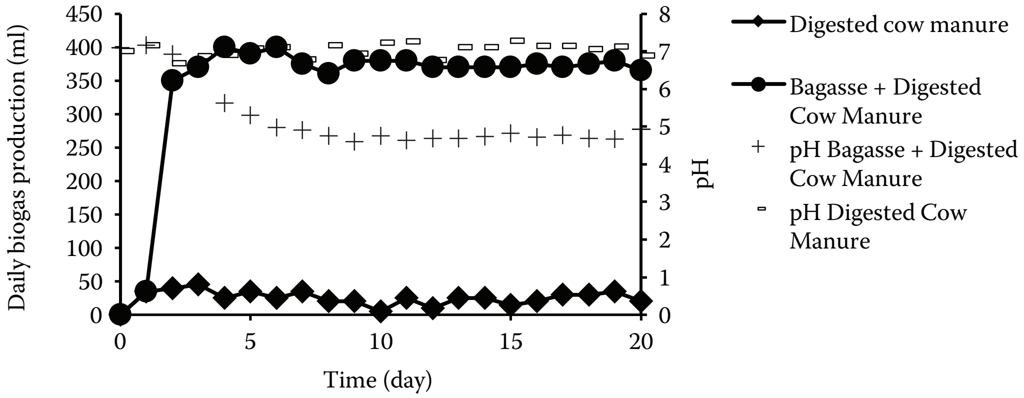

Fig. 2. Daily biogas production and pH trend in the anaerobic co-digestion of bagasse and digested cow manure during the entire experimental period

present study was pretty low compared with other studies. It occurred as short HRT and high organic loadinf rate (OLR) applied led to a significant drop of pH culture and resulted in a slight inhibition of anaerobic digestion process in the digester. The biodegradation efficiency of anaerobic co-digestion of bagasse with digested cow manure was not pretty well where it only had a volatile solids reduction which was around 8.71%. This condition occurred since not all organic matters loaded into the digester were completely degraded. Low VS reduction may also indicate that anaerobic co-digestion of bagasse with digested cow manure applied with short HRT and high organic loading rate was not able to convert all organic materials loaded into methane due to acid inhibitory as well as insufficient retention time introduced in the process.

An increase of total dissolved solids at both reactors indicated that some soluble matters were formed including solvents and some volatile fatty acids (Jayakody et al. 2007). This finding was in agreement with a previous research revealing that higher total dissolved solids also presented a lot of biochemical conversion products generated during anaerobic digestion process (Jayakody et al. 2007; Hidalgo et al. 2015). According to the results, low efficiency of digestion reflected in the low volatile solids reduction and high total dissolved solids may affect a soluble chemical oxygen demand in the culture increasing from 9,654.48 mg/l to 17,160 mg/l (Table 1).

Kinetic assessment of anaerobic co-digestion

In anaerobic digestion, the activity of microbial process can be evaluated by assessing the kinetics of substrate consumption as well as kinetics of microbial growth (Nwabanne et al. 2012). The study revealed that the first order reaction can be applied for estimating limited substrate utilization during anaerobic digestion process (Raj, Anjaneyulu 2005) where the expression can be stated as Eq. (1):

$$\frac{-ds}{dt} = K'S \tag{1}$$

where: K' – rate constant; ds – change of substrate concentration; dt – change of time; S – substrate concentration

Since Eq. (1) is considered as an exponential growth, it can be related to hydraulic retention time describing the substrate concentration.

$$S = S_0 \exp\,(-K_s t) \tag{2}$$

where: S_0 – influent substrate concentration (mg/l); S – effluent substrate concentration (mg/l); t – hydraulic retention time (days)

Eq. (2) depicts the exponential growth of the microbes as the food is consumed. When both sides of Eq. (2) are given natural logarithm, the formula can be expressed as Eqs (3) and (4):

$$ln\left(\frac{S}{S_0}\right) = -K_s\, t \tag{3}$$

$$K_s = \frac{-ln\left(\frac{S}{S_0}\right)}{t} \tag{4}$$

where: K_s – half-velocity constant (mg/l)

When $-ln\left(\frac{S}{S_0}\right)$ was plotted against t, it generated a linear curve with regression coefficient of 0.996.

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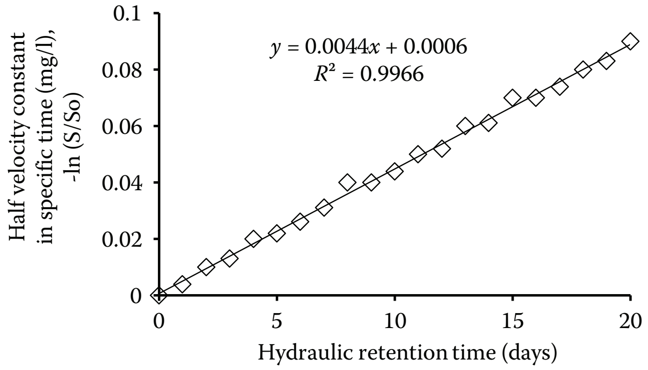

Fig. 3. First order kinetic plot for anaerobic co-digestion of bagasse with digested cow manure

This result indicated that the kinetics of anaerobic co-digestion of bagasse with digested cow manure followed a first order reaction (Fig. 3). Kinetic parameters in this anaerobic digestion process including the maximum specific growth rate of microorganism (μ_{max}) and the max. rate of substrate consumption (K) were derived from a plot of total substrate effluent (St) against T as a hydraulic retention time (Zainol 2012), and the expression can be stated as Eq. (5) and (6).

$$S_t = \frac{S_0 - S}{S} \qquad (5)$$

$$T = \frac{1}{\mu_{max}} + \frac{K}{\mu_{max}} \times \frac{S_0 - S}{S} \qquad (6)$$

Kinetic parameters and K were obtained from the intercept and the slope of the adjusted lines (Fig. 4). Therefore, based on Eq. (6), the values of μ_{max} and K were 1/intercept and slope/intercept, respectively. In the present study, anaerobic co-digestion of bagasse with digested cow manure generated the values of (μ_{max}) and K which were 3.917 day^{-1} and 870.309 mg/mg, respectively. Based on this result, the value of μ_{max} was pretty high indicating that the amount of biomass cell in the reactor was relatively small since the concentration of cell mass in the reactor is inversely proportional to the max. specific growth rate of microorganisms. Thus, the hydraulic retention time applied to the system was considered too short leading to insufficient time for the bacterial growth. The relationship between the rate of substrate consumption (U) and the effluent substrate concentration (S) can be expressed in Eq. (7) (Viessman, Hammer 1993).

$$\frac{1}{U} = \frac{K_s}{K \times S} + \frac{1}{K} \qquad (7)$$

In this study, the value of the half-velocity constant (K_s) was calculated as 15.09 mg/l with respect to the hydrolysed substrates (mass/volume) (Faisal, Unno 2001). Based on the values of K_s and K obtained, it was found that the anaerobic digestion process carried by microorganisms did not perform sufficiently well due to short hydraulic retention time and high loading rate applied. The results also suggested that longer hydraulic retention time was required for microorganisms to regenerate new biomass and for better performance of anaerobic digestion process. The specific rate of substrate consumption is related to biomass yield, mean cell residence time and the endogenous decay coefficient as expressed in Eq. (8).

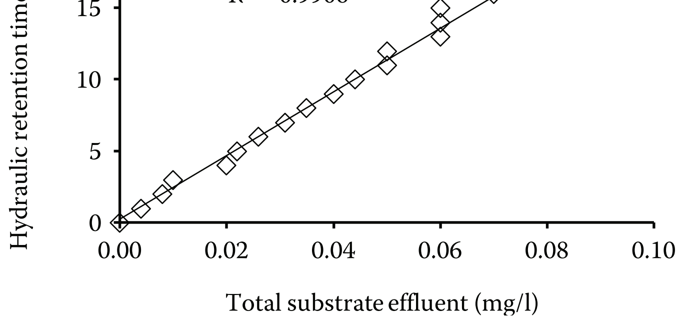

Fig. 4. Determination of the maximum specific growth rate of microorganisms and the maximum rate of substrate utilization

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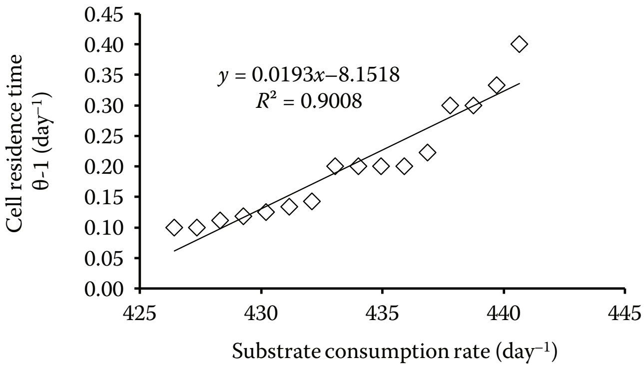

Fig. 5. Plot for determination of the biomass yield and the endogenous decay coefficient

$$\frac{1}{\theta} = YU - K_d \qquad (8)$$

where: θ – mean cell residence time (day); Y – biomass yield (mg/mg); K_d – the endogenous decay coefficient (day^{-1})

The value of the biomass yield and the endogenous decay coefficient were obtained by plotting U against 1/θ (Fig. 5). Based on the slope and intercept of the straight line curve, the biomass yield and endogenous decay coefficient acquired were 0.0193 mg/mg and 8.1518 day^{-1}, respectively. The endogenous decay coefficient obtained in this study is fairly high as the high dilution rate represented in the short hydraulic retention time as well as high organic loading rate applied to the digester was not fairly effective for the growth of biomass. It occurred as the high organic loading rate applied to the digester increased the rate of volatile fatty acid formation, which is responsible for lowering pH and leads to the acid accumulation in the digester, and finally this condition led to the inhibition of methanogenic growth. The short HRT of 10 day or 0.1 day^{-1} of dilution rate introduced to the anaerobic digester may cause washing out during the anaerobic digestion process where the biomass presented in the digester did not obtain sufficient time to grow and convert organic matters to methane; thus, this condition can lead to lower biomass yield in the anaerobic digester.

CONCLUSION

Short hydraulic retention time (10 days) and high organic loading rate (3.465 kg VS/m^3·day) applied in the anaerobic co-digestion of bagasse with digested cow manure did not extremely suppress the methanogenesis process to produce biogas. However, anaerobic co-digestion of bagasse with cow manure achieved biogas yield at only 69 ml/g VS added. The fairly high value of the maximum specific growth rate which was 3.917 day^{-1} indicated only a small amount of microorganisms retained in the reactor; thus, a longer retention time was required to allow the bacterial growth.

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