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Article

A Two-Stage Anaerobic Digester of Pig Manure and Food Waste for Biogas Production with Heat Exchanger

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Abstract. Pig manure is one of the most significant causative agents of environmental pollution in swine farm areas. To reduce this problem, research has suggested the use of piggery waste for sustainable energy production. The aim of the present study was to investigate the effects of feedstock ratio on the efficiency of 2-stage anaerobic co-digestion. A 100-L capacity digester was built with the variation of mixing ratios of pig manure to food waste to water of 50:20:30, 35:35:30 and 20:50:30, respectively. Biogas production at high temperature using hot water heating system was also investigated. The effluent in fermentation tank was collected every 5 day and analyzed for the following parameters: total solid (TS), suspended solid (SS), total dissolved solid (TDS), amount of fat oil and grease, and biological oxygen dissolved (BOD). The results revealed that feedstock with the mixing ratio of 50:20:30 and 35:35:30 produced high volume of biogas. The anaerobic digester under hot water treatment (40 ^{o}C) exhibited higher biogas volume than that under normal temperature (30 ^{o}C). The ratios of feedstock also affect the efficiency of anaerobic digester as indicated by the difference in the reduction of TS, SS, TDS, COD, BOD and fat oil and grease.

Keywords: Pig manure, biogas, food waste, two-stage anaerobic digester.

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1. Introduction

Thailand is an agricultural country in which most of the population is engaged in agriculture, including growing crops and raising farm animals. One of the most widely raised economic animals in Thailand is pig farming. However, one of the most significant problems of pig farming is the production of pollution, which is caused by swine waste, and consequentially causes impacts health of the residents nearby the animal farm. To attenuate these impacts, biogas production from pig manure as household fuel to replace the use of fuel from petroleum has been introduced.

Biogas is produced by anaerobe microorganisms using organic materials as a substrate. Typically, biogas consists of 45-70% methane, 30-35% CO_2 and small amount of nitrogen, hydrogen, hydrogen-sulphide, ammonia, and other remainder-gases [1]. The conversion of organic waste into biogas gives both environmental and economic benefits since it can replace fossil energy, improve air quality, and provide nutrient-rich crop fertilizer. Moreover, biogas is considered one of the most effective method for agricultural and industrial waste management. The process that converts organic waste to biogas is called Anaerobic Digestion (AD), which consists of 4 key stages, namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is referred to the cleavage of chemical bond with the present of water. Insoluble organic matters such as cellulose are degraded to soluble small molecule. The products from this step includes glucose $C_6H_{12}O_6$, hydrogen (H_2), and acetic acid (CH_3COOH). The CH_3COO^- and H_2 are further used by fermentative microorganism to form volatile fatty acids. Acidogenesis is the second stage, which fermentation takes place. The soluble compounds are degraded and converted to CO_2 and H_2 using acidogenic bacteria. Acidogenesis is a pH-dependent reaction. Volatile fatty acids increase if the process pH is higher than 5, while production of ethanol starts when pH is lower than 5, and if pH values go lower than 4, the reaction stops. The third stage is acetogenesis, which is known as dehydrogenation stage. The H_2 produced in this stage inhibit acetogenic bacteria however, it is consumed by hydrogen-scavenging bacteria to produce methane in the methanogenesis step. Thus, it is symbiosis necessary for acetogenesis and methanogenesis bacteria to use the H_2 produced in this stage. The last step for biogas production is methanogenesis. In this stage bacteria convert CH_3COOH and H_2 into CO_2 and CH_4. Bacteria responsible for this stage called methanogen and the notable methanogen species include *Methanobrevibacter ruminantium*, *M. bryantic* and M. *thermoautotrophicum*, *Methanogenium cariaci and M. marinsnigri* [2]. These bacteria are strictly anaerobe and very sensitive to change in environment. Methane-producing bacteria are divided into two maim groups; acetophillic and hydrogenophollic bacteria. The acetophillic bacteria produce CH_4 by decarboxylation of acetate from acetic acid while hydrogenophollic bacteria convert CO_2 and H_2 to CH_4 by reduction reaction.

Anaerobic Digestion (AD) can be performed in a single-stage process, which is easy and simple. However, the process is unstable due to quick hydrolysis, accumulation of volatile fatty acids, low pH which inhibits methanogenesis, high organic loading rate and low biogas production [3-5]. Therefore, a two-stage AD is performed by separating hydrolysis and acidogenesis (acid formation) from methanogenesis (acid consumption). Many studies have suggested that two-stage AD is a more effective than single-stage AD in biogas production. The advantages of two-stage AD include high process stability, high biogas production, better effluent quality. Moreover, co-digestion using different organic waste can achieve proper physiochemical properties of feedstock and resulting in high biogas production.

Raw materials for biogas production can be either agriculture raw materials or public waste such as food waste. The agriculture raw materials include the remains of dead plants and animals such as stem, leaves, roots, feather, blood, hair as well as waste from animals such as feces. These materials are biodegradable, which can be degraded to smaller molecules such as methane, ammonia, and carbon dioxide by micro-organism [6]. The composition of biogas and methane yield depend on types of feedstock [7]. Typically, feedstock for biogas production is manure from agricultural farm such as chicken, pig, and cow. Addition of co-substrates such as food waste or part of energy crops to the feedstock helps to increase organic material which consequently increase gas yield [8]. Co-digestion of different feedstocks with animal manure can increase biogas yield up to 400% compared to mono-digestion of the same substrate. Co-digestion of pig manure with glycerol at the ratio of pig manure: glycerol equal to 24:1 under mesophilic condition increased biogas yield up to 400% relative to mono-digestion of pig manure alone. [9, 10] Many researches have been conducted using co-digestion of different biogas feedstocks and ratios. Chakraborty and Mohan [11] investigate the effect of food to vegetable waste ratio on acidogenesis and methanogenesis during two-stage digestion. They compared the ratio of food waste (FW) to vegetable waste (VW) between 2:1 and 2:3 and they found that feedstock with 2:1 FW:VW gives higher hydrolysis rate and total volatile fatty acid. The 2:3 FW:VW ratio showed higher COD removal, acetate production and methane yield. VW addition helps to regulate pH, restricted propinoate and lactate production with enhanced methanogenesis by improving acetate production in two state AD process. Another research [12] was conducted to investigate the effect of food waste to sewage sludge ratio to biogas production. The results revealed that the optimum mixing ratio of food waste to sewage sludge was 7:1. This feedstock ratio can produce biogas with methane content up to 64%.

Pig manure in the campus farm and food waste from the campus cafeteria are a main source of unpleasant smell in the area of Rajamangala University of Technology Isan

Surin Campus. Producing biogas from these wastes is, therefore, a promising option in disposing these daily wastes in the campus area. This study aimed to investigate the optimum ratio of pig manure and food waste to produce biogas using two-stage AD. The ratio of pig manure, food waste and water were varied. Since AD is a thermophilic process, the AD process with and without heat exchanger were compared. The volume of biogas, gas composition, pH, Total Solid (TS), Suspended Solid (SS), Total Dissolved Solid (TDS), amount of Fat oil and grease, COD and BOD from each digest condition were measured.

2. Materials and Methods

2.1. Feeding Substrate

Pig manure was collected from the swine farm at Rajamangala University of Technology Isan, Surin Campus. Food waste containing rice, vegetable, meat, starch, and grease, was collected from the university canteen and was shredded into about 1 cm-size using griding machine.

Mixing ratio of pig manure, with food waste and water on the efficiency of biogas production were investigated using a two-stage anaerobic digestion method. Three experiments were carried out by varying ratio of pig manure, food waste and water to 50:20:30, 20:30:50 and 35:35:30, respectively, producing a sum of 100 kg total feedstock loading. In the beginning, the feedstock was stored in the acid tank for 3 days. After that the effluent was pumped into the gas fermentation tank and fermented for another 27-days, totaling a duration of 30 days.

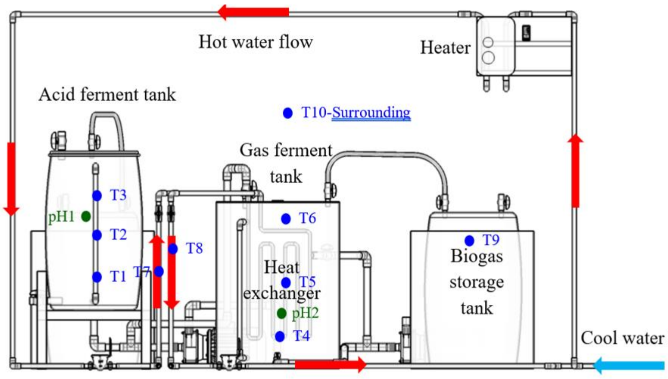

Fig. 1. The figure is schematic diagram of the two-stage anaerobic digester with heat exchanger.

2.2. Two-stage Anaerobic Digester Experiment

A two-stage anaerobic digester for co-digestion of pig manure and food waste was built according to the schematic diagram shown in Fig. 1. The digester consisted of a 150 L-acid tank and a 250 L- gas fermentation tank. Both tanks were made of cylindrical polyvinylchloride (PVC). The acid tank and fermentation tank were connected to a biogas collection tank via an airtight PVC tube. Volume of biogas was measured daily because anaerobic digestion exhibited high metabolic rate at high temperature (45^{o}C-65^{o}C) [13]. The second experiment was conducted using a heating equipment consisting of a 6000 W heater, a 10-L tank for hot water, and a heat exchanger of a 6.35 mm diameter cupper tube and a 28 cm length. In the gas fermentation tank, 3-cupper tube heat exchangers were installed to control the temperature inside the tank. When the water in the 10-L tank was heated to the desired temperature (45^{o}C), it was automatically circulated through the 3-cupper tube heat exchangers in gas fermentation tank. The temperature in the hot water tank was maintained at 45 ^{o}C for 27 days.

The temperature in gas fermentation tank was measured using a Type K thermocouple (±3^{o}C) and recoded in a data logger (GRAPHTECH, Midi LOGGER GL820) daily. The pH in acid tank and gas fermentation tank were measured daily using a portable pH meter (±0.01 pH, waterproof ExStik pH Meter, pH 100 Extech)

2.3. Analytical Methods

To evaluate the anaerobic digestion efficiency, effluent of the digestion was collected every five days and analyzed for the following parameters: total solid (TS), suspended solid (SS), total dissolved solid (TDS), biological oxygen demand (BOD), grease and oil and chemical oxygen demand (COD). The biogas was collected by passively filled into gas collection bags with a polypropylene valve and a septum fitting for sampling (Restek Corporation, USA). Biogas was analyzed by Gas chromatography (Agilent 7890A) with FID, TCD and FP detector.

3. Results and Discussion

Effects of pig manure and food waste ratio on the volume of biogas were investigated using a two-stage anaerobic digester. To select the optimum feedstock, the ratio of pig manure, food waste and water was varied and volume of biogas, gas composition, pH, TS, SS, TDS, amount of fat oil and grease, COD, and BOD were measured.

3.1. Effects of Mixing Ratio of Pig Manure and Food Waste on Gas Volume and Gas Composition

Figure 2 shows the volume of biogas produced in different feedstock ratios. The volume of biogas yield in acid fermentation tank (VAF) is low for all the three feedstock ratios and is low for both systems: one with hot water and the other without hot water. The volume of gas in acid fermentation tank is low because the effluent was pumped into gas fermentation tank after 3-day fermentation. The volume of biogas in gas fermentation tank (VGF) for all the three feedstock ratios produce highest gas volume after 15-day fermentation, then the gas reduces to 0.4 m^3/day for feedstock with the ratios of pig manure, food waste and water of 50:20:30 and 35:35:30,

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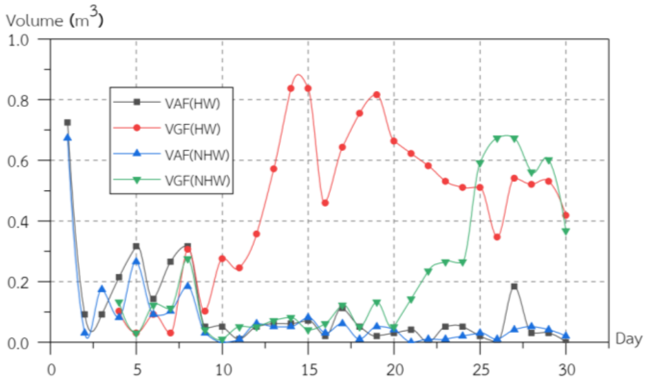
whereas the feedstock with ratio of pig manure, food waste and water of 20:50:30 yields the lowest gas volume on day 30.



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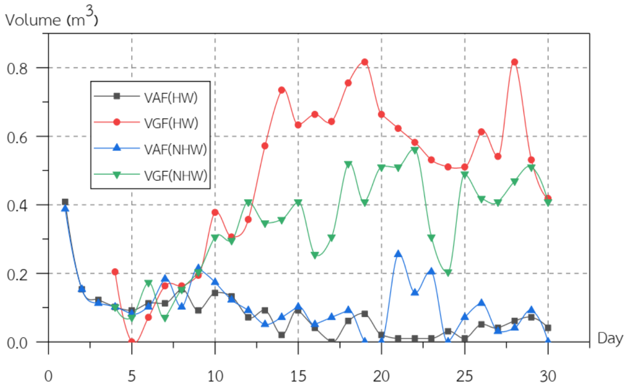

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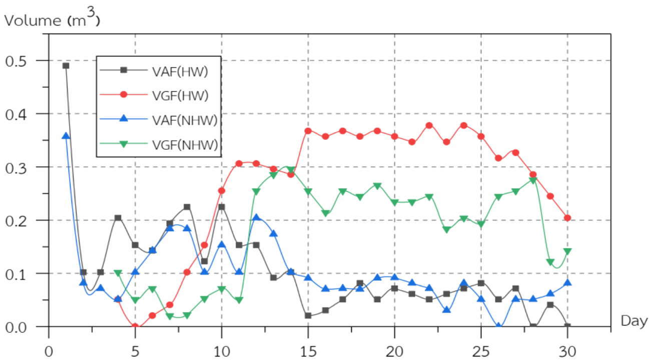
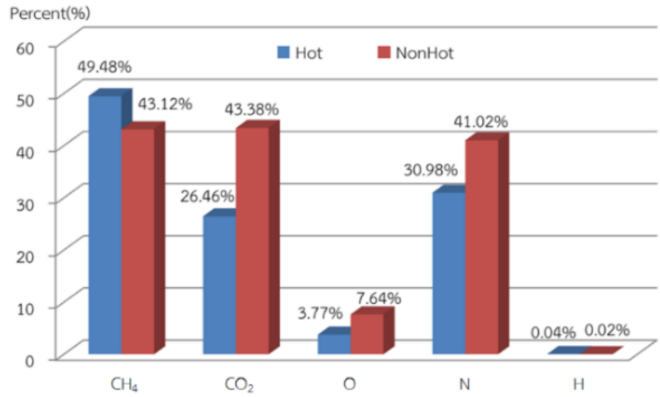


(c)

Fig. 2. The figure is volume of biogas produced from different ratios of pig manure, food waste and water: (a) 50:20:30, (b) 35:35:30, and (c) 20:50:30 (where VAF(HW) is volume of gas in acid fermentation tank with hot water, VGF(HW) is volume of gas in gas fermentation tank with hot water, VAF(NHW) is volume of gas in acid ferment tank without using hot water and VGF(NHW) is volume of gas in gas fermentation tank without using hot water.)



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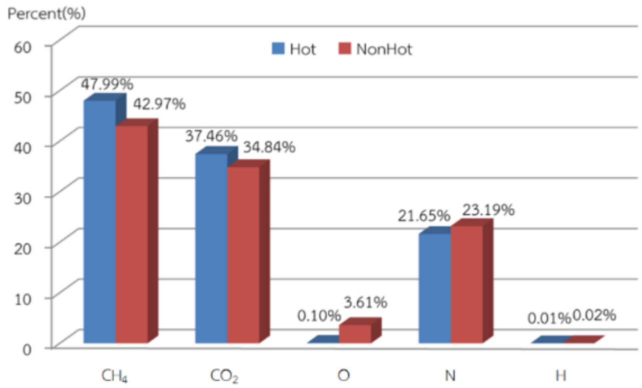

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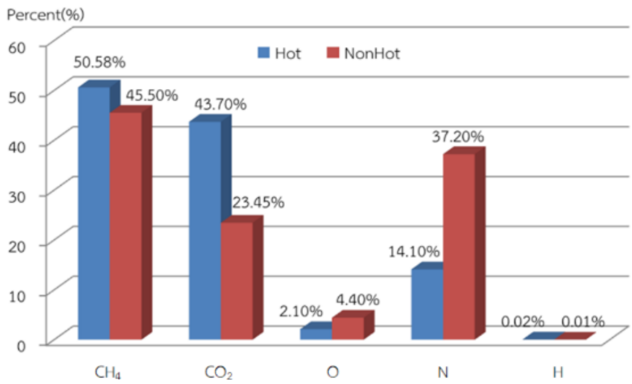

(c)

Fig. 3. The figure is composition of biogas produced from different ratios of pig manure, food waste and water: (a) 50:20:30, (b) 35:35:30, and (c) 20:50:30.

Figure 3 shows the composition of biogas produced from three different feedstock ratios which are almost similar. Since biogas is produced from the digestion process of anaerobic bacteria and source of bacteria from this study is from pig manure. Thus, feedstock with less amount of pig manure gives low biogas volume because the system does not have sufficient anaerobic bacteria to digest organic matters. The bacteria responsible for anaerobic process requires both carbon and nitrogen and they can consume carbon approximately 30 times faster than nitrogen. Thus, the feedstock with C/N ratio of approximately 30 could be the ideal feedstock for biogas production [14]. Considering the C/N ratio of pig manure

(12.5) [15] and food waste (30) [12], feedstock with ratio of pig manure, food waste and water of 20:50:30 yield a high amount of food waste which consequently produces a high C/N ratio. A higher C/N ratio of feedstock will leave carbon is still available while nitrogen runs out, resulting in starving anaerobic bacteria and finally they turn die. This effect may potentially be the reason that the feedstock with highest food waste (50%) gives lowest biogas volume. Thus, the optimal ratio of pig manure: food waste: water to produce biogas is 50:20:30 and 35:35:30.

Figure 3 illustrates the composition of biogas produced from different feedstock ratios. The main components of the biogas from three feedstock ratios are CH_4, CO_2, N_2 and trace amount of O_2. This composition is similar to that reported in the literature [16] which mostly CH_4(50-57%), CO_2 (25-50%) and N_2 (0-10%). However, N_2 content in biogas from this work is relatively high for all feedstock ratios. The presence of N_2 in biogas might be a result of food waste feedstock that contains meat that produces a high amount of N. The biogas produced from hot water treatment condition shows higher percentage of CH_4 than that from normal condition of all the 3 feedstock ratios. Considering the biogas produced from feedstock that contain high amount of pig manure (Fig. 3a), the composition of CO_2 is higher for the condition without hot water treatment. This effect might be the result from the activity of methanogen bacteria. Because the methanogen bacteria can work better in thermophilic condition (45°C-65°C) [17]. Thus, they can effectively convert CO_2 and H_2 into CH_4 at high temperature, resulting in a smaller amount in CO_2.

3.2. pH in Fermentation Tank

According to the graph shown in Fig. 2, it is obvious that biogas production from all feedstock ratios began on about the 6th day and the gas volume gradually increases until it reaches the maximum at the fifteenth day, after that the gas volume slightly reduces until the 30th day. This trend like the trend of volume of gas production per day from U.C. Okonkwo et al [14] showing that gas production begins at 7th day and increase sharply until it reaches the maximum at 18th day before declining. Typically, gas production from anaerobic digestion takes place in four major reactions: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis occurs at the first step of fermentation process. Mainly it turns cellulose into glucose by cleavage C-C bond of cellulose with the presence of water molecule thus, addition of water into the feedstock is necessary. The glucose produced from this step can undergo successive reactions produced methanoic acid (CH_2O_2) hydroxymethyl furfural ($C_6H_6O_3$) and levulinic acid ($C_5H_8O_3$). The compounds formed in hydrolysis reaction further degrades and turns into CO_2 and H_2 through acidogenesis reaction. Acetic acid (CH_3COOH) is also a major acid produced in this step and is the most significant organic acid used as a reactant for CH_4 formation by microorganism [18]. The acidic products from hydrolysis and acidogenesis results in low pH value (<6.5) of fermentation tank during the first 10 day of fermentation are shown in Fig. 4. Acetogenesis is the third step of anaerobic digestion process known as dehydrogenation step. H_2 produced in this step is consumed by methanogen bacteria in methanogenesis reactions, producing CH_4. Because the acidic compounds produced in the first two stage are converted into CH_4 and CO_2 accordingly. There is a sharp increase in pH in the fermentation tank to about 7.5 after 10th day fermentation. The rise of pH correlates with the increasing volume of gas produced after the 10th day of fermentation, as shown in Fig. 2. The pH in fermentation tank was maintained at 7.0 -7.5 which is the most suitable range for methanogenesis by anaerobic digestion process. Okonkwo et al. [14] investigated burning characteristic of biogas produced from various organic waste and weeds. They found that biogas produced at first five-fermentation day did not burn. However, the combustion began at 6th day – 8th day in an unsmooth manner. This was because gases produced during the early period was mainly comprised of CO_2 since methane-forming bacteria were not fully active yet. The proper combustion occurred after the 9th fermentation day, showing that methane-forming bacteria are actived and methane began to occur. These findings were consistent with the results from the present study, showing that biogas volume sharply increases after the 10th fermentation day and remains constant until 30th day.

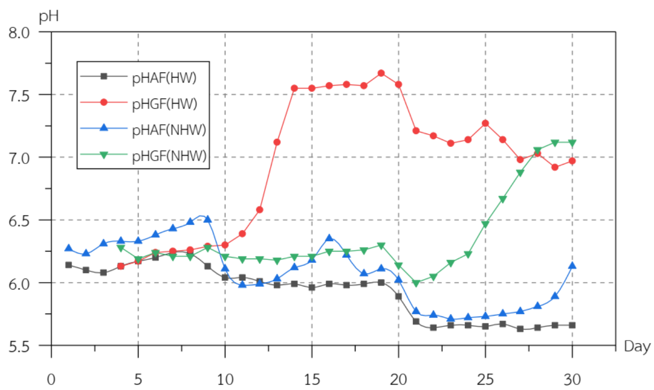

Fig. 4. The figure is pH of fermentation from day 1– day 30 when pHAF(HW) is pH in acid fermentation tank using hot water, pHGF(HW) is pH in gas fermentation tank using hot water, pHAF(NHW) is pH in acid fermentation tank without using hot water and pHGF(NHW) is pH in gas fermentation tank without using hot water.

3.3. Effect of Temperature on Biogas Production

It is known that the effectiveness of anaerobic bacteria depends on its activity. Therefore, it is essential to control factors affecting bacteria activity and temperature for anaerobic digestion. As a result, a study on biogas production from a digester with hot water treatment and

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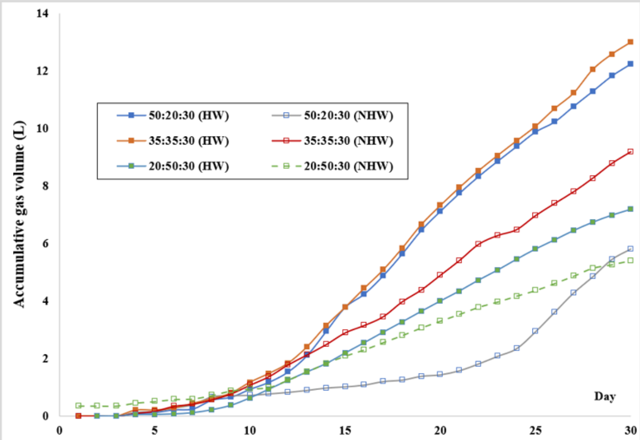
a digester without hot water treatment was carried out. The cumulative biogas volume along with the COD of effluent in digester with and without hot water were illustrated in Fig. 5 (a) and (b).



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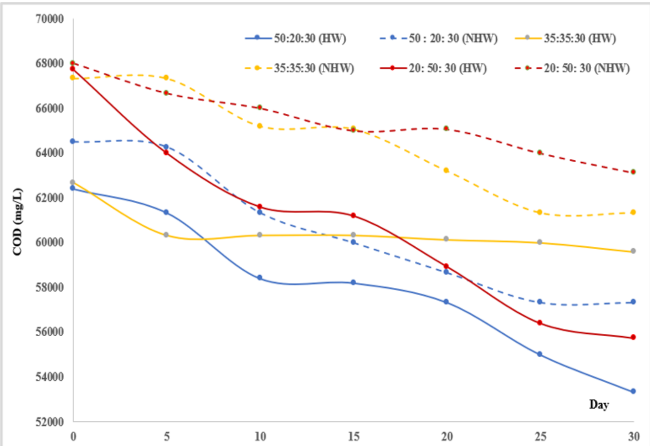


(b)

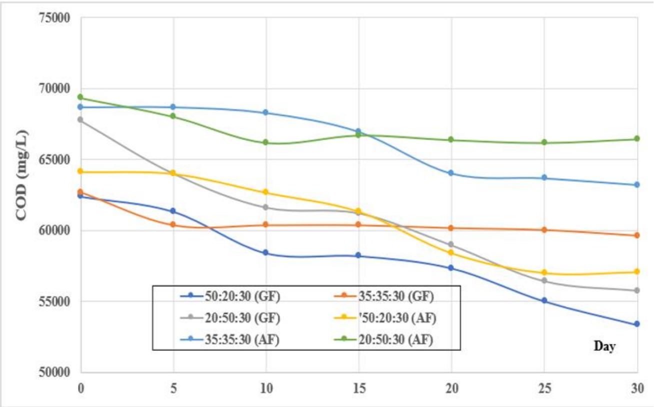
Fig. 5. The figure is (a) the cumulative biogas volume and (b) COD of effluent in digester, COD of samples in gas fermentation tank (GF) at different feedstock ratios under hot water (HW) and no hot water (NHW) condition.

The COD removal of system operated with hot water is higher than that without hot water for all three different feedstock ratios (Fig. 5(a)). The average temperature in GF tank for experiment with and without hot water are about 40^{o}C and 30^{o}C, respectively. Since bacteria converted organic matter into biogas are thermophilic bacteria, they can work more effective under high temperature condition. Thus, they can digest organic material under high temperature better than that under room temperature. Subsequently, the COD removal for an experiment under hot water is higher than that without hot water. The COD removals are consistent with the volume of biogas production from different conditions showing that anaerobic digestion under hot water condition give higher volume of biogas than an experiment without hot water. The results consistent with the finding from J G Zeikus and M R Winfrey [19] showing that optimum temperature for sediment methanogenesis is 35 to 42 °C. Guangliang Tian et al. [20] also reported that bacterial diversity involving hydrolysis, acidogenesis, and acetogenesis was observed when the temperature was raised to 45 °C. Products from hydrolysis, acidogenesis, and acetogenesis further undergo methanogenesis to produce methane. When temperature was raised to 55^{o}C, these bacteria will be decreased in number and acetotropic-type metabolism became major metabolic pathway. Additionally, Shiwei Wang et al. [21] investigate the effect of temperature (20-35^{o}C) on biogas production from cattle manure and corn starch and they found that maximum biogas volume was observed at 35 ^{o}C and it decreases sharply when temperature is decreased. The methane content accounted for 57.5% of total biogas production at 35^{o}C and the average methane content decrease slightly when temperature decreased. Apparently, the activity of methanogenic bacteria was relatively sensitive to low temperature disturbance.

3.4. Performance of Two-stage Anaerobic Digestion System

Chemical Oxygen Demand (COD) is an indicative measure of the amount of oxygen consumed over volume of solution. Typically, a COD value can be used to indicate the amount of organic matter in water. In biogas production process, organic matters in pig manure and food waste were converted into biogas by anaerobic microorganism thus the organic matters in the effluent would be reduced relative to that of feedstock. The COD value of sample in acidic fermentation (AF) tank and gas fermentation (GF) tank for biogas production using 3 different feedstock ratios were evaluated. The COD value and %COD removal by two stage anaerobic digestion is illustrated in Fig. 6.

The COD of samples in both AF and GF are gradually reduced from 5th day onwards until the 30th day of the experiment, indicating that organic matter in the solution was turned into biogas. COD removal (Fig. 6(b)) represents the quantity of organic material converted into biogas. Comparison between %COD removal in AF and GF, the COD removal of sample in GF is higher than that in AF. In acidic fermentation stage, organic matters were not yet converted into biogas, they were degraded into cellulose, carbohydrate, amino acid, and small organic compounds. Thus, the COD removal in AF tank is lower than that in GF tank. Normally, methanogenesis reaction takes place in gas fermentation stage. The methanogenic bacteria convert organic matter into biogas, consequently, reduces the amount of organic matter.



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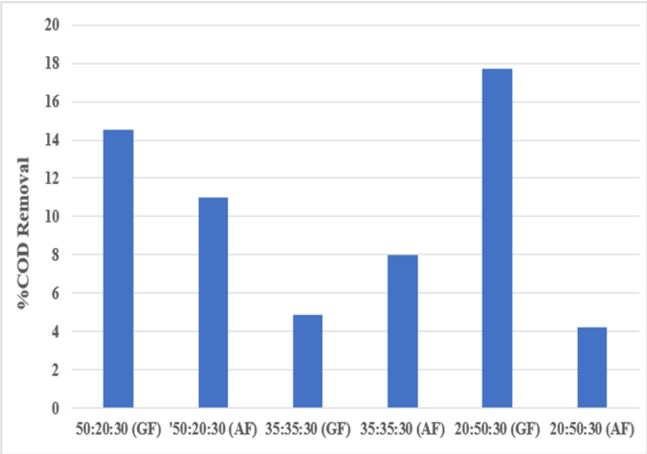
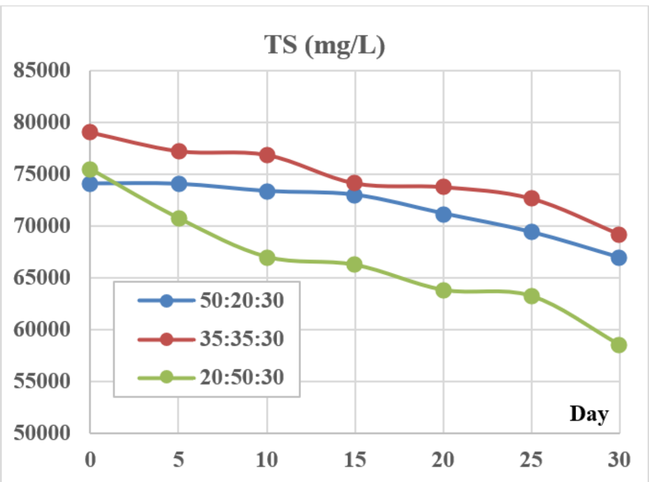


(b)

Fig. 6. The figure is (a) COD of sample and (b) %COD removal in acid fermentation tank (AF) and gas fermentation tank (GF) at different feedstock ratios.



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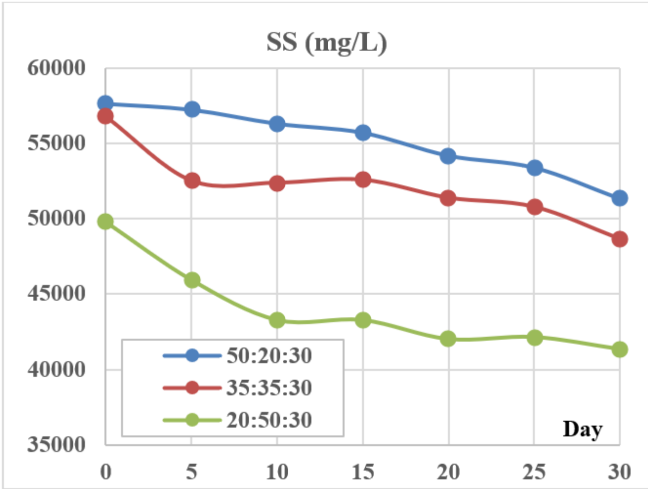

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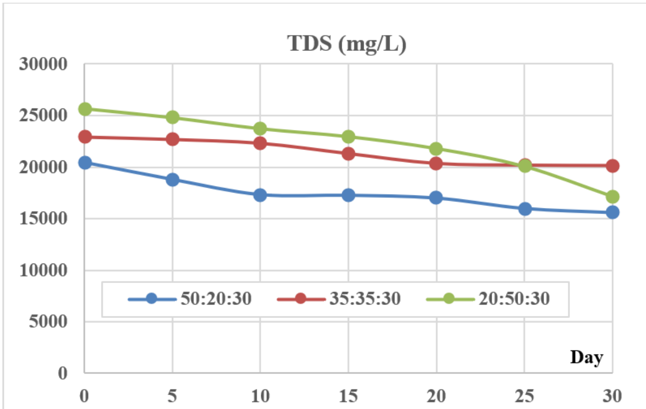

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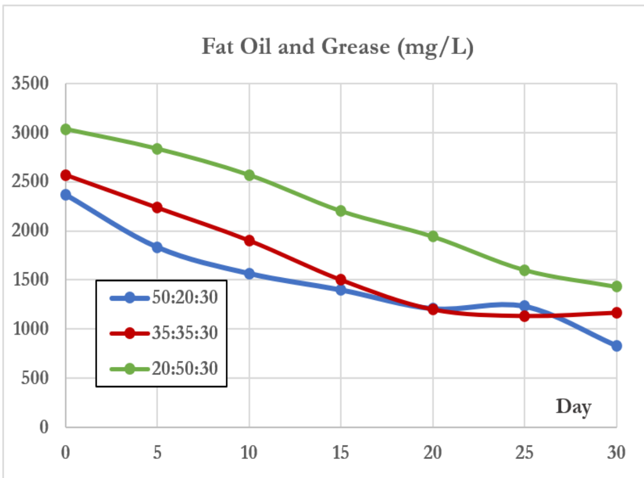

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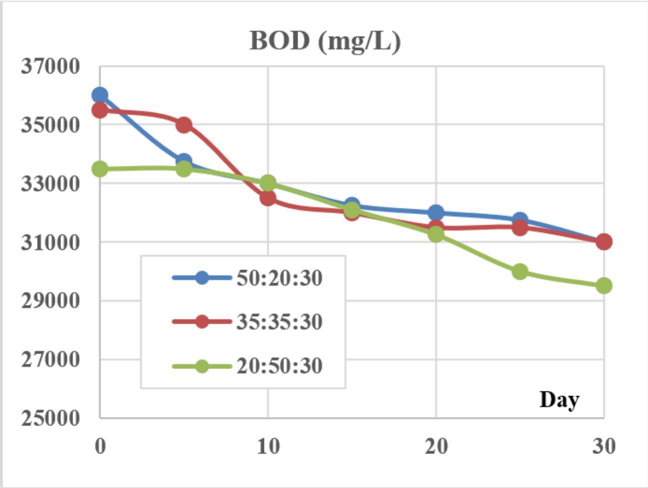

(e)

Fig. 7. The figure is (a) total solid, (b) suspended solid, (c) total dissolve solid, (d) amount of fat oil and grease and (e) BOD of sample in fermentation tank under hot water condition from day 1-day 30.

Figure 7 shows TS, SS, TDS, BOD and Fat Oil and grease of sample in fermentation tank. All parameters indicate the presence of organic matters in sample in the tank. An efficiency of anaerobic digestion can be evaluated by the reduction of these parameters and they were presented in Table 1. The results indicate that the mixing ratio of feed stock significantly affects the efficiency of anaerobic digestion.

Table 1. %Reduction of parameters characterized an effluent in gas fermentation tank with hot water treatment system.

Parameters	% Reduction		
	50:20:30	35:35:30	20:50:30
TDS	23.65	12.06	32.97
Fat Oil and Grease	64.79	54.54	52.85
BOD	13.89	12.67	11.94
TDS	23.65	12.06	32.98
SS	10.98	14.31	17.00
TS	9.67	12.39	22.43

4. Conclusions

The ratio of pig manure and food waste plays a significant row in a two-stage anaerobic co digestion. The ratios of pig manure, food waste and water at 50:20:30 and 35:35:30 favor biogas production. A major source of anaerobic bacteria is pig manure, the feedstock ratio with less amount of pig manure (20:50:35) produces less biogas because the system does not have enough bacteria. In addition, anaerobic digestion of food waste which contains a high C/N ratio causes the depletion of nitrogen while carbon is still available, resulting in starving anaerobic bacteria and they subsequently die. Products from hydrolysis and acidogenesis of feedstock cause pH in fermentation tank less than 6.5 during first-10 fermentation day. Acetogenesis and methanogenesis of acidic products cause the pH value in fermentation tank increase to 7.5 consequent to the volume of biogas state to occur at day 10. Hot-water treatment significantly increases volume of biogas for all feedstock ratios; however, the change in feedstock ratio results in differences in anaerobic co-digestion efficiency.

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