Int. J. Environ. Sci. Tech., 6 (1), 131-140, Winter 2009
ISSN: 1735-1472

Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application

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Received 3 June 2008; revised 13 September 2008; accepted 24 November 2008; available online 10 December 2008

ABSTRACT: In Thailand, sewage sludge production from the Bangkok metropolitan area can reach up to 63,000 ton/y by 2010. The Beer-Thai Company, Thailand, produces beer and generates lots of sludge as waste. Sewage sludge and brewery sludge can be used to generate energy which could be saved on the fossil fuels conventionally used as a source of energy. The possibility was explored to mix brewery sludge with sewage sludge at different mixing ratios for anaerobic digestion so that the energy can be generated as biogas and at the same time, digested sewage sludge can be used as fertilizer for agricultural applications. A batch anaerobic reactor under mesophilic condition for a digestion period of 40 days was used in the laboratory. The acrylic reactor was cylindrical with a working weight of 12 kg. The diameter was 23.7 cm and the height was 34.5 cm. Sludge mixtures at different ratios were fed into the reactors and the optimum mixing ratio was determined. Experimental results showed that the sludge mixture at ratio of 25:75 % by weight (sewage:brewery) yielded higher biogas production. A reduction in heavy metals and pathogens was observed at this ratio after the digestion indicating its safe use as fertilizer. Nitrogen content was about 4.95 % which is well above the commercial fertilizers. At optimum mixing ratio of 25:75, the amount of the generated biogas is 1.15×10^6 m^3/y. This large amount of biogas is equivalent to 1.44 million kWh/y of electricity, 561,000 L/y of diesel oil and 936,000 L/y of vehicle gasoline.

Key words: *Digested sludge, mixing ratio, nutrient recycling, energy, agricultural application*

INTRODUCTION

Bangkok, Thailand, with about 10 million people, generates large amounts of wastewater. During the wastewater treatment, it produces a huge amount of sludge which causes a serious disposal problem.

Utilization of sludge for agricultural application is increasing instead of the traditional disposal option as it recycles nutrients. It is predicted that Bangkok metropolitan administration (BMA) will produce up to 63,000 ton/y of sewage sludge by 2010 (Stoll, 1995; Eckhardt and Khatiwada, 1998). The Beer-Thai (1991) Co.,Ltd, Thailand, which produces beer, generates 100-120 m^3/day of sludge as waste (Pecharaply, 2007).

This is known to be one of the most interesting biosludges as it is rich in plant nutrients especially phosphorus and nitrogen. In addition, it has low heavy metal concentrations and is good for digestion. Sewage sludge and brewery sludge of the wastewater treatment plant (WWTP) represents a source of energy, biogas and a by-product of anaerobic digestion. Biogas can be considered as an alternative source of energy when facing an energy crisis.

In China, about 25 million people use biogas for cooking and lighting for 8-10 months a year. China also has sound experience in running diesel and gasoline engines with biogas (Marchaim, 1992). This could be saved on the nonrenewable sources of energy such as fossil fuels that tend to deplete rapidly and at the same time, sludge can be used to supply nutrients to soil and for soil amendment. However, if it be improperly managed, potential risk to both environment and public health may occur from the accumulation of heavy metals and organic compounds, as well as pathogen contamination. Co-treatment by anaerobic digestion of different types of wastes such as municipal waste, industrial waste, sewage sludge and other biowaste is a common practice for waste management elsewhere (Westlake, 1995; Voutsa *et al.*, 1996; Tang *et al.*, 1997). The co-treatment digester

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should receive wastes in a combination and digesting ratio that can steadily generate a high volume of biogas with high methane content. Luostarinen *et al*., (2008) investigated the increased biogas production at WWTP through co-digestion of sewage sludge with grease trap sludge from a meat processing plant and found that 66 % of methane gas could be yielded when sewage sludge and grease trap sludge was used at 95:5 feed on volatile solids basis.

Cecchi *et al*. (1988) and Hamzawi *et al*. (1998) found that cumulative biogas production of mixtures increased with increasing proportions of municipal solid waste under mesophilic condition.

Rosenwinkel and meyer (1999) noted that methane concentration in biogas yielded from anaerobic digestion of slaughterhouse residues and municipal wastes was between 66-67 %. Digestion of sewage sludge and macro algae gave 61.4-71.8 % methane (Cecchi, 1996). It may be a win-win situation for both parties if the brewery sludge is mixed with BMA sludge. This will help in treatment of the brewery sludge instead of disposal on land with no use and BMA would also benefit, since sludge mixtures can be applied to agricultural fields due to low concentrations of heavy metals. The objective of this study is to determine the amount of biogas generated during anaerobic digestion of sewage and brewery sludge at different mixing ratios in laboratory scale experiments. It also investigated the potential use of digested sludge for land application.

MATERIALS AND METHODS

Raw material and reactor preparation

Sewage sludge was collected from BMA central WWTP, Nong-Khaem, Bangkok and brewery sludge from Beer-Thai Co., Ltd. Lab-scale batch experiments were carried out at the ambient laboratory of Asian institute of technology, Pathumthani, Thailand. This research was carried out in 2003-2004. Energy calculations were done based on the current rates of 2008. The reactor was cylindrical in shape and made up of acrylic. The diameter was 23.7 cm and height was 34.5 cm. The mixed sludge of 12 kg was introduced into the reactor manually at the beginning and was closed for the anaerobic digestion process. Two continuous stirrers were operated at 150 rpm and were driven through a guide shaft which ended 25 cm below the liquid level to avoid gas losses. From the 4.5 L headspace each digester provided, volumetric biogas production was monitored daily by a gas metering unit using water replacement and digital counter which was directly connected to the headspace of the digesters. A U shaped glass tube linked between the digester and gas collector to avoid moisture and minimize analysis error. The reactor was covered by micro fiber in order to maintain the temperature mesophilic condition. A temperature sensor was also installed. The schematic diagram of the anaerobic digester used in this study is shown in Fig. 1.

Determination of sewage sludge and brewery sludge characteristics

Both types of collected raw sludge were analyzed for various parameters such as pH, moisture content (% MC), total solids (% TS), volatile solids (% VS), total nitrogen (% TN), total phosphorus (% TP), total potassium (% TK), organic carbon (%), total heavy metal (mg/kg of Cd, Cr, Cu, Pb, Ni, Zn, Hg) and pathogens (MPN/100 g of fecal coliforms). The anaerobically digested sludge from the reactor was also analyzed for the above parameters in order to find its use for land application/agricultural activities. Sewage and brewery sludge were analyzed following the methods as shown in Table 1. Most of the parameters were analyzed following standard methods (APHA, 1995).

Co-digestion of sewage sludge and brewery sludge at various ratios

The sewage and brewery sludge were mixed at different ratios of 100:0, 75:25, 50:50, 25:75 and 0:100 by weight, respectively. Water was added to the pure brewery sludge in order to maintain TS in the digester to be around 5-10 %, the desired range for anaerobic digestion. Sludge mixtures were analyzed for the following parameters: pH, % MC, % TS, % VS and % TCOD before feeding into the digester. The reactor was operated under the ambient temperature, 31-37 ºC which represents mesophilic condition. The retention time was about 40 days and is normally enough for complete digestion. Nitrogen gas was flushed initially to maintain anaerobic conditions and alkali was added to the reactor to maintain neutral pH which might drop due to VFA generation. The sludge mixture was continuously mixed using stirrers. The amount of biogas, ambient temperature and pH were monitored everyday. The produced gas was collected in a gas displacement chamber which was directly connected to the headspace of the reactor and measured continuously by the gas metering unit (Fig. 1). Gas chromatography (Shimadzu GC14A) was employed for measuring biogas composition using helium as the carrier gas. The detector is thermal conductivity detector (TCD) with the pack column (WG-100 SS Col.1/4 O.D.×1.8 m) and the working pressure of 0.75 kg/cm^2. The Injection/ column/detector temperatures were as 50/50/100 °C, respectively. The optimum mixing ratio was found based on the amount of produced biogas and on the usage of digested sludge for land application.

RESULTS AND DISCUSSION

Characteristic of sewage sludge and brewery sludge as a baseline

The characteristics of raw sewage sludge and brewery sludge are shown in Table 2. Brewery sludge was slightly alkaline with a very offensive odor. VS were found to be 70.7 % and the sludge was also rich in nutrients such as nitrogen. In sewage sludge, the VS were 39.6 %. Some heavy metals in both types of sludge exceeded the standards; for example, Cu in BMA sludge which may be from metal pipes during conveyance or due to discharges from small industries. High concentrations of Cd, Pb and Zn were also observed in brewery sludge and require further investigation to identify the possible sources. BMA sludge had fecal coliforms under the standard Class B (more than 1,000 MPN/g dry weight). Brewery sludge can be classified under the standard Class A (US EPA, 1994) as the fecal coliforms were less than 1,000 MPN/g dry weight.

Characteristics of sewage sludge and brewery sludge at different mixing ratios

Table 3 depicts the characteristics of sludge mixtures at different mixing ratios. The pH ranged from 7.1-8.4. Moisture content was the highest in pure BMA sludge. VS were found to be high in pure brewery sludge and low in pure BMA sludge. High TCOD values in all sludge indicate high organic content.

Biogas production at different mixing ratios

It is evident that from all sludge mixing ratios, pure brewery sludge would yield the maximum biogas production due to high organic content. However, maximum biogas production was not the only criterion to select the optimum mixing ratio. Digested sludge should also be safe to be used for agricultural application.

According to Metcalf and Eddy (1991), total gas production is estimated usually from the percentage of VS reduction. Typical values range from 0.75-1.12 m^3/kg of destroyed VS. Fig. 2 shows cumulative gas production at different mixing ratios with time. From Fig. 2, it can be seen that the biogas production still showed an upward trend, but the experiment was conducted for 40 days only. When pure BMA sludge was used, only 0.08 L of biogas was generated. High VFA produced during the digestion may also inhibit the methanogenesis process. It is well known that the presence of heavy metal, oxygen or too high VFA can cause failure of the anaerobic digester (Polprasert, 1996). The greater the brewery sludge content, the higher was the biogas production. Biogas production at the ratio of 25:75 (sewage sludge:brewery sludge) was 126.67 L and was the highest among three different mixing ratios (75:25, 50:50 and 25:75) used in this study. This was considered to be the optimum mixing ratio based on higher biogas production and the safety of

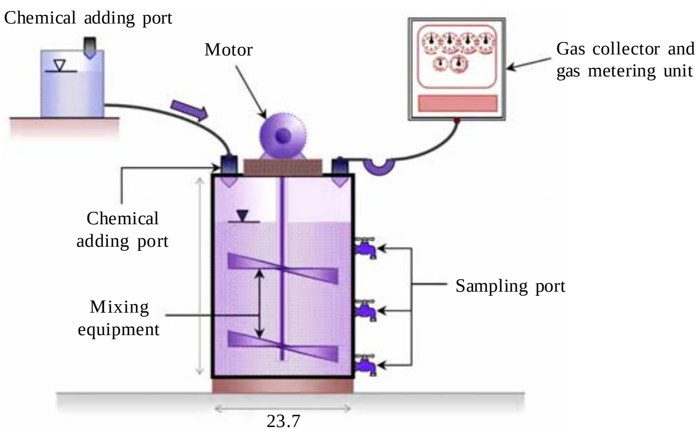

Fig. 1: The schematic diagram of anaerobic digester

Table 1: Parameters and analytical methods of sewage and brewery sludge

Parameters	Units	Analytical methods
pH	-	Standard methods part 4500 B: Electrometric method, pH meter (Glass electrode)
Moisture content	%	ASTM D2974-87: Evaporation at 105 °C
Total solids (TS)	%	Standard method part 2540 B: TS dried at 105 °C
Total volatile solids (TVS)	%	Standard method part 2540 E: TS loss after ignited at 550 °C
Total nitrogen	%	Semi-Micro Kjeldahl method (McGill and Figueiredo, 1993)
Total phosphorus	mg/kg	$HCLO_4$ acid digestion method (Carter, 1993)[a]
Total potassium	mg/kg	Ammonium acetate method at pH = 7 (Hendershot *et al.*, 1993)
Organic carbon	%	Walkley-Black method (Rhoades, 1982)
Total metal concentration: Cd, Cr, Cu, Pb, Ni, Zn, Hg	mg/kg	Mixed acid digestion technique followed by detection using AAS (Soon and Abboud, 1993)
Pathogen (Fecal coliforms)	MPN/100 g	MPN technique

Table 2: Characteristics of raw sewage sludge and brewery sludge before digestion

Parameters	Units	Sewage sludge	Brewery sludge
pH	-	7.4	8.40
Moisture content	%	96	87.5
Total solids (TS)	%	4.0	12.5
Volatile solids (VS)	%	39.6	70.7
5 Total nitrogen	%	2.74	5.98
Total phosphorus	%	3.23	5.48
Total potassium	%	0.54	0.92
Organic carbon	%	32.8	269
C/N	-	12.0	45
Total COD (TCOD)	mg/L	20,393	111,915
Total heavy metal concentration			
Cd		2.5	28
Cr		385	16
Cu	mg/kg	4,673	75
Pb		139	336
Ni		156	7
Zn		2,387	691
Hg		0.19	0.3
Pathogen (Fecal coliforms)	MPN/g air- dried sludge	$4×10^4$	$5.6×10^2$

digested sludge for agricultural application. Experiments with 100:0 and 0:100 were done to obtain the baseline data. Murto *et al.* (2004) conducted the experiment on anaerobic co-digestion of sewage sludge and potato processing industrial waste. They found that the highest biogas production rate was 1.2 L/day at an organic loading rate of 4.2 kg VS/m^3/day. Hawkes and Hawkes (1987) reported a gas yield of 0.6 m^3/kg VS from the digestion of sewage sludge and Gunaseelan (1997) also obsereved a methane yield of 0.42 m^3/kg VS for potato waste. For co-digestion of manure, slaughterhouse and agricultural waste, gas yields were 1 m^3/kg VS. The theoretical gas yield for starch is 0.8 m^3/kg. Reported gas yield for pig manure is 0.4 m^3/kg VS (Hashimoto,1983) with the methane content in the biogas around 70 %.

Composition of biogas was also analysed each day for all ratios (data not shown). Fig. 3 shows the percent of the methane gas produced with time at different mixing ratio. For sewage sludge to brewery sludge ratio at 100:0, 40 days digestion period might not be enough to have complete digestion, thus the methane gas was still increasing slowly. Very small amounts of methane gas could be detected during the first 24 days. During the system imbalance, methane production will decrease (Parkin and Owen, 1986). The total gas production rate may remain unchanged despite falling methane production rates because of increased CO_2 production.

Maximum methane gas concentration was about 65.4 %. The presence of oxygen in the biogas composition can be one of the reasons that inhibited the biogas production which might be due to high moisture content in BMA sludge itself. Activity of methanogenic bacteria may have been also inhibited by high heavy metals concentration in BMA sludge. From the study of BMA (1995), it was found that Cu was above the standard and was considered as a limiting factor. From the results, it can be concluded that the operation of the reactor under high levels of oxygen gas and heavy metals suppressed the activity of methanogenic bacteria. For sewage sludge to brewery sludge ratio at 75:25, production of methane gas is rapid during the first six days and after that it increases slowly. Methane gas could reach up to 71.8 % of total gas composition during the operation period and was 64.9 % on the last day. Compared with the pure sewage sludge, this ratio shows a better result due to the addition of brewery sludge. The co-fermentation experiment with the mixture of sewage sludge, (75 %), and an organic fraction of municipal solid waste (OFMSW), 25 %, resulted in a steady increase in methane content in biogas from 15 % in the acidogenic phase to 75 % volume of methane while the carbon dioxide content decreased from 80 % to almost 20 % volume (Sosnowski *et al.*, 2002). OFMSW can be compared with brewery sludge as it has high organic content. The methane content is almost the same. For sewage sludge to brewery sludge ratio at 50:50, methane gas production increased rapidly for the first seven days and after that a slow increase was observed with time. Methane gas could reach up to 71 % of total gas composition during the operation period and was 63 % on the last day. For sewage sludge to brewery sludge ratio at 25:75, a rapid increase in the methane gas was observed during the first seven days and after that it increased slowly. Methane gas could reach up to 72.9 % of the total gas composition during the operation period and was 68.6 % on last day. Biogas composition at 25:75 contains CH_4, CO_2, N_2 and O_2 as 68.6 %, 26.8 %, 0.7 % and 3.9 %, respectively. For sewage sludge to brewery sludge ratio at 0:100, methane gas was produced rapidly during the first seven days. After that a slow increase was observed with time and reached to 72.4 % on the last day. At the ratio of 0:100, pure brewery sludge could generate the highest amount of biogas.

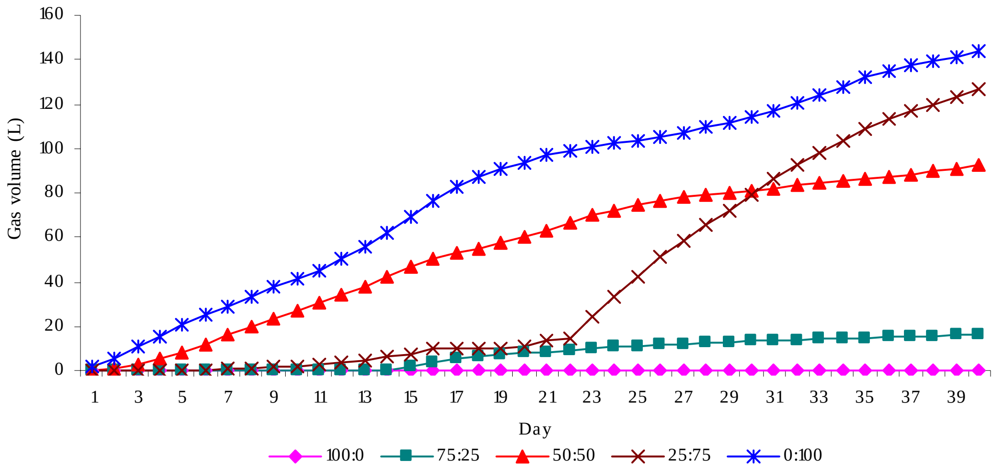

Fig. 2: Cumulative biogas production with time at different mixing ratios (sewage sludge to brewery sludge)

Table 3: Characteristics of sewage sludge and brewery sludge mixtures at different ratios

Parameters analysis	Unit	Sewage sludge to brewery sludge				
		100:0	75:25	50:50	25:75	0:100
pH	-	7.4	7.10	7.30	7.30	8.40
MC	%	96	94.2	92.1	92.2	92.1
TS	%	4.0	5.80	7.90	7.80	7.90
VS	%	39.6	52.9	61.2	63.2	68.9
TCOD	mg/L	20,393	42,000	61,280	65,619	70,800

Energy potential at optimum ratio

The equivalent amounts of alternative sources of energy as compared to the amount of biogas generated at 25:75 are shown in Table 4. This shows that a large amount of biogas can be produced by anaerobic digestion. BMA and Beer-Thai produce about 73 and 110 m^3/day of sludge, respectively (density of 1.02 and 1.7 kg/L). At 25:75 ratio, BMA sludge amounting to 27,177,900 kg (73 m^3/day) and brewery sludge to 54,355,800 kg (87.6 m^3/day, not all used for 25:75 ratio) can generate 1,147,541 m^3/y of biogas and 777,831 m^3/y of methane. The calculations are based on the total amount of BMA generated sludge and the amount of biogas produced at the optimum mixing ratio of 25:75. Thus, all BMA sludge can be treated producing a large amount of biogas. Different types of energy that can be generated from the total amount of produced biogas are discussed below and also presented in Table 4.

- Heat: Biogas can be directly burnt in boilers to produce hot water and steam used for heating and sanitary washing.
- Automobile fuel: After removing carbon dioxide and hydrogen sulfide from biogas to obtain usable methane, the technique of fueling is basically the same as that used for compressed natural gas (CNG) vehicles. It is an environmentally attractive alternative and generates less sound which is a positive aspect, particularly in urban areas. As methane burns very cleanly, exhaust fume emissions are considerably lower than the emission from diesel engines and the emission of nitrogen oxides is very low. If it be used instead of diesel fuel and gasoline, this replacement would save about 19.6 million Baht/y or 604, 606.41 USD/y and 36.1 million Baht/y or USD 1.12 million/y, respectively.
- Coal: Biogas production from this study, 1.15×10^6 m^3/y) could substitute 918,032 kg/y of coal which is equivalent to 4.6×10^5 Baht /y or 12,089.36 USD/y.
- Liquefied petroleum gas (LPG): LPG is the most versatile of fuels for heating, hot water, cooking and a host of other uses. The energy replacement from biogas produced in this study to LPG cooking gas is equal to 5.3×10^5 kg/y of LPG and will save about 10.2 million Baht/y or 315,515.11 USD/y.
- Electricity generation: Biogas can be burned to produce steam which has high temperature and pressure. The high pressurized steam can be used to rotate a turbine and generate electricity. The amount of biogas generated each year from BMA sludge and brewery sludge (1.15×10^6 m^3/y) is equivalent to 1.44×10^6 kWh and can generate a saving of 5.33 million Baht/y or 140,078.84 USD/y.

Characteristics of digested sludge at different ratios and its suitability for land application

Characteristics of sewage sludge and brewery sludge after digestion at different ratios are shown in Table 5. All digested sludges had a pH around neutral.

TS were reduced to about 13.3-26.2 %. VS reduction ranged from 14.6 % to 33.6 %. The optimum VS reduction should be about 30 % after sludge digestion (Metcalf and Eddy, 1991). The greater the amount of the brewery sludge, the higher is the nitrogen content. All of the

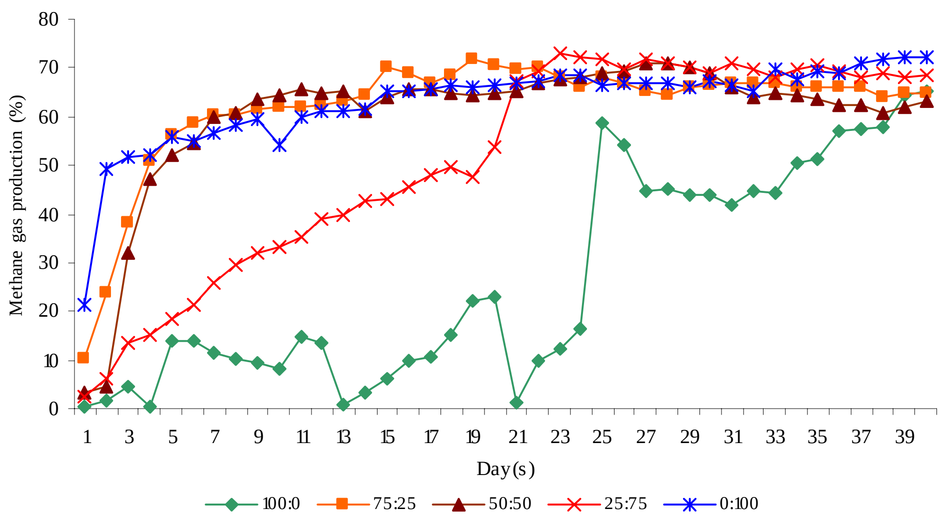

Fig. 3: Percent methane gas production with time at different mixing ratios (sewage sludge to brewery sludge)

mixed sludge can be applied to soil as a source of plant nutrients. Total nitrogen in digested BMA sewage sludge was lower than the typical anaerobically digested sludge which is about 3 % (Polprasert, 1996). For optimum microbial decomposition, C/N ratio should be 25:1 (Polprasert, 1996). For this study, C/N ratio was not adjusted. The sludge mixtures were kept in anaerobic condition for a long period of time (40 days) at about 30-35 °C and this condition was sufficient to inactivate some of the pathogenic bacteria and helminth eggs. Compared with the baseline study of BMA sewage sludge and brewery sludge, the fecal coliforms were less than 1,000 MPN/g dry weight and were well within the limits of Class A standard (US EPA, 1994) indicating that the digested sludges can be directly used for agricultural application without restrictions. According to AGSS (1995), the survival of fecal coliforms in all digested sludges can be considered under category 2 and is safe for agricultural applications. Digested sludge could meet the compost standards and also proposed BMA standards. Sludge contains high amounts of nitrogen and phosphorus indicating high nutrient value.

Heavy metals concentration in the digested sludge mixtures and comparison with standards

For 100:0, following the German standard and the Australian guidelines, Cu must be treated so that the sludge can be considered safe for Class B (for agriculture). This sludge can be applied to the land that has low Zn concentration as the Zn content is slightly high. The sludges meet the U.S standards for clean sludge except Cu which was higher than both the clean sludge limits and ceiling concentration limits.

For 75:25, following the Australian standard, the sludge was well below the standard for Class B. According to the German standard, heavy metals concentration were well below the limit for sludge except Cd and Cu. However, relaxation on Cd concentration can be provided that the pH of soil is in the range of 5-6. According to US Standards, heavy metals concentration were well below the clean sludge limit and ceiling concentration limit except Cu. For 50:50, according to Australian guidelines, it is considered safe for class B. Following German standards, the sludge was considered safe for agricultural application except for Cd and Cu concentration. For US standards, the sludges can be used without restriction. For 25:75, which was considered as the optimum mixing ratio, different standards/guidelines are presented in Table 6. It can be seen that according to Australian guidelines, this sludge mixture can not be applied for unrestricted use in class A because of Cd, Pb, Cu and Zn. However, all of the heavy metals concentration in this sludge mixture were well below the standard class B. According to German

Table 4: End use of biogas from BMA sewage sludge to brewery sludge at 25:75 by weight

	Unit	Value
Biogas production	m^3/y	1.15×10^6
Energy	Kcal/y [1]	5.74×10^9
	MJ/y [1]	2.41×10^7
Diesel fuel	Kg/y [1]	4.60×10^5
	L/y [2]	5.61×10^5
	Baht/y [3]	1.96×10^7
	USD/y	604,606.41
Gasoline	Kg/y [1]	6.90×10^5
	L/y [2]	9.36×10^5
	Baht/y [3]	3.61×10^7
	USD/y	1.12×10^6
Coal	Kg/y [1]	9.20×10^5
	Baht/y [4]	4.60×10^5
	USD/y	12,089.36
LPG	Kg/y [5]	5.30×10^5
	Baht/y [6]	1.02×10^7
	USD/y	315,515.11
Electricity	kWh [7]	1.44×10^6
	Baht/y [8]	5.33×10^6
	USD/y	140,078.84

Note: 1 USD = 32.42 Baht Biogas has a heat value of 4,500-5,000 kcal/m^3 when its methane content is in range of 60-70 %. Assume that all carbondioxide is scrubbed out than 1 m^3 of biogas has heat value of 5,000 kcal or 21 MJ and is equivalent to 0.4 kg of diesel oil, 0.6 kg of gasoline or 0.8 kg of coal.
[2] Diesel fuel oil 20 to 60 at 15 °C density is 820-950 kg/m^3, gasoline (vehicle) at 15.5 °C (60 °F) density is 737.22 kg/m^3; [3] 1 L of diesel fuel is 34.94 Baht; 1 L of gasoline is 38.59 Baht; [4] 1 metric ton of coal costs 500 Baht.; [5] 1 m^3 of biogas is equivalent to 0.46 kg of LPG (liquid petroleum gases); [6] LPG price is at 19.3 Baht/kg (290 Baht/15-kg cylinders); [7] 1 m^3 of biogas is sufficient to provide 1.25 kw/h of electricity; [8] Electricity of 1 kW/h is equal to 3.7 Baht

Table 5: Characteristics of sewage sludge and brewery sludge at different mixing ratios after digestion

Parameters	Proposed BMA standards/ USEPA standards[4]	Compost Standards[4]	Sewage sludge to brewery sludge 100:0	75:25	50:50	25:75	0:100
pH	-	5.5-8.5	7.30	7.20	7.50	7.20	7.40
Total solid (%)	-	> 65	3.50	4.20	5.80	5.80	6.00
Volatile solid (%)	-	-	38.3	43.5	55.1	57.6	61.8
Total nitrogen (%)		0.2-1	2.34	3.41	4.37	4.95	5.71
Total phosphorus (%)		0.2-1	2.95	3.64	4.30	4.86	5.11
Total potassium (%)		-	0.51	0.72	0.83	0.86	0.88
Organic carbon (%)		-	12.77	13.17	12.43	14.76	15.25
Organic matter[1] (%)		15-60	21.96	22.65	21.38	25.38	26.23
C/N ratio		-	5.45	3.86	2.84	2.98	2.67
Fecal coliforms (MPN/g air-dried sludge)	- /1 x 10^3 – 2 x 10^6	-	110	2	13	ND	25
Heavy metals[2] (mg/kg dry wt.)							
Cr	1,000/1,200	-	333	243	90	69	13
Ni	400/420	-	127	81	43	30	7.0
Pb	1,000/300	565	102	122	274	285	305
Cd	20/39	19	1.6	9.40	19.8	22.1	25.3
Hg[3]		-	0.18	0.23	0.57	0.24	0.3
Cu	900/1,500	725	4,425	2,123	1,415	368	67
Zn	3,000/2,800	1,000	2,125	1,432	1,045	795	630

ND = Not detected
[1] Percent organic matter = % Organic carbon × 1.72
[2] The accuracy of the heavy metals determination is based on the precision of AAS flame type (HITACHI Z-A230)
[3] Hg was analyzed by the Office of Public Health and Environmental Technology Services, Faculty of Public Health, Mahidol University, Bangkok, Thailand (AAS flame type VARIANCE 600)
[4] (Dacera, 2007)

Table 6: Comparison of heavy metals with standards in digested sludge at 25:75 (BMA sludge to brewery sludge)

Heavy metals	Value (mg/kg)	BMA standard[1]	Australian guidelines[2]		German standards[3]		US standard[4]	
			Class A	Class B	Limit for sludge	Limit for soil	Clean sludge limit	Ceiling conc. limit
Cd	22.1	×	×	✓	×	×	✓	✓
Pb	285	✓	×	✓	✓	×	✓	✓
Hg	0.24	✓	✓	✓	✓	✓	✓	✓
Cr	69	✓	✓	✓	✓	✓	✓	✓
Cu	368	✓	×	✓	✓	×	✓	✓
Ni	30	✓	✓	✓	✓	✓	✓	✓
Zn	795	✓	×	✓	✓	×	✓	✓

✓= within standards; × = beyond standard limits
[1] AIT (1998)
[2] Australian guidelines for sewerage system: Bio-solid management, 1995
[3] Eckhardt and Khatiwada (1998)
[4] USEPA (1993)

standards, all the heavy metals were in permissible limits for sludge except Cd. For US standards, all of the heavy metals concentration were under clean sludge limits, as well as ceiling concentration limits. For 0:100, heavy metals concentration were well below the Australian guidelines. The concentrations of Cd, Pb and Zn were above the guidelines for Class A. However, the sludge was considered safe in Class B. Following German standards, all heavy metals were within the standard allowable limits for sludge except Cd concentration. For US standards, all of the heavy metals concentration of sludge were well below the clean sludge limit, as well as the ceiling concentration limit except Pb which was a little bit above the clean sludge limit. Compared with BMA guidelines, at 100:0, only Cd and Zn are in the range. These are probably due to the difference between the incoming raw wastewater and seasonal variation. However, Hg was not studied by the BMA. All heavy metals were well below the BMA guidelines except Cu. For 75:25, it is considered safe for agricultural application. For 50:50, Cu should be treated. For 25:75 and 0:100, Cd should be treated. The heavy metals after treating under anaerobic condition was predominated in the forms of sulfide bound and organic matter bound fractions (Kanatip, 1995; Pichit, 2000) which resulting in the least soluble forms and is safe for agricultural use with suggestion for close monitoring after sludge application (Parkpian *et al.*, 2002).

CONCLUSION

Observing the amount of the biogas generated at different ratios, it was found that the maximum quantity of biogas was generated at a mixing ratio of 25:75 (optimum) and was 126.67 L. However, a longer digestion period may be required because the biogas production was still increasing slowly after 40 days at every mixing ratio. At the optimum mixing ratio (25:75), methane gas could reach up to 72.9 %. Biogas contains CH_4, CO_2, N_2 and O_2 as 68.6 %, 26.8 %, 0.7 % and 3.9 %, respectively. This ratio was considered to be the best as it can produce the maximum quantity of biogas and the quality of the digested sludge is also good. It was found that at the optimum mixing ratio, total biogas production is 1,147,541 m^3/y. Once it burnt, it will generate about 5,737,707, 650 kcal/y of energy or 24,098,361 MJ/y which is enough to produce 5.61×10^5 L/y of diesel fuel, 9.36×10^5 L/y of gasoline, 9.2×10^5 kg of coal, 5.3×10^5 kg of LPG and 1.44×10^6 kWh/y of electricity. For heat generation, the biogas can be directly burnt to generate heat. In terms of cost saving, 604,606.41 USD/y of diesel fuel, 1,114,134.48 USD/y of gasoline, 12,089.36 USD/y of coal, 315,515.11 USD/y of LPG and 140,078.84 USD/y of electricity could be realized. Digested sludge from a mixture of 25:75 is recommended to be used for agricultural application due to its low concentration of heavy metals, high nutrient content (nitrogen content of 4.95 %) and removal of fecal coliforms. The biogas production was also high at this ratio. With the good sludge quality, BMA can save the cost for fertilizers to be applied in public parks in Bangkok and can also produce biogas which can be used as a source of energy for different purposes.

ACKNOWLEDGEMENTS

This work was supported partially through Master's scholarship by Asian Institute of Technology (AIT), Pathumthani, Thailand and their financial support is gratefully acknowledged.

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This article should be referenced as follows:
Babel, S.; Sae-Tang, J.; Pecharaply, A., (2008). Anaerobic co-digestion of sewage and brewery sludge for biogas production and land application. Int. J. Environ. Sci. Tech., 6 (1), 131-140.