A THESIS FOR MASTER OF SCIENCE

Mesophilic underground anaerobic digestion of swine slurry

Net energy gain and digester performance

돈슬러리의 중온(中溫) 지하 혐기성 소화

순(純) 에너지 증가와 소화조 성능

August 2014

Seoul National University Graduate School

Department of Agricultural Biotechnology

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Advisor: Professor Hong Lim Choi

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ABSTRACT

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Anaerobic digestion is a suitable technology to treat high strength wastewater which has more than 3% of chemical oxygen demand (COD) such as swine slurry. It reduces and converts organic matter biologically into biogas that has high energy value. The effluent of anaerobic digestion has a high nutrient value of total ammonia nitrogen (TAN) and total phosphorus (TP) that are essential for plant growth. Therefore, the digestate has potential to be utilized as a fertilizer. However, anaerobic digestion in a temperate region has been associated with negative energy gains due to comparatively colder and longer winter seasons. Soil temperature at 3.0 m below the surface varies in a range of ±5ºC over the seasons, thus, it could be possible to achieve net energy gain if an anaerobic digester is placed underground. However, the performance of an UGAD needs to be investigated throughout the seasons in a temperate region in terms of energy balance, biogas production, and reduction of biochemical parameters.

An UGAD with a working volume of 20 m^3 was built and operated at mesophilic conditions (35^oC) from November 2009 and still operating until today. The UGAD was equipped with the polystyrene media which act as attachment media to prevent the wash out of

anaerobic microbial biomass. The whole experiment period has been broken into two phases. The UGAD had been operated to investigate its energy balance hydraulic retention time (HRT) of 27-day for the 1st phase experiment from October 2010 to July 2011. The raw swine slurry was screened through a slant separator with 4 mm mesh in the first phase experiment. The second phase experiment was done from August 2012 to July 2013 and mainly investigated the effect of shorter HRT of 19-day on the UGAD performance such as biogas production rate and biochemical parameters reduction. The raw swine slurry for the 2nd phase was screened through 0.5 mm mesh and liquid portion was fed to the UGAD.

The first phase experiment showed that the estimated daily energy production and daily energy consumption was 301.3 MJ day^{-1} and 242.5 MJ day^{-1}, respectively. It turns out to be net energy gain of 58.8 MJ day^{-1} during the winter season, December 2010 to February 2011, with average ambient temperature of -2.1ºC. In addition, average methane production at a standard temperature and pressure (STP, 273 K and 1 atm) was 7.90 m^3 day^{-1} with a specific yield of 362 L-CH_4 kg $COD_{removed}^{-1}$ throughout the 268-day experiment. Total chemical oxygen demand ($tCOD_{cr}$), 5-day biological oxygen demand (BOD_5), and *E. coli* removal efficiency was 63.66, 85.82, and 99.79%, respectively. Combination of long HRT (27-day) and free ammonia (FA) concentration may attribute to high pathogen removal efficiency.

The second phase experiment showed that shorter HRT (19-day) resulted in a higher biogas production rate but a lower organic matter removal efficiency and a lower specific methane yield compared to longer HRT of 27-day. The daily energy production rate and daily energy consumption was 349.6 MJ day^{-1} and 213.9 MJ day^{-1}, respectively. It turns out to be net energy gain of 135.7 MJ day^{-1} during the winter season, December 2012 to February 2013, with average ambient temperature of -2.4^{o}C. Higher net energy gain of the second phase experiment than the first phase experiment is mainly due to higher biogas production which is caused by higher COD and VS of the more influent than that of the first phase experiment. The removal efficiencies of TS, VS, $tCOD_{cr,}$ and BOD_5 during the second phase experiment were 32.75, 41.53, 59.63, 67.17, and 84.62%, respectively. The average methane production rate at the standard temperature and pressure (STP, 273 K and 1 atm) was 10.08 m^3 day^{-1} which accounts for 127.6% of that of the first phase experiment. However, the specific methane yield at the standard temperature and pressure (STP, 273 K and 1 atm) was only 322 L kg $COD_{removed}^{-1}$ which accounts for 88.9% of that of the first phase experiment. It seems natural that a shorter HRT means it gets the substrate less biodegraded which leads to less conversion and biodegradation of organic matter into biogas.

The average $tCOD_{cr}$ and VS removal at 19-day HRT with 1000 L day^{-1} feeding rate was 34,662 and 9,443 mg L^{-1}, respectively. This means around 34.62 kg COD and 9.44 kg VS can be removed daily at 19-day HRT. Meanwhile, the average $tCOD_{cr}$ and VS removal at 27 days HRT with 700 L day^{-1} feeding rate was 34,436 and 10,234 mg L^{-1}, respectively. This means only 24.11 kg COD and 7.16 kg VS can be removed daily, which are equivalent to only 69.64 and 75.85% of those of the 19-day HRT, respectively.

This experiment suggests an UGAD can be used as an alternative system for anaerobic treatment of swine slurry in a temperate region because it demonstrated net energy gain even during winter season and high organic and pathogen removal efficiency. In addition, the UGAD performance in shorter HRT in term of biogas production rate was better than that of longer HRT. However, new operational strategies needs to be considered and developed to improve organic matter removal efficiency and specific methane production in shorter HRT so that it can be equal or better than that of the longer HRT.

Keywords: hydraulic retention time, net energy gain, swine slurry, temperate region, underground anaerobic digester

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1. INTRODUCTION

In recent years, the number of produced swine has reached 1 billion head worldwide (faostat3.fao.org/home/index.html#DOWNLOAD). At the same time, concentrated swine operation becomes a trend which led to the accumulation of swine slurry in a limited area. Approximately 10 million of swine is raised annually in South Korea (faostat3.fao.org/home/index.html#DOWNLOAD) with an estimated 13 million tons of slurry produced every year.

Swine slurry is a mixture of feces, urine, and small fraction of wasted feeds that have been diluted with flushing water (Sanchez et al., 2005; Suresh & Choi, 2012). It contains organic matters, nutrients, and pathogens, so that the accumulation of swine slurry will generate various environmental problems such as greenhouse gas and odor emission during storage and pollution of water body (Chae et al., 2004; Cheng & Liu, 2002; Holm-Nielsen et al., 2009; Lee & Han, 2012; Sanchez et al., 2005). Its characteristics may vary depending on growth phase, feed, and amount of flushing water used (Ndegwa et al., 2002). However, previous works have reported that total solid (TS) content ranges from 0.6–12.6% (moisture content ranges from 87.4-99.4%) with a volatile to total solid ratio (VS TS^{-1}) of 56-84% (Suresh et al., 2009). High moisture content means that the slurry exists in a liquid form, thus making slurry transportation become uneconomical. This makes on-site treatment of swine slurry is preferred (Hobson et al., 1974).

A high proportion of volatile solid in swine slurry indicates it has potential to be utilized as substrate to produce various products such as enzyme, renewable energy, microbial biomass, etc. Recent experiments showed that the energy content of swine manure was equal to 19.44 MJ kg^{-1} dry matters and it is the highest among all different types of livestock manure (pig, broiler, layer, duck, beef cattle, and dairy cattle) available in South Korea. In addition, it was also found that the energy content of livestock waste has a positive correlation with the volatile solid content of the waste (Choi et al., 2014). However, if not being handled properly swine slurry will enhance undesirable microbial growth that can pollute the environment. Therefore, it is important to find suitable methods to treat swine slurry so that the potency of swine slurry can be maximized and utilized as value-added from swine farming activities.

Anaerobic digestion is one of wastewater treatment processes that is suitable to treat high strength wastewater with more than 3% COD such as swine slurry. It reduces and converts organic matters into biogas which has a high energy value. In addition, it is a common practice to destroy pathogens such as *E. coli* and *Salmonella* spp. within organic waste (Chae et al., 2008; Hobson et al., 1974). The effluent of anaerobic digestion processes (digestate) can be used directly as a fertilizer or after receiving further treatment such as composting or pelletizing since it has a high concentration of nutrients (nitrogen and phosphorus) that are suitable for plant growth (Moller & Muller, 2012).

However, anaerobic digestion plants operating in a temperate region for example in South Korea need high supplemental heat to maintain digester at desired temperature, especially in the winter season. This happens because of the average seasonal temperature difference that fluctuates from -9.1 °C in the winter to 30.7 °C in the summer (ASHRAE, 2013). This indicates that the seasonal temperature differences between the two most extremes (hot-cold) at a significance level of less than 1% are almost 39.8 °C, which is considerably high. As a comparison, the seasonal temperature difference is 35.7 °C in Germany and 34.7 °C in Netherlands, respectively (ASHRAE, 2013). A large seasonal temperature difference often results in a net energy loss.

Nevertheless, a need for generating energy from renewable sources and treating livestock wastes has increased interest in the application of anaerobic digestion technology (van Lier et al., 2001). It is known that the soil temperature 3.0 m below the surface only fluctuates within a range of ±5°C; therefore, an underground digester would not be affected by diurnal and seasonal temperature fluctuations (Philip & Itodo, 2007) and might be a solution to energy balance problems in a temperate region such as South Korea. However, there is little information regarding underground anaerobic digester (UGAD) performance throughout the seasons in a temperate region.

In addition, anaerobic digestion of swine slurry is often associated with poor operational stability which may be caused by the presence of inhibitory compounds. Ammonia is one of inhibitory compounds to an anaerobic digestion process. It is already contained within substrate and produced during the digestion of nitrogenous compounds such as protein and urea (Chen et al., 2008; Rajagopal et al., 2013). Swine slurry is known to have a high amount of total ammonia nitrogen (TAN) compared to the other livestock wastes. Suresh et al. (2009) reported that swine slurry produced in South Korea has TAN in the range of 1,130 to 10,400 mg L^{-1}. TAN in wastewater exist in two forms which are ammonium, NH_4^+, (soluble in water) and free ammonia, FA, (insoluble in water). Free ammonia (FA) is known to have an inhibition effect on the anaerobic digestion, especially the methanogenesis process.

The proportion of ammonium and free ammonia inside the digester is affected by pH and temperature of wastewater (Angelidaki & Ahring, 1994). Since pH of swine slurry in an anaerobic digester usually high, the proportion of FA is higher than that of ammonium. Therefore, anaerobic digestion of swine slurry often has poor operational stability. The negative net energy gain and the presence of inhibitory compounds are main reasons that currently only a few farm-scale or full-scale (centralized) anaerobic digestion plants are operating in South Korea (Chae et al., 2008).

During anaerobic digestion, macromolecules (organic solids) in swine slurry such as carbohydrates, lipids, and protein are converted into associated monomers (glucose, fatty acids, and amino acids) by hydrolytic bacteria. The monomers are then converted into acetic acid, propionic acid, butyric acid, hydrogen, and carbon dioxide by acid-forming bacteria. Propionic and butyric acids are converted into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria. In the final step, the acetic acid is converted into methane by acetoclastic methanogens. Moreover, hydrogen and carbon dioxides are converted into methane by hydrogen-using methanogens (Bitton, 2011; Gerardi, 2003). Therefore, anaerobic digester performance can be determined from the removal efficiency of organic solids throughout the digestion process.

Hydraulic Retention Time (HRT) determines the duration of substrate stay inside the digester. It is an important operational condition of anaerobic digestion that controls the conversion of volatile solids into biogas (Gerardi, 2003). Although a long HRT increase the rate of biogas production and volatile solid conversion it may not be applicable in the field because a long HRT reduces the amount of organic wastes being treated daily or it needs a large reactor volume to treat a high amount of waste. Therefore, it is important to find optimum HRT that gives a high biogas production rate and organic material degradation while still treating a high amount of waste everyday.

A pilot scale UGAD with 20 m^3 working volume was built and operated at a mesophilic condition (35^{o}C) for this experiment. It had been operated from November 2009 and still working until today although there are several times of temporary halts to modify or repair the digester. The whole experiment period has been divided into two phases. The net energy gain of the UGAD will be examined at the first phase experiment. Moreover, UGAD efficiency for methane production, organic matter and pathogen removal, and free ammonia toxicity were also investigated to examine whether or not UGAD is able to properly treat swine slurry. The effect of a shorter HRT (19-day) on the UGAD efficiency for methane production, organic matter removal, and free ammonia toxicity were investigated at the second phase experiment and the results will be compared with those of the first phase experiment which had a 27-day HRT.

2. MATERIAL AND METHODS

2.1. Experiment setup

A pilot single-phase anaerobic fermenter with a completely stirred tank reactor (CSTR) was built underground at the Livestock Experiment Station at SNU in Suwon, South Korea. The whole system consists of underground screened raw slurry reception pit, homogenizer with heating water jacket, underground anaerobic digester, overflow tank, effluent storage tank, and electric water heater with electric meter (**Figure 1**). High-grade PVC pipes were bedded at the bottom and 300 mm above the bottom sidewalls around the circumference and filled with hot water to maintain the underground anaerobic digester (UGAD) at 35°C. Moreover, the UGAD was insulated with a 100 mm thick styrofoam panel to prevent heat loss. Mixing was completed by a submerged pump in the UGAD. The schematic flow diagram of a pilot UGAD can be seen in **Figure 2**. The experiment is divided into two phases. The first phase was done from October 2010 to July 2011 with HRT of 27-day and the second phase was done from August 2012 to July 2013 with HRT of 19-day.

Figure 1.Photo of Underground Anaerobic Digester (UGAD): ① Underground screened raw slurry reception pit; ② Homogenizer with heating water jacket; ③ Underground anaerobic digester; ④ Overflow tank; ⑤ Inoculum densifier reactor also acts as an effluent storage tank; and ⑥ Electric water heater with electric meter

The working volume of UGAD was initially 20 m^3. However, polystyrene cubes (1 cm^3 each) were added as a microbial attachment media and they occupied about 1 m^3 of the digester to provide more shelter for microbes. As a result, the working volume was reduced to 19 m^3. The start-up operation after the addition of polystyrene cubes lasted for about one and half months (September to late October 2010). During the start-up period, the feeding rate was maintained at 550 L day^{-1}. After a steady state condition (continuous gas production) was reached, the feeding rate was increased to 700 L day^{-1}, which was fixed as the feeding rate for the entire first phase experiment period from late

October 2010 to mid-July 2011 which included all seasonal variations in a temperate region.

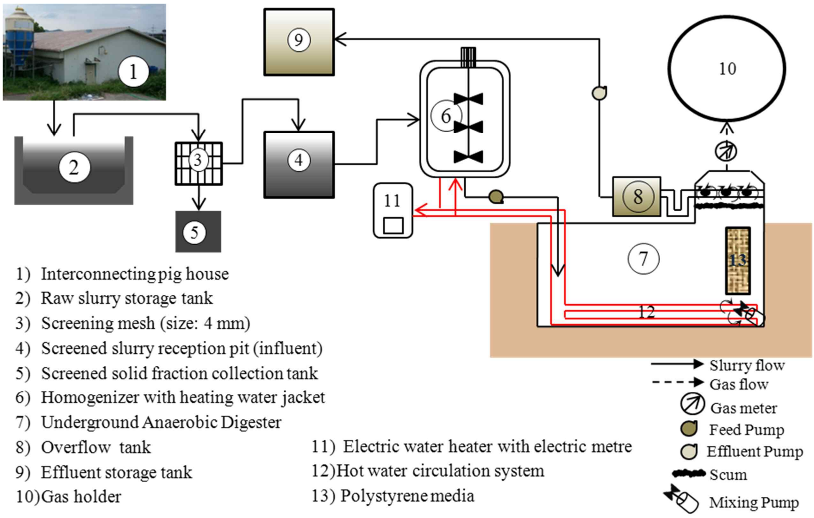

Figure 2.Schematic flow diagram of the pilot UGAD

Prior to the second phase experiment, the UGAD has been operated with the feeding rate at 700 L day^{-1} which is equal to 27-day HRT for almost 1 year. Then, at the beginning of July 2011, the feeding rate was increased to 1000L day^{-1}, which was fixed as the feeding rate for the entire second phase experiment period from August 2012 to July 2013. The HRT of the second phase experiment was shorter (19-day) than that of the first phase experiment (27-day).

2.2. Raw swine slurry

The raw swine slurry used for the experiment phase was pumped from the raw swine slurry storage tank of an interconnecting pig house without bedding materials that housed 200 growing pigs and sieved through a 4 mm wire mesh before stored in an underground reception reactor to ensure uniformity. For the second experiment, the raw swine slurry was pumped from the same place. However, during this period saw dust was used as a bedding material in the interconnecting pig house and the raw swine slurry was sieved through a 0.5 mm wire mesh. Everyday, screened slurry was transported into a homogenizer with a hot water jacket system to maintain the slurry temperature at 35°C for one day before it was fed into the UGAD.

During the first experiment phase, the organic loading rate (OLR) varied largely from 0.77 kg COD_{cr} m^{-3} day^{-1} to 3.14 kg COD_{cr} m^{-3} day^{-1} with an average of 1.9 kg COD_{cr} m^{-3} day^{-1} because it was difficult to control the solid content of swine slurry obtained from the pig house. The OLR for the second experiment phase also varied largely from 0.71 kg COD_{cr} m^{-3} day^{-1} to 5.53 kg COD_{cr} m^{-3} day^{-1} with an average of 2.98 kg COD_{cr} m^{-3} day^{-1}. The influent feeding and effluent discharge rate was maintained at 700 L day^{-1} for the first experiment phase, thus the hydraulic retention time (HRT) was equal to 27 days. Meanwhile, the influent feeding and discharge rate was maintained at 1000 L day^{-1} for the second experiment phase, thus the HRT was equal to 19 days or 8 days shorter than that of the first experiment phase.

2.3. Analytical methods

A digital thermometer was used to check the digester temperature. The influent and effluent samples were collected in 50 mL sterile centrifuge tubes. Total solid (TS), volatile solid (VS), and 5-day biological oxygen demand (BOD_5) values were analyzed according to

APHA standard methods nos. 2540 B, 2540 E and 5210 B, respectively. Total chemical oxygen demand ($tCOD_{cr}$), ammonia nitrogen (TAN), and total phosphorus (TP) was analyzed according to Hach chemical reagents and protocol manuals (DR 5000, Hach, USA). Free ammonia (FA), active compound generating ammonia inhibition, and concentration inside a UGAD depend primarily on three factors: pH, total ammonia nitrogen (TAN) concentration, and temperature of the digestate. Therefore, FA concentration was determined by applying the equation suggested byHansen et al. (1998) Eq. (1):

$$[NH_3] = \frac{[TNH_3]}{\left(1+\frac{10^{-pH}}{10^{-\left(0.09018+\frac{2729.92}{T}\right)}}\right)} \qquad (1)$$

Where,[TNH_3] : TAN concentration, mg-N L^{-1}
[NH_3] : Free Ammonia concentration, mg-N L^{-1}
T :Digestate temperature, Kelvin (K)

E. coli from the collected samples were analyzed to observe pathogen removal efficiency. The analysis method used was described in Suresh et al. (2011). In summary, the samples were pre-treated by mixing 20 mL samples with 180 mL sterile Ringer's solution. Afterwards, the mixtures were sequentially diluted. Chromocult coliform agar plates (Merck, USA) were used to determine *E. coli* count. This media can differentiate *E. coli* from other coliforms. Colonies of *E. coli* have dark blue to purple colour while other coliforms have pink to red colour.

Daily biogas production rate was measured by a gas meter (model G1.6R, Keuk Dong Ki Jeon, Korea). Gas samples were collected in a 0.5 L tedlar bag and the gas composition was analyzed using gas chromatography (HP 6890N, Agilent Technologies, USA) equipped with HP-PLOT Q capillary column (Supelco, Sigma-Aldrich, USA) and a thermal conductivity detector. The injection conditions were that inlet temperature was maintained at 35^{o}C, oven was maintained at isothermal condition or 35^{o}C for 5 minutes, and the thermal conductivity detector was maintained at 200^{o}C.

2.4. Net energy balance

The energy consumption to maintain a mesophilic state for the UGAD and homogenizer was recorded using an electric gauge which is able to measure six instances of a Wh pulse^{-1} (Model No. G.00.06, AMSYS, Korea). The obtained values (kWh) were then converted into MJ. The energy balance was determined by measuring the differences between daily energy production and consumption. The daily energy production was determined using Eq. (2):

$$E = \beta * CH_4 * \eta \qquad (2)$$

Where, E : Daily energy production, MJ
B : Pure methane energy value, 37.3 MJ m^{-3} (Demirbas & Balat, 2009)
CH_4 : Daily amount of methane produce, m^3
η : total efficiency of the conversion engine, %

The typical electrical and thermal conversion efficiencies of combined heating and power (CHP) engines ranged from 30 to 40% and 50 to 60%, respectively. This indicates that the total conversion efficiency of the CHP engine can be as high as 100%. However, the total conversion efficiency of the CHP engine is known to vary from 80 to 90% (Lansche & Muller, 2012; Pilavachi, 2000), thus the η value used in this experiment was 80%.

2.5 Data analysis

The statistical evaluation was carried out by using SPSS software package (version 21.0 for windows, Chicago, USA). Correlations of biogas production with OLR were estimated by Pearson correlation test. Moreover, independent sample t-test was used to investigate significant differences of the HRT effects on UGAD performances such as $tCOD_{cr}$, TS, VS, BOD_5 removal and specific methane yield.

3. RESULTS AND DISCUSSIONS

3.1. First experiment phase (October 2010~July 2011)

3.1.1 Characteristics of raw swine slurry

The characteristics of raw swine slurry used in the first phase experiment are shown in **Table 1**. The raw swine slurry had a high organic matter content (VS:TS ratio = 67.8%). This indicates that the raw slurry had high energy potentials for anaerobic digestion. The average TS concentration was equal to 3%, which indicated such high moisture content that the raw slurry could be easily pumped and mixed. Moreover, the average influent pH (7.24) was higher than the lower pH limit for acid-forming bacteria and methane-forming archaea (methanogens). The activity of acid-forming bacteria is inhibited when the pH is lower than 5.0 and methanogens cannot produce methane when the pH is lower than 6.8 (Gerardi, 2003; Zielonka et al., 2010). The average *E. coli* concentration in the raw slurry was observed to be 3×10^5 CFU mL^{-1}. In general, the characteristics of the swine slurry used fell within the ranges previously reported (Suresh et al., 2009).

Table 1. Characteristics of raw and treated swine slurry of the pilot UGAD from October 2010 to July 2011

Parameters	Unit	Raw Slurry	Treated Slurry	% Reduction[a]
pH		7.24 ± 0.22	7.93 ± 0.09	
TS	mg L^{-1}	30040 ± 9285	19393 ± 3459	37.75
VS	mg L^{-1}	20600 ± 7338	9671 ± 2092	47.61
VS/TS	%	67.79 ± 3.84	53.92 ± 7.49	
$tCOD_{cr}$	mg L^{-1}	52096 ± 15031	17660 ± 2501	63.66
TAN	mg L^{-1}	2474 ± 821	2863 ± 713	-23.92
BOD_5	mg L^{-1}	20237 ± 7875	2435 ± 1501	85.42
E. coli	CFU mL^{-1}	3.39×10^5	1.55×10^2	99.79

[a] Positive value indicates % removal; negative value indicates % increase

3.1.2 Energy consumption to maintain the optimum temperature of UGAD

As methanogens are susceptible to temperature changes (Chae et al., 2008; Gerardi, 2003), an improper range of digestion temperature may result in the reduction of anaerobic microbial activity and, thus, biogas production. In this experiment, the ambient temperature ranged from -11.2 (winter season) to 29.9 °C (summer season) with an average of 8.7 °C (Figure 3). A hot water circulation system heated by electricity was packed and circulated in the UGAD and the homogenizer wall to maintain a mesophilic temperature (35±1°C). Therefore, the energy consumption observed in this experiment was the sum of the energy consumed by the UGAD and homogenizer.

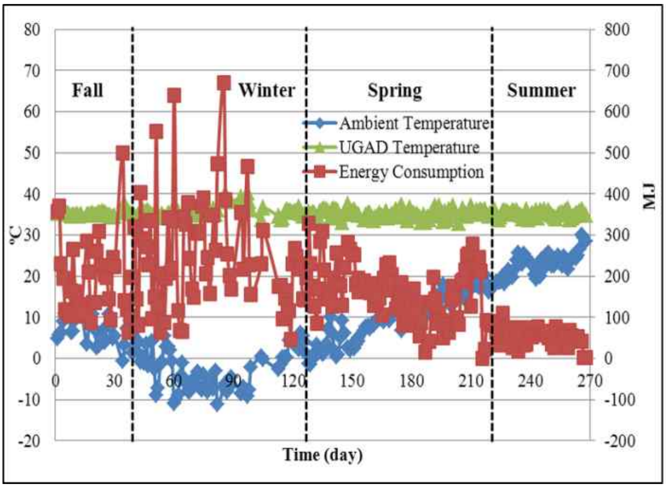

Figure 3. Daily ambient temperature, UGAD temperature, and energy consumption of the pilot UGAD from October 2010 to July 2011

The average daily energy consumption to maintain a mesophilic temperature range was approximately 166.3 MJ throughout the experiment. As the daily average energy production from the produced CH_4 was 255.1 MJ, a net energy gain was about 88.8 MJ day^{-1}. This is equivalent to 24.6 kWh and can be used for farm operations. The position of a homogenizer and an electric water heater which are located above-ground (**Figure 1**) explains the variation in energy consumption throughout the season. In addition, methane production variation explains the variation in energy production throughout the season (**Figure 4**).

January, the coldest month in South Korea, experienced the highest energy consumption of 299.3 MJ (**Figure 4**). In terms of net energy gain (**Figure 4**), the lowest daily net energy gain was 2.3 MJ and this occurred in March 2011. This may be attributed to the fact that the ambient temperature was still low (3.5ºC) in March (day 127 to 157) and the OLR was low (about 1.4 kg COD m^{-3} digester day^{-1}) in comparison to the average OLR of 1.9 kg COD m^{-3} digester day^{-1} throughout the experiment. Although low OLR was also observed in July 2011 (about 1.38 kg COD m^{-3} digester day^{-1}), the ambient temperature was warm (24.8ºC), so only a small amount of supplemental heat was required to maintain the optimum temperature in the UGAD in summer (**Figure 4**).

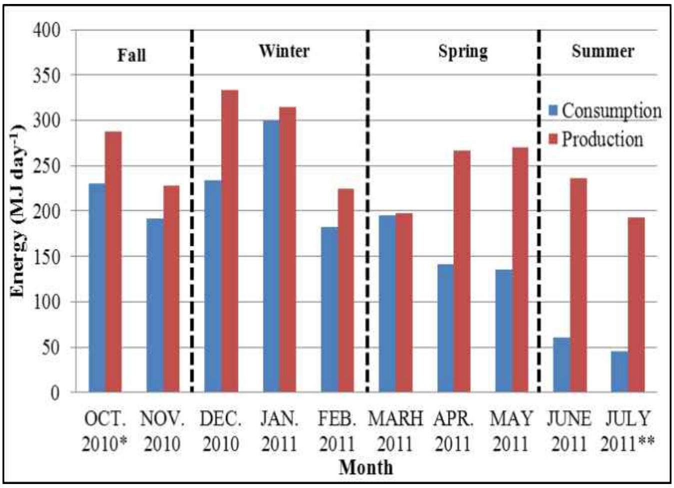

Figure 4. Monthly average energy consumption and estimated energy production of the pilot UGAD from October 2010 to July 2011. (*) 6 days observation and (**) 20 days observation

Table 2 shows that the highest average daily energy consumption was observed in the winter when the average ambient temperature was -2.1ºC. Nevertheless, there was a daily net energy gain of 58.8 MJ. Higher OLR in the winter resulted in higher biogas production. The surplus renewable energy is equivalent to 16.3 kWh and can be used for farm operations such as heating and lighting livestock housing. In terms of net energy gain, the highest net energy gain was observed in the summer (**Table 2**). Only a small amount of energy was consumed to maintain a mesophilic temperature because of the warm ambient temperature in the summer (22.6 ºC). Interestingly, the lowest net energy gain was observed in the fall and not winter. This may be attributed to a lower OLR in the fall than that in the winter, although the average ambient temperature in the fall was higher by about 9.3ºC than that in the winter (**Table 2**).

Table 2. Seasonal average OLR, ambient temperature, energy consumption, energy production, and net energy gain of the pilot UGAD from October 2010 to July 2011

Season	**OLR**[a]	**Mean Ambient Temperature**[b]	**Energy Consumption**[c]	**Energy Production**[c]	**Net Energy Gain**[c]
Fall	1.61	7.2	198.8	239.8	41.0
Winter	2.23	-2.1	242.5	301.3	58.8
Spring	1.88	10.0	157.7	244.2	86.5
Summer	1.66	22.6	54.3	219.0	164.7

[a] Unit in kg COD m^{-3} digester day^{-1}, [b] Unit in ºC, [c] Unit in MJ day^{-1}

3.1.3 Underground anaerobic digester (UGAD) performance

3.1.3.1 Pollutant removal

Table 1 shows the properties of the treated pig slurry (digestate). There were some changes in slurry characteristics: TS, VS, $tCOD_{cr}$, and BOD_5 values were reduced, whereas pH and total ammonia nitrogen (TAN) were increased after the anaerobic digestion process. The average removal efficiency for TS, VS, $tCOD_{cr}$, and BOD_5 were 37.75, 47.61, 63.66, and 85.82%, respectively. TS, VS, $tCOD_{cr}$, and BOD_5

concentrations indicate the organic solids in swine slurry (Gerardi, 2003). A decrease in organic solids concentration was caused by microbial activity inside the anaerobic digester. An increase in TAN concentration and pH value was due to protein degradation, which produces ammonia as a by-product (Angelidaki & Ahring, 1994; Chen et al., 2008).A high pH value of the effluent is a consequence of pH not being controlled throughout the experiment.

Per $tCOD_{cr}$ removal efficiency, the observed values in this experiment were higher than those in other studies using the same substrate. Specifically, the rates were 40.2% (Regueiro et al., 2012), 54.9% (Bonmati et al., 2001), and 58% (Costa et al., 2007), respectively. In another experiment, VS and $tCOD_{cr}$ removal efficiencies were 55% and 81%, respectively, (Chae et al., 2004) which were higher than those in this experiment. The higher VS and $tCOD_{cr}$ removal efficiencies observed are believed to be due to the 30 minutes of solid sedimentation before effluent samples were taken. This method may cause undigested solids to settle at the bottom of the digester and lead to a bias in removal efficiency analysis. Effluent samples throughout this experiment were taken during the mixing period to ensure there was no solid stratification.

Zabranska et al. (2002) and Nielsen and Petersen (2000) suggested that mesophilic anaerobic digestion had a low pathogen removal efficiency, compared to thermophilic anaerobic digestion. Interestingly, the average *E. coli* removal efficiency observed was very high (99.79%) and pathogen bacteria in the effluent were almost reduced completely. Costa et al. (2007) and Duarte et al. (1992) also reported the same results (about 99%). While pathogen removal during thermophilic anaerobic is believed to be due to a direct effect of the temperature and retention time, the exact cause of pathogen removal in mesophilic anaerobic digestion remains unclear. Nevertheless, it is suggested that pathogen removal during mesophilic anaerobic digestion may occur because of pH, nutrient availability, microbial competition, system operation, chemical interactions, or a combination of these factors (Sahlstrom, 2003; Smith et al., 2005).

The pathogen reduction observed in this experiment might be due to the presence of free ammonia (FA), which is known to have a toxic effect on microorganisms, and was in the range of 101.3 to 653.5 mg-N L^{-1}, with an average of 263.5 mg-N L^{-1}. Moreover, Park and Diez-Gonzalez (2003) showed that a FA concentration of more than 420 mg-N L^{-1} is able to reduce three log cells of *E. coli* in dairy manure that was stored for seven days. Duarte et al. (1992) showed that higher pathogen removal was achieved when a longer HRT of 15-day was used, thus, 27-days of HRT may be sufficient to remove pathogens even though the average FA concentration in this experiment was only 263.5 mg-N L^{-1}. Nevertheless, the mechanism of pathogen removal during mesophilic anaerobic digestion of swine slurry still needs further experiment.

3.1.3.2 Biogas production and specific methane yield

Figure 5 shows that there was fluctuation in daily biogas production attributed to the variation in daily OLR. The absence of lag phase in the biogas production indicates that the microorganisms were active and the start-up process of the pilot UGAD was completed. The Pearson correlation coefficient between biogas production and OLR was 0.921 (data not shown) indicating that biogas production is highly correlated with OLR. The average biogas production rate at the standard temperature and pressure (STP, 273 K and 1 atm) was 7.90 m^3 day^{-1}. The average methane and carbon dioxide proportion in the biogas produced was 72.45 and 26.09%, respectively. The specific biogas and methane yield in this experiment at the standard temperature and pressure (STP, 273 K and 1 atm) was 500 and 362 L kg $COD_{removed}^{-1}$ which was equal to 306 and 222 L kg COD_{added}^{-1}, respectively. The yield was also equal to 507 L-CH_4 kg VS_{added}^{-1}. The specific methane yield was higher than 350 L kg $COD_{removed}^{-1}$ (standard methane yield at 273 K and 1 atm). This is because the UGAD was operated under a continuous mode operation so that the anaerobic microorganisms were active to convert organic compounds to methane. The observed values are higher than those previously reported, which are 209.7 L-CH_4 kg COD_{added}^{-1} (Regueiro et al., 2012) and 163 L-CH_4 kg COD_{added}^{-1} (Chae et al., 2008), respectively.

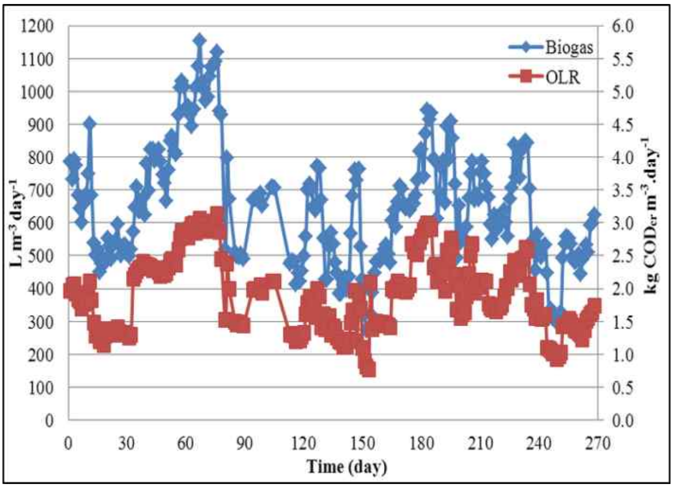

Figure 5. Daily biogas production and organic loading rate of the pilot UGAD from October 2010 to July 2011

3.1.3.3 Effect of free ammonia (FA) on digester performance

The average TAN concentration and pH were 2,863 mg-N L^{-1} (23.92% increase) and 7.96 in the effluent, respectively (**Table 1**). High pH value and TAN concentration in an anaerobic digester were often avoided, because they can lead to FA accumulation that is toxic to the methanogens. It is known that FA is able to cause proton imbalance, potassium deficiency, and rapid alkalinisation of cytoplasm in the methanogens cell (Chen et al., 2008; Park & Diez-Gonzalez, 2003; Rajagopal et al., 2013). TAN concentration between 1500-3000 mg-N L^{-1} and even a low FA concentration between 100-150 mg-N L^{-1} are known to inhibit an anaerobic digestion process (Gerardi, 2003; Hansen et al., 1998). The high pH value and TAN concentration indicated that there was FA accumulation inside the digester (**Figure 6**), and the average FA concentration was 263.6 mg-N L^{-1}. A high TAN concentration in treated swine slurry indicates that further treatment is needed to reduce it.

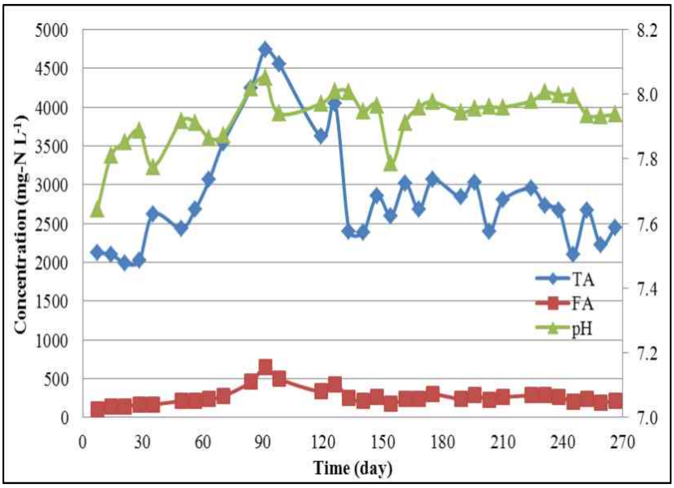

Figure 6. Observed pH value, total ammonia (TA), and free ammonia (FA) concentration of the pilot UGAD from October 2010 to July 2011

FA might not inhibit pilot UGAD performance, because the biogas production persists high even at high FA concentrations. This can be seen from the specific methane production at the standard temperature and pressure (STP, 273 K and 1 atm) on week 13, which was equal to 219.6 L kg COD_{added}^{-1} or 345.3 L kg $COD_{removed}^{-1}$ with $tCOD_{cr}$ removal efficiency of 63.6% even when the FA concentration reached 653.5 mg-N L^{-1} on that particular week (**Figure 6**). Rodirguez et al. (2011) also reported that the digester performance was not inhibited when FA concentration was 375 mg-N L^{-1}. The reason biogas was still produced at a high FA concentration might be due to methanogens in the UGAD adapting to the presence of FA. The methanogens adapted to the presence of FA because the methanogens seed used in this experiment were obtained from a working mesophilic digester fermenting swine slurry, which had been operated for 2 years. In addition, the adapted cells were not lost into the effluent because the UGAD was equipped with polystyrene media for sheltering microorganisms.

Table 3. Characteristics of raw and treated swine slurry of the pilot UGAD from August 2012 to July 2013

Parameters	Unit	Raw Slurry	Treated Slurry	% Reduction
pH		7.32 ± 0.42	7.98 ± 0.13	
TS	mg L^{-1}	30574 ± 8465	20208 ± 6351	32.75
VS	mg L^{-1}	22183 ± 6653	12740 ± 4450	41.53
VS/TS	%	72.06 ± 3.04	62.31 ± 4.78	
$tCOD_{cr}$	mg L^{-1}	56570 ± 19519	21948 ± 8280	59.63
sCOD	mg L^{-1}	19806 ± 9280	5767 ± 2017	67.17
TAN	mg-N L^{-1}	2303 ± 570	2886 ± 632	-22.35
TP	mg L^{-1}	1641 ± 694	2640 ± 866	-89.96
BOD_5	mg L^{-1}	11042 ± 3928	1576 ± 665	84.62

[a] Positive value indicates reduction; negative value indicates increase

Prolonged methanogens adaptation to a high FA concentration inside the digester makes the digester performance more resistant to inhibitory compounds that were present, like ammonia (Hansen et al., 1998). Angelidaki and Ahring (1994) showed that adapted methanogens seed (about 1 year) were unaffected by the presence of FA as high as 700 mg-N L^{-1}. An increase in methanogens retention times by addition of attachment or immobilizing media is also known to improve digestion stability (Chen et al., 2008) because the adapted methanogens in the digester, due to the presence of FA, are not lost into the effluent.

3.2. Second experiment phase (August 2012~July 2013)

3.2.1 Characteristics of raw swine slurry

The characteristics of raw swine slurry used in the second phase experiment are shown in **Table 3**. The raw swine slurry had a high organic matter content (VS:TS ratio = 72.1%), which means that the raw slurry had high energy potentials for anaerobic digestion. The average TS concentration was equal to 3%. This indicates that, like the first phase experiment, the raw slurry had high moisture content that it could be easily pumped and mixed. Moreover, the average influent pH (7.32) was higher compared to the lower pH limit for acid-forming bacteria and methane-forming archaea (methanogens). The activity of acid-forming bacteria is inhibited when the pH is lower than 5.0 and methanogens cannot produce methane when the pH is lower than 6.8 (Gerardi, 2003; Zielonka et al., 2010). In general, the characteristics of the swine slurry used were within the ranges previously reported (Suresh et al., 2009).

Comparing with the characteristic of swine slurry from the first experiment phase, there is no significant difference ($P>0.05$) for the total solid content in the raw slurry (**Figure 7**). However, the volatile solid (VS) and total chemical oxygen demand ($tCOD_{cr}$) of the swine slurry in the second phase experiment was significantly higher compared to the first phase experiment ($P<0.05$). This indicates more organic materials were available to be converted into biogas that the biogas production rate in the second phase experiment should be higher compared to the first phase experiment.

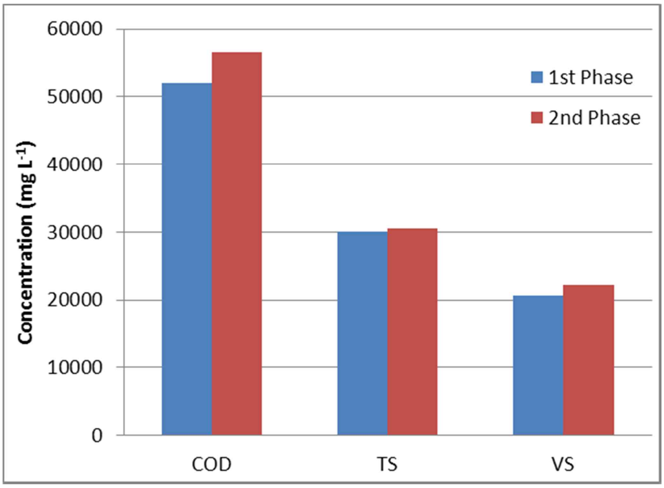

Figure 7. Comparison of organic matter contents ($tCOD_{cr}$, TS, and VS) in the raw swine slurry (influent) between first and second phases experiment

3.2.2 Underground anaerobic digester (UGAD) performance

3.2.2.1 Pollutant removal

Table 3 shows the properties of the treated pig slurry (digestate) in for the second phase experiment. There were some changes in slurry characteristics: TS, VS, $tCOD_{cr}$, $sCOD_{cr}$, and BOD_5 values were reduced, whereas pH, TAN, and TP were increased after the digestion process. The average removal efficiency for TS, VS, $tCOD_{cr}$, $sCOD_{cr}$, and BOD_5 were 32.75, 41.53, 59.63, 67.17, and 84.62%, respectively. TS, VS, $tCOD_{cr}$, $sCOD_{cr}$, and BOD_5 concentrations indicate organic solids in swine slurry (Gerardi, 2003). A decrease in organic solids concentration was caused by microbial activity inside the anaerobic digester. The soluble organic matter is easier to be digested by the anaerobic microorganisms so that the $sCOD_{cr}$ removal efficiency was higher than the TS, VS, and $tCOD_{cr}$ removal efficiency.

An increase in TAN concentration and pH value was due to protein degradation, which produces ammonia as a by-product (Angelidaki & Ahring, 1994; Chen et al., 2008). The high pH value of the effluent is a consequence of pH not being controlled throughout the experiment. The total phosphorus (TP) concentration increases because phosphorus will be taken up and incorporated into cell biomass. Therefore, the cell biomass needs to be discharged in order to remove phosphorus from the digester. In this experiment, the washed out microbial biomass was returned again to the digester by recycling of inoculum from IDR to UGAD. Therefore anaerobic microbial biomass and phosphorus accumulates inside the digester. Returning the anaerobic microbial biomass has a purpose to preserve microorganisms adapted to the digester condition so that the digestion process will not fail even if there is some change to the digestion condition. High TAN and TP concentrations of the effluent show that it can be utilized as a good organic fertilizer since it contain nutrients that are needed by plant. On the other hand, it also indicates that the effluent needs to undergo further treatment if it will be discharged to the water body. It is because a high nutrient content in the effluent may cause algae blooming in the water body.

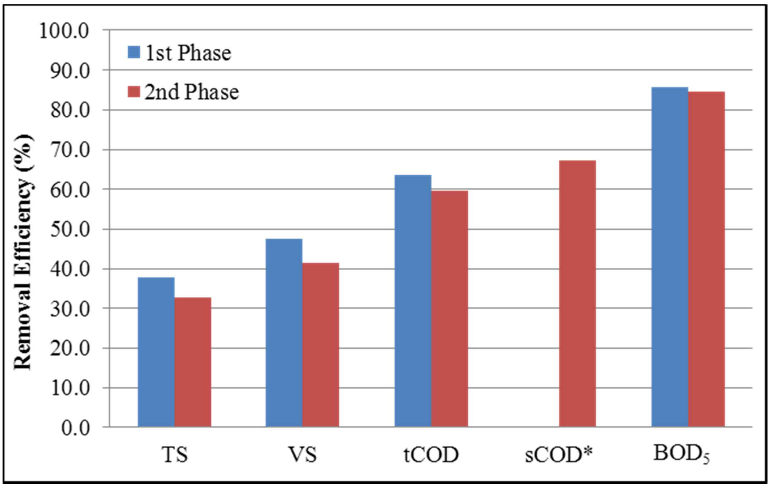

Figure 8.Comparison of organic matters ($tCOD_{cr}$, TS, VS, $sCOD_{cr}$, and BOD_5) removal efficiency between the first and second phase experiment. * There is no available $sCOD_{cr}$ removal efficiency analysis in the first phase experiment

The removal efficiency of organic matters (TS, VS, $tCOD_{cr}$, and BOD_5) in the second experiment phase was lower compared to the first experiment phase (**Figure 8**). However, only the VS and $tCOD_{cr}$ removal efficiencies of the second phase experiment which are significantly lower ($p<0.05$) than those of the first phase experiment. A lower removal efficiency of the second phase experiment is believed due to shorter HRT compared to the first phase experiment. The HRT for the second phase experiment is 8 days shorter than that for the first phase experiment. This makes some organic matters not being properly digested. HRT is an important operational factor that affects the conversion of organic matters during anaerobic digestion (Gerardi, 2003). Even though the particle size for the second phase experiment was reduced to 0.5 mm it is still not able to make organic matter conversion similar to HRT 27 days with 4 mm particle size. A small particle size is known to increase the surface area between anaerobic microorganisms and the substrate (Izumi et al., 2010). However the $tCOD_{cr}$ removal efficiency in this experiment (59.63%) was still higher than those reported in other studies which were 40.2% (Regueiro et al., 2012), 54.9% (Bonmati et al., 2001), and 58% (Costa et al., 2007), respectively.

3.2.2.2 Biogas production and specific methane yield

Figure 9 shows that there were fluctuations in daily biogas production. However, unlike the first phase experiment, the daily biogas variation was not supported by the OLR variation especially for the data obtained between days 30 to 60 (red circle). Since there is no reduction in the $tCOD_{cr}$ removal efficiency during this time period, there might be a problem in the biogas pipeline. The $tCOD_{cr}$ average removal efficiency between days 30 to 60 was equal to 55.75%. The problem might be due to foam formation that trapped the produced biogas at the surface of the digester. The foam was produced from the accumulation of scum at the digester surface. In mature digester, the layer of scum in the UGAD system could be developed because of microbial biomass accumulation at the digester surface. Moreover, there was a technical problem with the scum removal system in the UGAD so that the accumulation became worse. After the fixing was done, the scum could be removed from the digester and the biogas production became normal again.

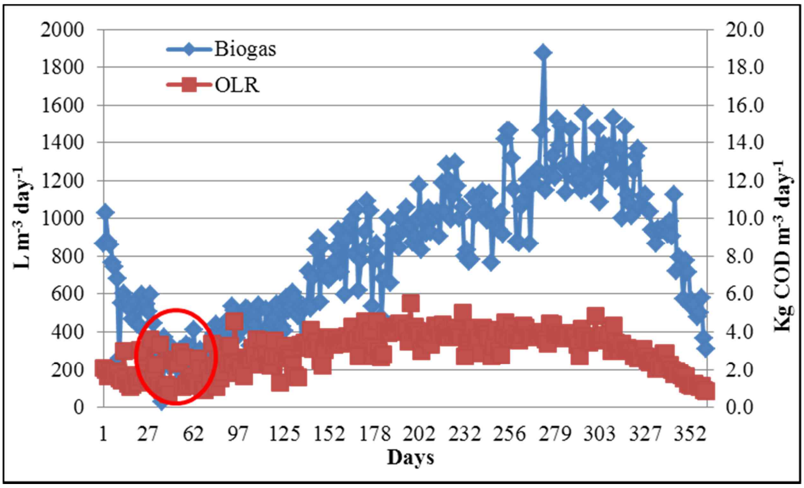

Figure 9. Daily biogas production and organic loading rate of the pilot UGAD from August 2012 to July 2013

The Pearson correlation coefficient between biogas production and OLR for the second phase experiment was only 0.635 (data not shown), indicating biogas production is moderately correlated with OLR. This is different from the result obtained from the first phase experiment which showed that biogas production and OLR has the Pearson correlation coefficient of 0.921, indicating biogas production is highly correlated with OLR. Apart from technical problems that cause foam formation, a lower correlation between biogas production and OLR in the second phase experiment compared to the first phase experiment might be due to short HRT. As explained before, HRT is an important operational factor during an anaerobic digestion process because it determines the substrate duration being digested in the digester that will affect organic solid conversion into biogas.

The average methane and carbon dioxide proportions in the biogas produced were 75.79 and 23.55%, respectively (**Figure 10**). This was significantly higher than the methane proportion at the first experiment phase which was 72.45% ($p<0.05$) and might be due to smaller screening mesh (0.5 mm) utilized in the second phase experiment compared to the first phase experiment (4 mm). Smaller screening mesh results in smaller particle size being treated. This increases the production of methane because the surface contact between substrates and the microorganisms increases.

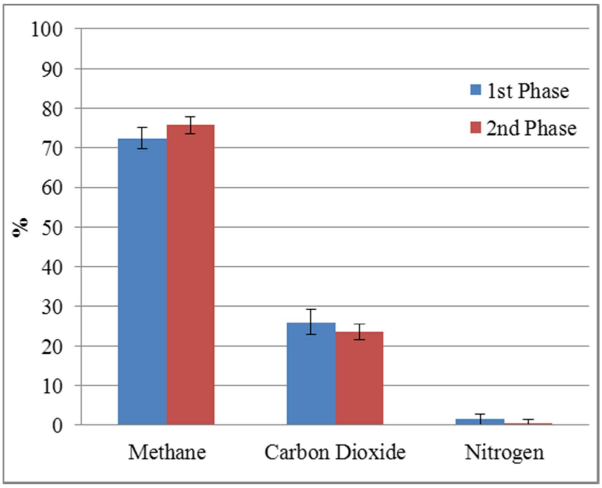

Figure 10. Comparison of biogas composition between first phase experiment and second phase experiment

The daily energy production and daily energy consumption were 349.6 MJ day^{-1} and 213.9 MJ day^{-1}, respectively. It turns out to be the net energy gain of 135.7 MJ day^{-1} during the winter season, December 2012 to February 2013, with the average ambient temperature of -2.4^{o}C. Higher net energy gain of the second phase experiment than that of the first phase experiment is mainly due to higher biogas production caused by higher COD and VS of the influent than those of the first phase experiment (**Figure 7**). The average biogas production at the standard temperature and pressure (STP, 273 K and 1 atm) was 13.75 m^3 day^{-1}. This was significantly higher than that of the first phase experiment.

However, the specific biogas and methane yields at the standard temperature and pressure (STP, 273 K and 1 atm) in this experiment were 438 and 322 L kg $COD_{removed}^{-1}$ which were equal to 252 and 182 L kg COD_{added}^{-1}, respectively. The yield was also equal to 473 L-CH_4 kg VS_{added}^{-1}. The specific methane yield from the second phase experiment is significantly lower (11% lower) than that from the first phase experiment ($p<0.05$). Shorter HRT during the second phase experiment (8 days shorter than that during the first phase experiment) might be a main cause since it makes the conversion of organic matters in the swine slurry to biogas has not been finished completely. Shorter HRT in the second phase experiment also resulted in lower removal efficiency of organic matters such as VS and $tCOD_{cr}$ compared to the first phase experiment. The specific methane yields in the second phase experiment, however, are still higher than previously reported, which is 163 L-CH_4 kg COD_{added}^{-1} (Chae et al., 2008).

The average $tCOD_{cr}$ and VS removals at 19-day HRT with 1000 L day^{-1} feeding rate was 34,662 and 9,443 mg L^{-1}, respectively. This means around 34.62 kg COD and 9.44 kg VS can be removed daily at 19 days HRT. Meanwhile, the average $tCOD_{cr}$ and VS removals at 27-

day HRT with 700 L day^{-1} feeding rate were 34,436 and 10,234 mg L^{-1}, respectively. This means only 24.11 kg COD and 7.16 kg VS can be removed daily. These values correspond to 69.64 and 75.85% of the COD and VS that can be removed at 19-day HRT, respectively. The values show that although a long HRT (27-day) resulted in better specific methane yield at the standard temperature and pressure and organic matter removal efficiency than that for the short HRT (19-day) only less organic matters can be removed by long HRT compared to short HRT. Therefore, an operational strategy of the UGAD is needed so that specific methane yield and organic matter removal efficiency at short HRT can be increased.

3.2.2.3 Effect of free ammonia (FA) on digester performance

The average TAN concentration and pH were 2,303 mg-N L^{-1} (23.92% increases) and 7.98 in the effluent, respectively (**Table 3**). These values are not significantly different from the results obtained from the first experiment phase. High pH value and TAN concentration in an anaerobic digester can lead to FA accumulation that is toxic to the methanogens. The high pH value and TAN concentration indicated that there was FA accumulation inside the digester and the average FA concentration was 297.5 mg-N L^{-1}.

Being the same as the first phase experiment, FA might not inhibit pilot UGAD performance because the biogas production persists high even at high FA concentrations. This can be seen from the specific methane production on day 197 at the standard temperature and pressure (STP, 273 K and 1 atm), which was equal to 183.1 L kg COD_{added}^{-1} or 299.9 L kg $COD_{removed}^{-1}$ with $tCOD_{cr}$ removal efficiency of 61.06% even when the FA concentration reached 627.6 mg-N L^{-1} on that particular day. This result is similar to that from the first experiment phase and indicates that the anaerobic microorganisms inside the UGAD might be adapted to the presence of FA.

4. CONCLUSION

The UGAD showed that it was able to acquire net daily energy gain of 88.8 MJ, which was equal to 24.7 kWh. This was obtained from a 268-day experiment done in the first phase. That amount of energy could be used for farm operations. In addition, the UGAD showed a good performance for treating swine slurry based on stable biogas production with high methane content of 72.45% and that fluctuation in daily biogas production was only due to the variation in the organic loading rate (OLR) of screened swine slurry.

The removal efficiency of organic solids and pathogen was also exemplary with average removal efficiencies for TS, VS, $tCOD_{cr}$, and BOD_5 being 37.75, 47.61, 63.66, and 85.82, respectively. Moreover, the presence of free ammonia might not inhibit the anaerobic digestion process. This can be seen from biogas and methane yields at the standard temperature and pressure (STP, 273 K and 1 atm) of 500 and 362 L kg $COD_{removed}^{-1}$ or 306 and 222 L kg COD_{added}^{-1}, respectively, throughout the experiment. These values are higher than those found in previous research. No inhibition from free ammonia might be due to the methanogen seeds obtained from working mesophilic anaerobic digester of swine slurry that had been working for years, which makes it adapted to the presence of free ammonia.

It was also observed that 99.79% of *E. coli* was removed after the digestion process. The combination of free ammonia concentration of 263.5 mg-N L^{-1} and long HRT of 27 days may be the cause of high *E. coli* removal efficiency. Nevertheless, the mechanism of pathogen removal during mesophilic anaerobic digestion of swine slurry still needs further experiments.

Shorter hydraulic retention time (HRT) of 19-day for the second phase experiment results in lower organic matter average removal efficiencies and methane yields compared to a longer HRT of 27-day although the concentration of volatile solid and total chemical oxygen demand was higher than that for the longer HRT.However, there was net energy gain of 135.7 MJ day^{-1} during the winter season with the average ambient temperature of -2.4^{o}C at the second year experiment.

The average removal efficiencies of TS, VS, $tCOD_{cr,}$ $sCOD_{cr}$, and BOD_5during the second phase experiment were 32.75, 41.53, 59.63, 67.17, and 84.62%, respectively. At the same time the specific methane yield from the second phase experiment at the standard temperature and pressure (STP, 273 K and 1 atm) was only 322 L kg $COD_{removed}{}^{-1}$. Being compared with specific methane yield from first phase experiment which was 362 L kg $COD_{removed}{}^{-1}$, means that shorter HRT produces 89% of specific methane yield than that for the longer HRT. This happened because a short HRT makes the substrate only stay inside the digester for a short period of time that the conversion or degradation of organic matters into biogas has not been completed yet.

Shorter HRT did not affect the methanogen adaptation to the presence of FA since when the FA concentration inside the digester was high (627.6 mg-N L^{-1}) the specific methane production at the standard temperature and pressure (STP, 273 K and 1 atm) on that particular day was equal to 183.1 L kg COD_{added}^{-1} or 299.9 L kg $COD_{removed}^{-1}$ with $tCOD_{cr}$ removal efficiency of 61.06%.

The effluent of UGAD systems shows a high concentration of TAN and TP equal to 2886 mg-N $L^{-1}$and 2640 mg L^{-1}, respectively. This makes the effluent have potential to be used as a liquid fertilizer. However, if the effluent will not be utilized as a fertilizer it needs to be further treated before being discharged to the water body to meet the effluent discharge standard.

The average $tCOD_{cr}$ and VS removal at 19-day HRT with 1000 L day^{-1} feeding rate was 34,662 and 9,443 mg L^{-1}, respectively. This means that around 34.62 kg COD and 9.44 kg VS can be removed daily at 19-day HRT. Meanwhile, the average $tCOD_{cr}$ and VS removal at 27 days HRT with 700 L day^{-1} feeding rate was 34,436 and 10,234 mg L^{-1}, respectively. This means only 24.11 kg COD and 7.16 kg VS can be removed daily, which are equivalent to only 69.64 and 75.85% of those of the 19-day HRT, respectively.

In conclusion, an UGAD can be used as an alternative system for anaerobic treatment of swine slurry in a temperate region because it demonstrated net energy gain even during the winter season and high organic and pathogen removal efficiency. In addition, the UGAD performance in shorter HRT in term of biogas production rate and amount of organic matters being treated was better than that of longer HRT. However, new operational strategies need to be considered and developed to improve organic matter removal efficiency and specific methane production in shorter HRT so that they can be equal to or better than those of the longer HRT.

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초록

돈슬러리의 중온(中溫) 지하 혐기성 소화

순(純) 에너지 증가와 소화조 성능

혐기성 소화는 돈슬러리는 화학적 산소요구량(COD)이 3% 이상인 고농도 폐수를 처리하는 데 적합한 기술이다. 혐기성 소화는 유기물을 생물학적 분해를 통하여 에너지가가 높은 biogas로 전환시킨다. 혐기성 소화의 폐수에는 고농도 총질소, 암모니아(TAN)와 총인(TP) 등 함유되어 있는데 이것들은 비료로서 식물성장에 필수적이다. 동절(冬節)과 하절(夏節)의 기온차가 심한 온대 지방에서의 혐기성 소화는 상대적으로 춥고 긴 겨울 때문에 에너지 손실이 매우 크다. 그러나 지표면 이하 3.0m의 토양 온도는 사계절에 온도편차가 ±5°C에 이르러 혐기성 소화조를 지하에 매설할 경우 에너지손실을 줄여, 순에너지 증가를 유도할 수 있다. 그러므로 본 연구에서는 pilot UGAD (Under-Ground Anaerobic Digester)를 설계, 제작, 운영하여 에너지 수지(收支), biogas 생산율, 및 생화학적 변수 등을 분석하여 온대 지방의 사계절에 걸쳐 줄곧 UGAD의 성적을 분석하여 이의 잠재력을 검정하였다.

소화조 용적이 20m^{3}인 UGAD을 축조하여 중온(中溫)조건(35°C)에서 2009년 11월부터 소화조의 오늘에 이르기 까지 약 5년간 UGAD를 지속적으로 가동하고 있다. 전체 실험 기간은

1단계 실험은 2010년 10월부터 2011년 7월까지 HRT (체류시간) -27일 약 8개월간, 2단계 실험은 2012년 8월부터 2013년 7월까지 HRT-19일 약 12개월간 실험하였다. 기본적으올 돈슬러리리를 4mm mesh 경사고액 분리기를 통해 고액을 분리하였다. 분리 돈슬러리액을 1단계 HRT-27과 2단계 HRT-19일 혐기소화조에 인입시켜 체류시일에 따른 Biogas생산수율 및 COD 농도 감소 등의 UGAD성적을 분석하였다.

1단계 실험에서는 에너지 생산 및 에너지소비 추정치가 각각 301.3 MJ day^{-1}및 242.5 MJ day^{-1}으로 분석되었다. 2010년 12월부터 2011년 2월까지 겨울 동안에는 순에너지 증가가 58.8 MJ day^{-1}로 나타났으며 평균 대기온도는 −2.1°C이었다. 표준온도와 압력(STP, 273 K 및 1 atm) 하에서 평균 메탄생성율은 7.90m^3 day^{-1}이었고 268일 간의 총실험기간 중 메탄생성율은 평균 362 L-CH_4 kg $COD_{removed}{}^{-1}$이었다. $tCOD_{cr}$, BOD_5, 대장균 제거효율은 각각 63.7, 85.8, 99.8%로 관찰되었다. HRT-27일과 FA농도의 조합이 병원균 제거효율을 높인 것으로 여겨진다.

실험 2단계, HRT-19일은 Biogas생성율은 HRT-27에 비하여 높지만 유기물 제거효율 및 특정 메탄생성율이 낮았다. 에너지 생성율 및 에너지 소비율은 각각 349.6 MJ day^{-1} 및 213.9 MJ day^{-1} 이었다 2012년 12월부터 2013년 2월까지 겨울철 동안에 순 에너지 증가는 135.7 MJ day^{-1} 이었으며 평균 대기온도

는 −2.4℃ 이었다. 실험 1단계보다 실험 2단계에서 순 에너지 증가는 높게 관찰되었다. 이는 biogas 생산량 증가 때문으로 여겨진다. 즉, 실험 1단계 때보다 고농도 COD 및 VS 유입되기 때문이다. 실험 2단계 중 TS, VS, $tCOD_{cr}$ 및 BOD_5의 제거효율은 각각 32.75, 41.53, 59.63, 67.17, 및 84.62%이었다. 표준온도와 압력(STP, 273 K 및 1 atm)에서 평균 메탄생성율은 10.08 m^3 day^{-1}이었는데, 이는 실험 1단계 메탄생성율의 127.6%에 해당하는 것이다. 하지만, 표준온도와 압력(STP, 273 K 및 1 atm)에서 특정 메탄생성율은 322 L kg $COD_{removed}^{-1}$밖에 되지 않았는데 이는 실험 1단계에서 그것의 88.9%에 해당하는 것이다. HRT -19일에는 기질이 덜 생분해되므로 biogas 생성율이 낮아지는 것은 자연스러운 현상인 듯하다.

축산폐수 유입율, 1000 L day^{-1}이며, HRT-19일의 경우, 평균 $tCOD_{cr}$ 및 VS 제거율은 각각 34,662 및 9,443 mg L^{-1}로서, 이는 약 34.62 kg-COD day^{-1} 및 9.44 kg-VS day^{-1}이 제거됨을 의미한다. 한편, 700L day^{-1} 유입율 및 HRT-27일에서 평균 $tCOD_{cr}$ 및 VS 제거율은 각각 34,436 및 10,234 mg L^{-1}이었다. 이것은 24.11 kg-COD day^{-1} 및 7.16 kg-VS day^{-1} 제거될 수 있음을 의미하는데, 이는 각각 HRT-19일 제거율의 69.64 및 75.85%에 해당한다.

이 실험은 UGAD가 계절적 기온차가 심한 온대지방에서 돈슬러리의 혐기성 처리공정 중 하나로 선택할 수 있음을 시사한

다. 왜냐하면 이것은 겨울철에도 순(純) 에너지증가 뿐만 아니라 유기물 및 병원균 제거효율도 높게 관찰되었기 때문이다. HRT-19에서 UGAD 성능은 biogas 생성율의 측면에서 볼 때 HRT-27보다 나았다. 하지만, 새로운 운용 전략은 더 깊이 고찰하고 개발해서, 비교적 짧은 HRT을 통한 유기물 제거효율 및 메탄생성율을 개선해야 할 것이다. 그리하여 HRT-메탄생성율-축산유입율 등의 관계를 구명(究明)할 수 있을 것이다.

핵심 단어: 유압 보유 시간, 순 에너지 증가, 돼지 슬러리, 온대 지방, 지하 혐기성 소화제

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