Desalination and Water Treatment
www.deswater.com
2 (2009) 30–38

Estimation of biodegradability and biogas recovery from a two-phase anaerobic process treating piggery wastewater

Sung Mo Oh[a], Moon Ho Kim[b], Yoon Sun Bae[b], Seung Mo Hong[c], Chul Hwi Park[b*]

[a]*Center for Environmental Technology Research, Korea Institute of Science and Technology, 131 Cheongryang, Seoul, Korea*
[b]*Department of Environmental Engineering, University of Seoul, 90 Cheonnong-dong, Seoul, Korea*
Tel.+ 82 2 2210-2176; Fax. +82 2 2244-2245; email: chpark@uos.ac.kr
[c]*Daewoo Institute of Construction Technology, 60 Songjyk-dong, Suwon, Korea*

Received 30 July 2007; Accepted 14 September 2007

ABSTRACT

The purpose of this study was to investigate the biodegradability, as well as the organic removal and methane production rates, when treating piggery wastewater, using a pilot-scale two-phase anaerobic system, with a volumetric rate of up to 10 m^3/d. The acidogenic CSTR was operated at organic loading rates between 1.8 and 14.4 kg COD/m^3·d, and the methanogenic UASB reactor between 0.5 and 5.6 kg COD/m^3·d. A stable maximum biogas production rate of 81 m^3/d was observed, but the conversion rate of the organic matter to methane varied between 0.30 and 0.42 L CH_4/g COD removed (average 0.40) at hydraulic retention time above 3.5 days. The methane content ranged from 73 to 82% during the experimental period, implying that most of the removed organic matter was converted to methane gas, which might be of high quality for subsequent use. The gas produced could be directly used as a fuel source to increase the reactor temperature, with a potential electronic power production of 167 kWh.

Keywords: Two-phase anaerobic process; Piggery wastewater; BMP test; Biogas recovery; Methanogenesis

1. Introduction

Piggeries, which produce 56% of the total liverstock waste in Korea, have rapidly developed due to the specialization and development of livestock. In 2003, 142,000 tons/d of livestock waste were produced due to wastewater from 410,000 piggeries. This is a very important pollutant because it causes eutrophication in lakes, rivers and other national waters, and is difficult to be controlled. The government enforced stringent effluent standards for piggery wastewaters, limiting the effluent concentration of organic and other pollutants for treatment facilities in Korea [1]. However, meeting the regulations imposed for the effluent discharge of piggery wastewater is difficult using a treatment process due to the poor infrastructure and socioeconomic climate of the neigh-boring district of the drinking water. In addition, the frequent use of antibiotics can result in increased levels in the body and also in wastewater, which have a detrimental influence on the microbial metabolism [2,3]. Also, antibiotics such as tetracycline and penicillin are a persistent contaminant and cause toxicity at treatment facilities, which can result in a lowering of the process efficiency, and have an an unfavorable influence on humans [4]. Especially, the high percentage of water

*Corresponding author.

Presented at IWA Efficient 2007, May 20–23, 2007, Jeju, Korea.

within piggery wastewater is difficult to separate from the piggery sludge. Therefore, an appropriate treatment solution for livestock farms is required.

The purposes of this study were to evaluate the biodegradability, as well as the organic removal and methane production rates when treating piggery wastewater by the application of the two-phase anaerobic process, with control of the acidogenic (pH 5.5–6.5) and methanogenic (pH 6.8–7.4) phases [5,6]. There was also a reduction of the residence time and improvement in the treatment efficiency by optimizing the production of methane.

2. Materials and methods

2.1. Sources of piggery wastewater and sludge

The piggery wastewater used in this study was provided by the National Livestock Research Institute, Korea. Solids-free wastewater was obtained by separating the solids from the raw wastewater, which contained urine, washing water and feces, using centrifugation. The characteristics and features of the raw wastewater are summarized in Table 1. The value of the BOD was approximately 40% lower than that of the COD. The reactors were seeded with both granulated and activated sludge from a distillery wastewater treatment plant previously adapted for a 2-month period to piggery wastewater (TSS = 37,570 mg/L, VSS = 29,793 mg/L and VSS/TSS = 0.79).

Table 1
Characteristics of influent piggery wastewater

Parameters	Value (mean value)
Organics:	
BOD, mg/L	1,781–9,722 (4,254)
$TCOD_{Cr}$, mg/L	3,740–23,116 (10,519)
$SCOD_{Cr}$, mg/L	1,781–9,722 (4,254)
TKN, mg/L	1,650–3,996 (2,639)
Nutrients:	
NH_4^+-N, mg/L	890–1,520 (1,228)
PO_4^{3-}-P, mg/L	32–70 (44)
Solid:	
TS, %	0.3–1.21 (0.8)
VS, %	0.2–0.95 (0.52)
SO_4^{2-}, mg/L	9–118 (31)
NaCl, mg/L	395–1,892 (945)
Miscellaneous:	
Alkalinity (as $CaCO_3$), mg/L	5,135–10,976 (7,688)
pH	7.5–8.1 (7.8)

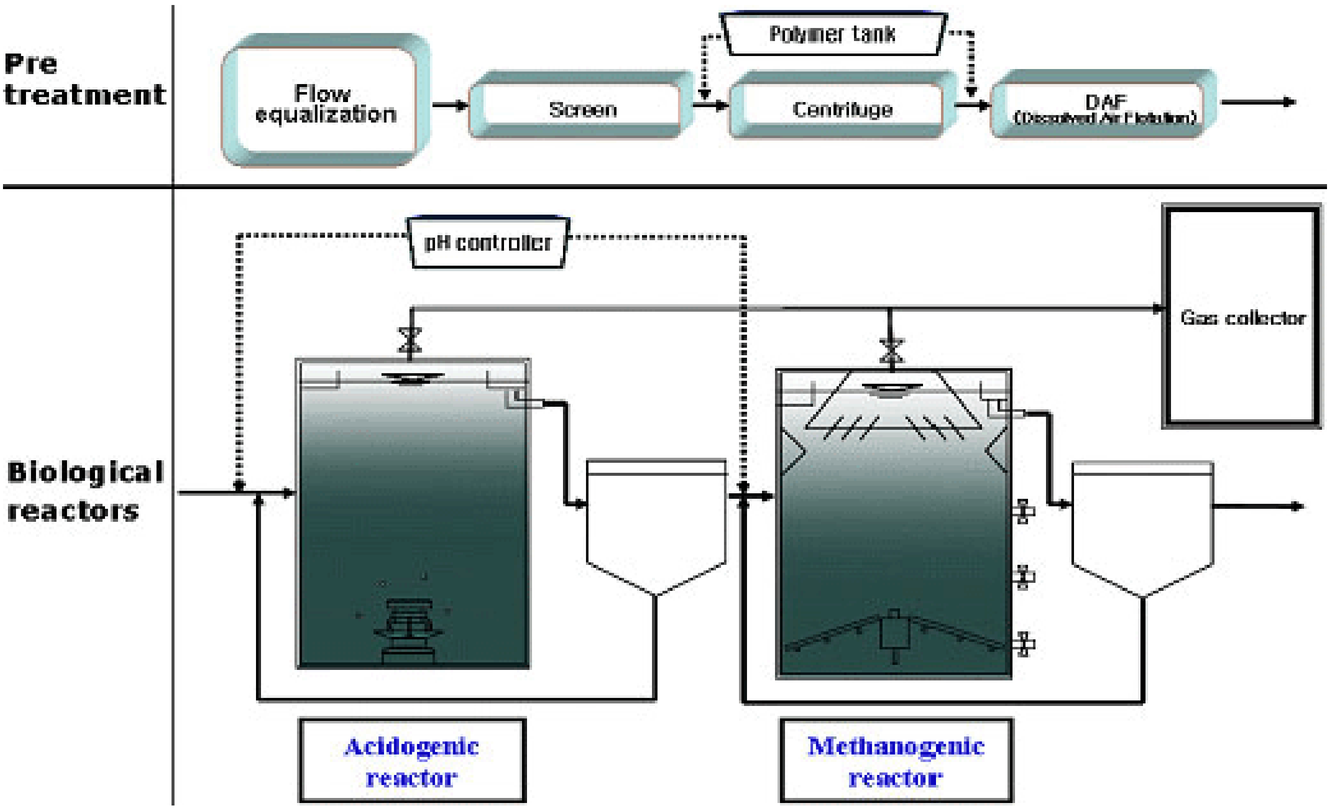


Fig. 1. Schematic diagram of two-phase anaerobic process.

2.2. BMP test

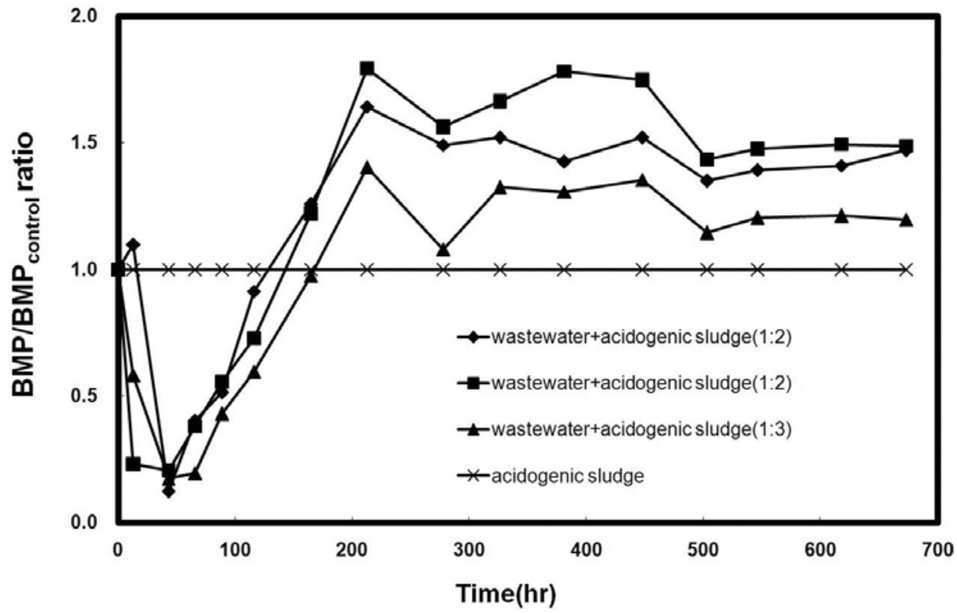
The biochemical methane potential (BMP) test, outlined by Owen et al. [7] and the serum bottle reactors test outlined by Gupta et al. [8], with a few modifications, were previously used to study the above objective employing batch tests. The sludge for the BMP test was sampled from pilot-scale reactors. Approximately 40 mL samples were added to 160 mL serum vials, along with 20 mL of bacterial seed sludge at 35°C.

2.3. Pilot-scale reactor

The employed process was divided in two reactions (Fig. 1). Piggery wastewater, containing about 0.9% of total TS, was collected from the influent and the particle size reduced by screening, then centrifuged and subjected to dissolved air flotation.

The pilot-scale two-phase anaerobic process consisted of a continuously stirred tank reactor (CSTR) for the acidification phase and an upflow anaerobic sludge

(a)



(b)

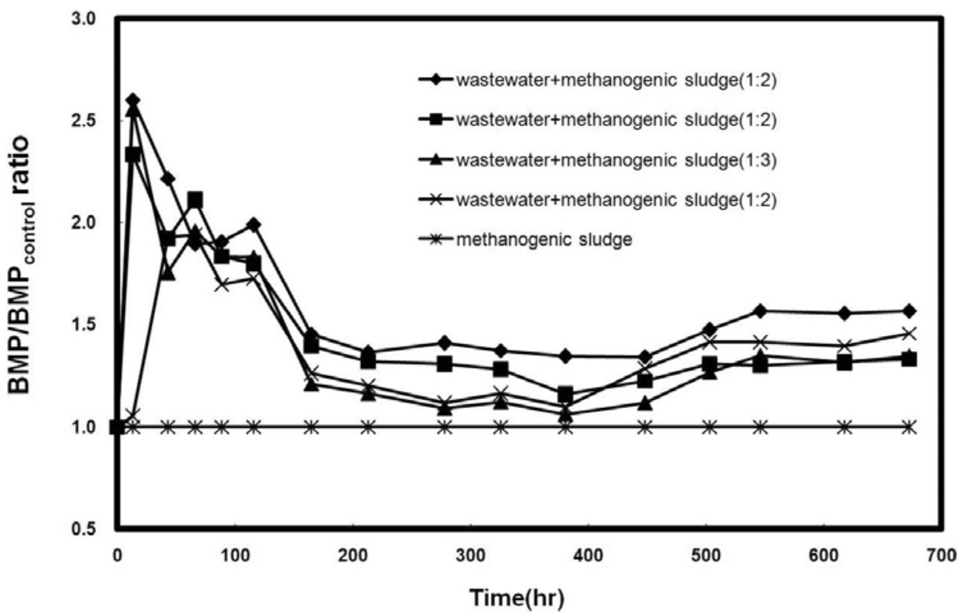


Fig. 2. (a) BMP/BMP$_{control}$ of acidogenic sludge. (b) BMP/BMP$_{control}$ of methanogenic sludge.

blanket reactor (UASB) for the methanogenesis. The biological reactors were operated within the temperature range 32–35 °C. The acidogenic reactor played the key roles of reducing the periodically applied shock-loading and the acidification of the influent organics [9,10]. The volumes of the acidogenic and methanogenic reactors were 15 and 35 m^3, respectively.

2.4. Analytical methods

The COD, BOD, solids (TS, VS) and nutrients (TKN, NH_4^+-N and PO_4^{3-}-P), etc. (SO_4^{2-}, NaCl, alkalinity and pH) were determined according to Standard Methods. The soluble and volatile fatty acids (VFAs) of membrane-filtered samples were measured. The biogas produced in the bioreactors was collected using a gas collector, with the composition of a gas analyzer (GA 2000 Plus, France) and a gas chromatograph (TCD, GC-8A, Shimadzu). The detected compounds were methane, carbon dioxide, nitrogen, oxygen, ammonia and hydrogen sulfide.

3. Results and discussion

3.1. BMP test

Figs. 2(a) and (b) present the BMP/$BMP_{control}$ of acidogenic and methanogenic sludges, respectively. Due to the generation of VFA, the BMP/$BMP_{control}$ of acidogenic sludge was decreased to nearly 0.08, with 54.4% contents of methane. In the case of methanogenic sludge in a UASB reactor, the BMP/$BMP_{control}$ immediately increased to above 2.5, producing over 81% of methane. Batch test results showed that sludge in the UASB reactor was able to substantially generate methane for the BMP test.

3.2. Pilot-scale reactor

3.2.1. Reactor loading capacity

Fig. 3 shows the variations OLR and HRT for continuous operation of each reactor. During the operation, the organic loading rate was changed four times, the acidogenic and UASB reactors were operated with organic loading rates (OLR) between 1.8 and 14.4 kg COD/m^3·d, and 0.5 and 5.6 kg COD/m^3·d, respectively, when treating piggery wastewater employing a pilot-scale two-phase anaerobic process with a volumetric rate of up to 10 m^3/d.

3.2.2. Total COD and VFAs removal efficiency

Fig. 4 shows the variations in the TCOD concentration within each reactor. The two-phase anaerobic system showed a TCOD removal efficiency of between 69.7 and 87.0%; with influent COD concentrations ranging from 11,579 to 23,116 mg/L (average concentration was 17,468 mg/L). Once a steady state had been established, the average effluent TCOD concentration in the methanogenic reactor was 4,041 mg/L.

As shown in Fig. 5, the VFA produced rapidly increased to above 11,500 mg/L, with TCOD loadings from 9.4 to 14.4 kg COD/m^3·d in step 3. This time the influent increased 7.0 m^3/d, the organic loading rate was 14.4 kg COD/m^3·d in the acidogenic reactor, 5.6 kg COD/m^3·d in the methanogenic reactor until it increased. When OLR was raised to step 3, the generated VFA concentration was the increased about 10 times than the step 2. This could be due to system creating the periodically applied shock-loading and the acidification of the influent organics.

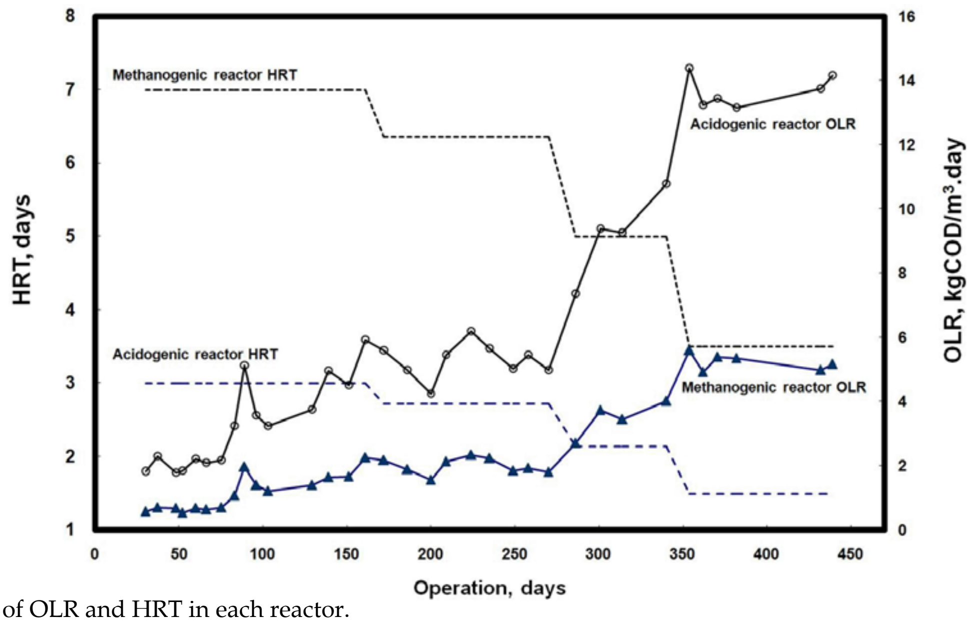


Fig. 3. Variation of OLR and HRT in each reactor.

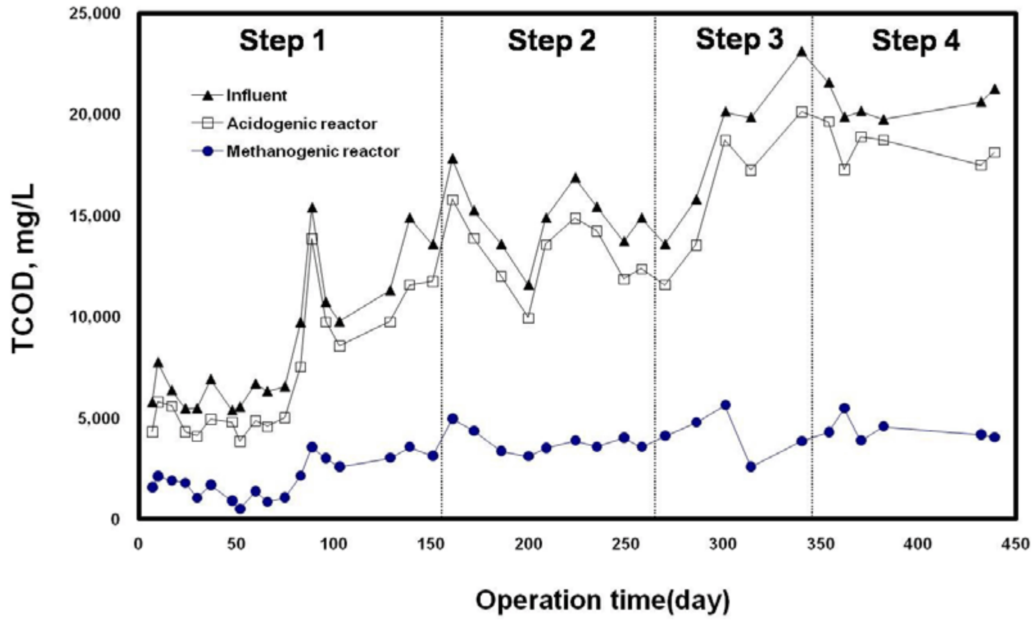


Fig. 4. Variation of TCOD concentration in each reactor.

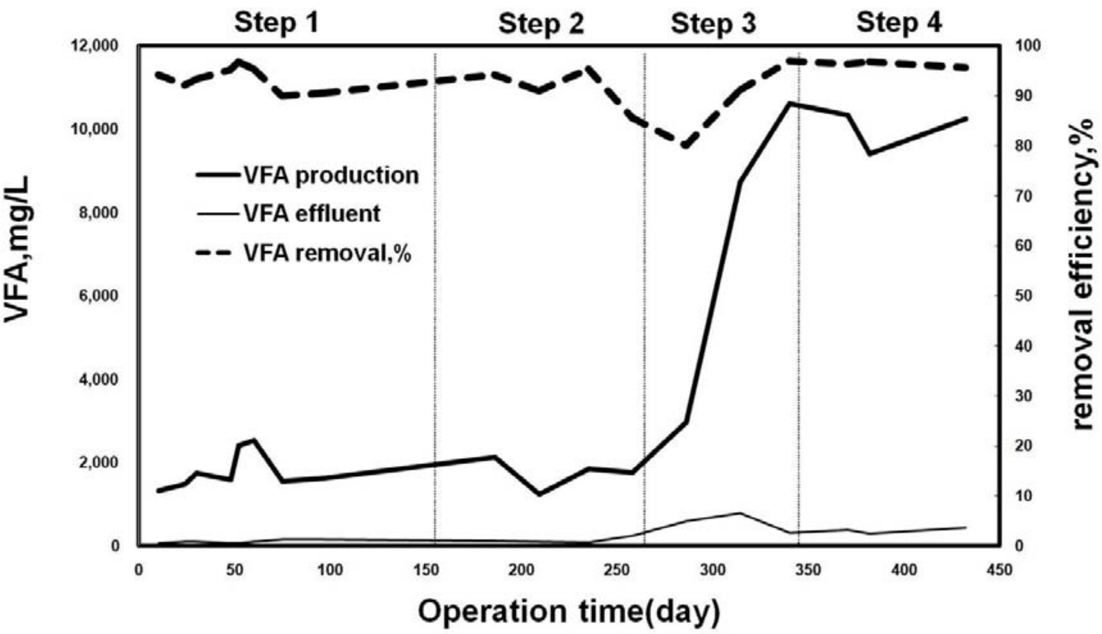


Fig. 5. Variation of VFA concentration.

However, it lowers the organic loading rate from step 4 and the possibility of getting the effluent, which is stabilized gradually and was averaging 239 mg/L. TCOD removal efficiency in step 4 was 80.1%–96.9%, the average volume was 92.8%.

Fig. 6 presents the correlation equation of the volatile organic acid by the loading of the influenced organic matter as $Y = 48.19X$ ($R^2 = 0.8224$). Approximately 10–18% is removed in the acidogenic reactor. The surplus which is fatty acid by the microorganism of hydrolysis is removed by the methanogenic microorganism in the methanogenic phase with the maximum (87 %); the role of the acidogenic and methanogenic phases were carried out efficiently [11]. Normally, the high molecular substance as humic acid is impossible to remove by biological disposal; it is 3.0–3.5% in the COD to total wastewater ratio.

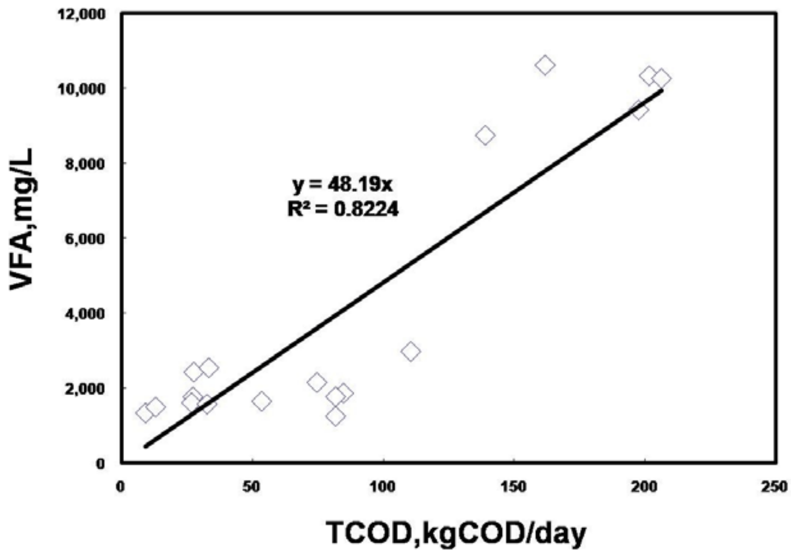


Fig. 6. Relationship between VFA production and TCOD.

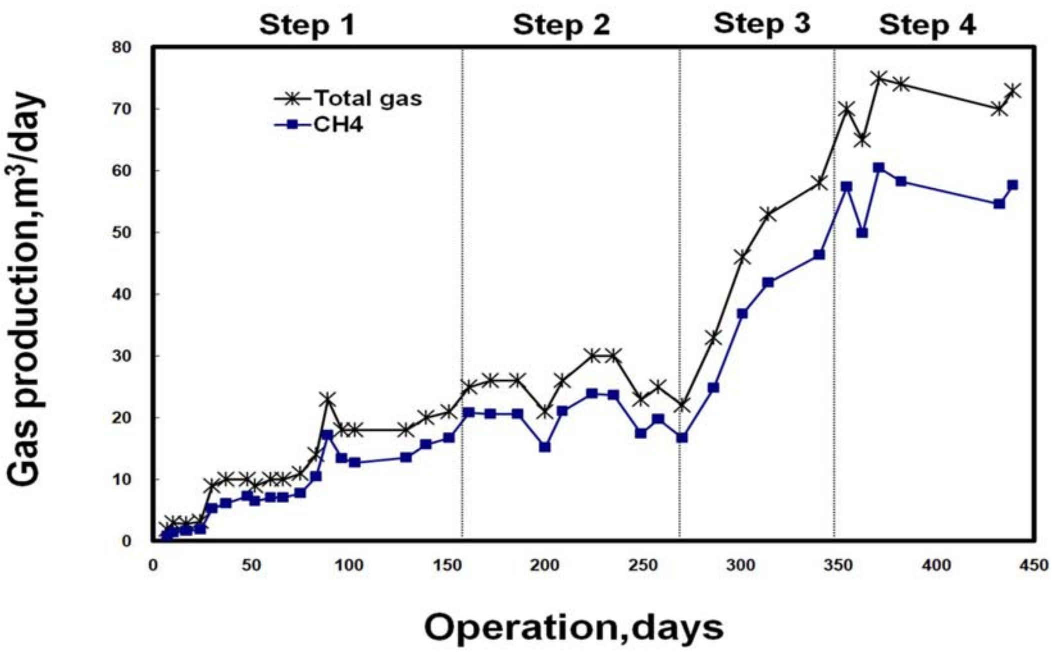


Fig. 7. Variation of biogas production in the UASB reactor.

3.2.3. Total biogas production and methane yield

The majority of CH_4 production was related to the performance of the methanogenic UASB reactor. Initially the reactor generated 46% methane and 28% carbon dioxide, but the methane content increased to a maximum of 82% after step 2. Due to the high alkalinity and pH of the effluent in the methanogenic reactor, over 80% methane, as biogas, was consistently produced. A stable maximum biogas production rate of 81 m^3/d was maintained (Fig. 7). Fig. 8 shows that CH_4 production increased proportionally with increasing the organic loading rate. The conversion rate of the organic matter to methane varied from 0.30 to 0.42 L CH_4/g $COD_{removed}$ (average 0.40, 32–35°C) at hydraulic retention times (HRT) above 3.5 days. Due to successful phase separation during the experimental period, the methane content ranged from 73 to 82%, implying that most of the removed organic matter was converted to methane, and the biogas produced might be of high quality for subsequent use.

Fig. 9 shows the relationship between the OLR and total gas production in the UASB reactor. The correlation equation was $Y = 15.839X$ ($R^2 = 0.806$), and similar results

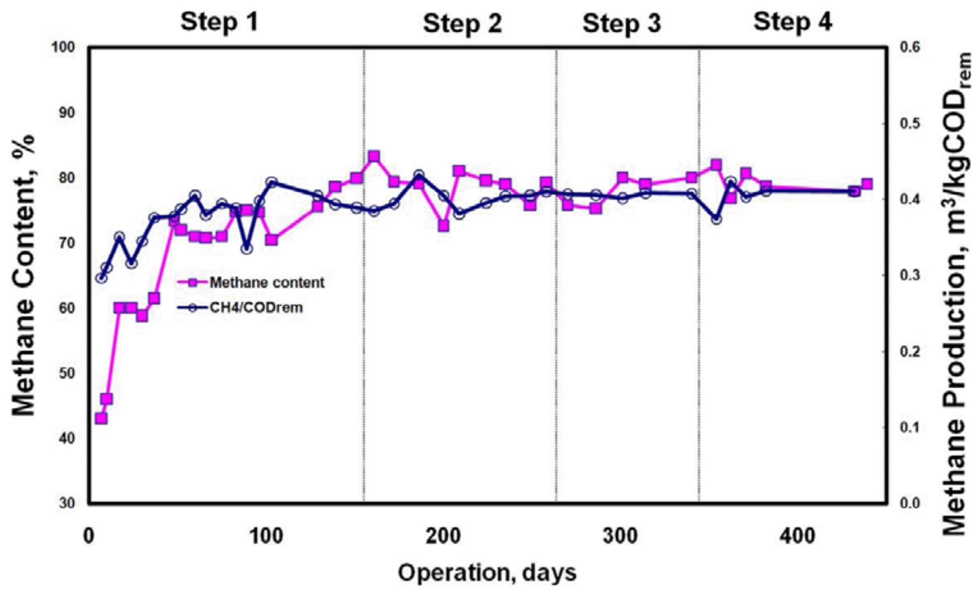


Fig. 8. Methane content and specific methane production rate.

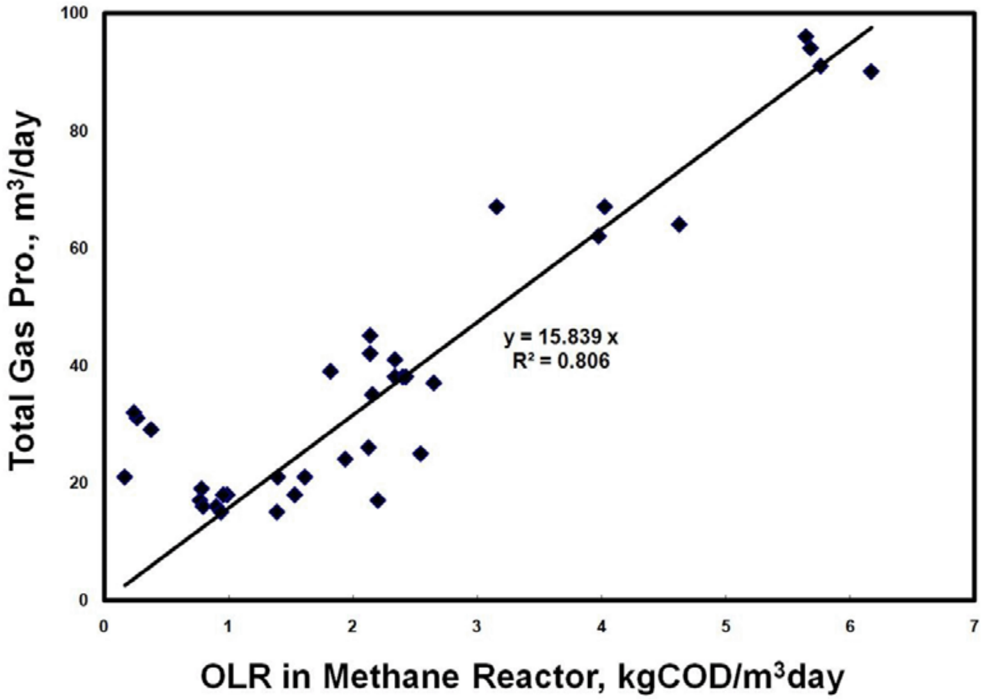


Fig. 9. Relationship between OLR and total gas production in UASB reactor.

have previously been reported by others [4]. The produced gas could be directly used as a fuel source to increase the reactor temperature, with a potential to produce 167 kWh of electric power.

3.2.4. Granule characteristics

Fig.10 shows the biomass concentration in the UASB reactor during continuous operation. Because no artificial method was adopted to control MLVSS, it was maintained or made a granule naturally. MLVSS concentration increased continuously and MLVSS/MLSS seemed to stable in operation. The MLVSS/MLSS was maintained at 70%, as shown in Table 2, with particle diameters ranging between 0.85 and 2.0 mm accounting for 62.1% of the granules in UASB reactor.

Table 2
Particle size distribution of granule sludge in UASB reactor

Sieve no. (mesh)	Diameter (mm)	Fraction of weight (%)
10	>2.0	5.5
20	**0.85–2.0**	**62.1**
40	0.425–0.85	31.7
60	0.250–0.425	0.5
100	0.150–0.250	0.2
200	0.075–0.150	—

The height characteristics of granules in the UASB reactor are shown in Fig. 11. The ability of the biomass to settle in the UASB reactor was good due to the high concentration of the microorganisms within the UASB reactor. Improvement in the settling efficiency, by the formation of granular sludges, via self-immobilization of the microorganisms, is being still being developed.

In Fig. 12, the relationship between MLVSS and TCOD removal showed to be in proportion. By increasing organic matter removal from UASB, MLVSS affected the

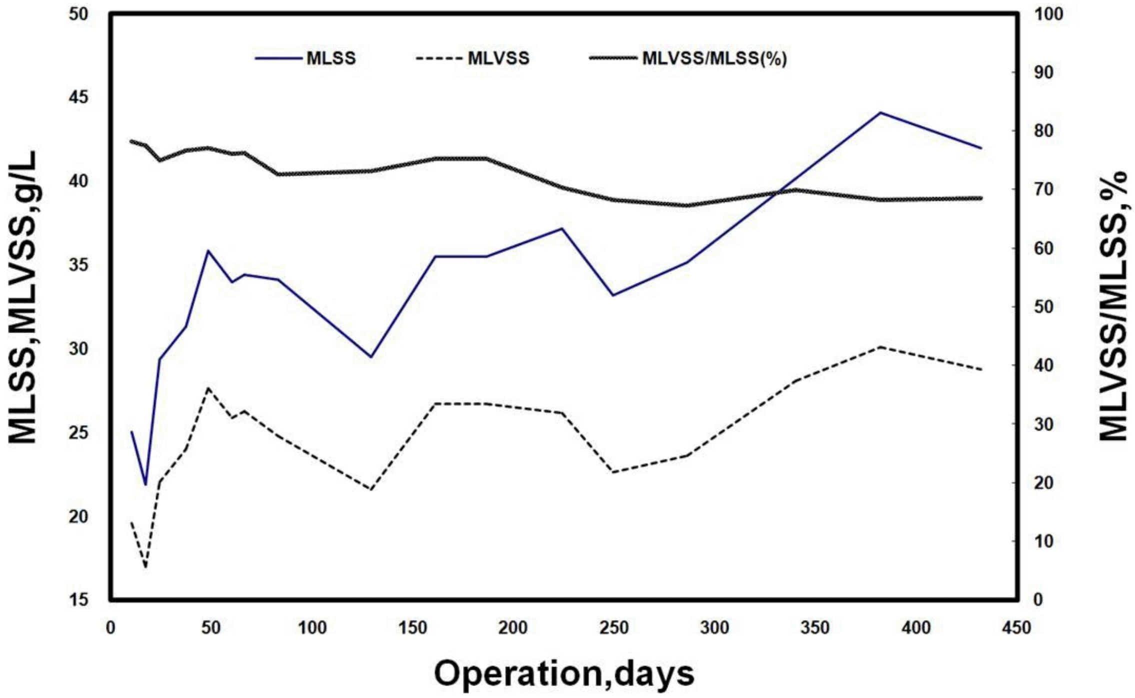


Fig. 10. Biomass concentration in the UASB reactor.

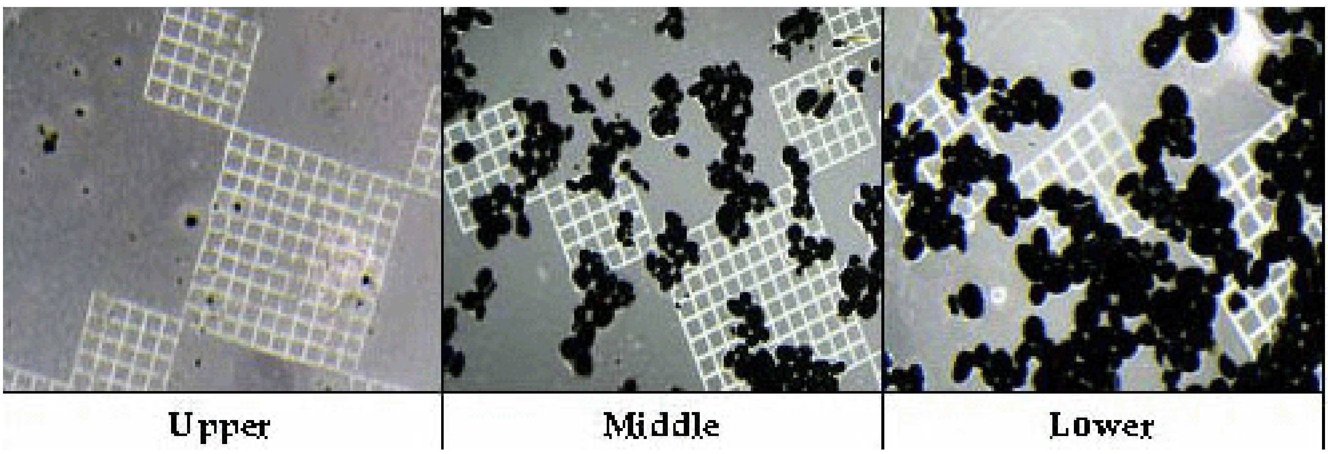


Fig. 11. Characteristics of granule in height of UASB reactor.

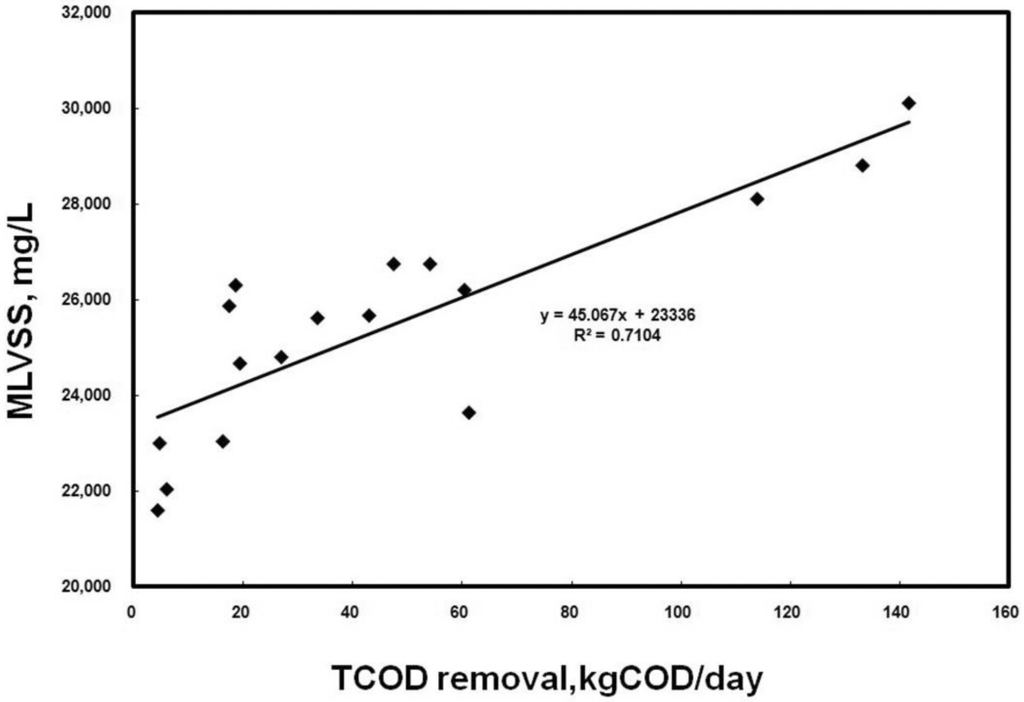


Fig. 12. Relationship between TCOD removal and MLVSS.

proportional increase. The correlation equation of the MLVSS concentration in the UASB reactor is $Y = 45.067X + 23336$ ($R^2 = 0.7140$).

4. Conclusions

The operation of the two-phase anaerobic process, with control of the acidogenic (pH 5.5–6.5) and methanogenic (pH 6.8–7.4) phases, resulted in biodegradability as well as organic removal and methane production when treating piggery wastewater. Due to the successful phase separation, the operation can be stable.

The acidogenic CSTR reactor was operated with OLR between 1.8 and 14.4 kg COD/m^3/d, and the methanogenic UASB reactor between 0.5 and 5.6 kg COD/m^3/d. A stable maximum biogas production rate of 81 m^3/d was observed, but the conversion rate of the organic matter to methane varied from 0.30 to 0.42 L CH_4/g $COD_{removed}$ (average 0.40) at HRT above 3.5 days. The MLVSS/MLSS was maintained at 70, with particle diameters ranging between 0.85 and 2.0 mm accounting for 62.1% of the granules in UASB reactor. And the methane content ranged from 73 to 82% during the experimental period, and the produced gas could be directly used as a fuel source to increase the reactor temperature, with a potential electric power production of 167 kWh.

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