Simultaneous treatment of sewage sludge and food waste by the unified high-rate anaerobic digestion system

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Abstract This study aimed to evaluate the performance of the unified high-rate anaerobic digestion (UHAD) system treating co-substrate of sewage sludge and food waste. A 24-hr operating sequence consisted of four steps including fill, react, settle, and draw. The effects of co-substrate and organic loading rate (OLR) on the performance were investigated to verify the system applicability. In each OLR, the UHAD system showed higher CH_4 recovery (>70%), CH_4 yield (0.3 L CH_4/g VS_{added}) and CH_4 production rate (0.6 L CH_4/L/d) than the control system. In the specific methanogenic activity (SMA) tests on thermophilic biomass of the UHAD system, the average SMA of acetate (102 mL CH_4/gVSS/d) was much higher than those of butyrate (85 mL CH_4/g SS/d) and propionate (42 mL CH_4/gVSS/d). It was demonstrated that the UHAD system for co-digestion resulted in higher methane yield and methane production rate due to sequencing batch operation, thermophilic digestion, and co-digestion. The enhanced performance could be attributed to longer retention time of active biomass, faster hydrolysis, higher CH_4 conversion rate, and balanced nutrient conditions of co-substrate in the UHAD system. Consequently, this optimized unification could be a viable option for the simultaneous treatment of two types of OFMSW with high stability.

Keywords Anaerobic digestion; co-digestion; food waste; sequencing batch; sewage sludge; thermophilic

Introduction

In the environmental protection, it is a great burden for the prosperous countries to continue investing enormously in applications of updated or renovated new methods. Therefore, it is natural that methods following the natural biological mineralization sequence should be developed and applied for sustainability. In that sense, the applications of anaerobic biological systems could be a viable option due to low operational costs and energy recovery from organic waste (Lettinga *et al.*, 1979; Jetten *et al.*, 1997; Lettinga, 2005).

Systems based on anaerobic biological processes have traditionally been adopted to stabilize both primary and secondary waste sludge (Parkin and Owen, 1986). The ratio of volatile solids (VS)/total solids (TS) in typical sewage sludge is less than 0.6, which is the main cause of low efficiency in conventional anaerobic digestion when the old combined sewer systems are mainly used. Feed characteristics are one of the important governing factors in anaerobic digestion of sewage sludge. Co-digestion could be one of the most useful strategies for the treatment of organic waste because it could treat two or more organic substrates simultaneously as a homogeneous mixture. Several studies demonstrated that co-digestion of different organic wastes led to distinct enhancement in process performance including CH_4 yield due to synergistic effects between different substrates, which could compensate for lack of carbon sources or nutrients and dilute

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excess inhibitory or toxic substances (Del Borghi *et al.*, 1999; Mata-Alvarez *et al.*, 2000; Braun, 2002; Viotti *et al.*, 2004).

However, the efficiencies of anaerobic co-digestion processes for solid waste treatment were not high due to limitations on reactor performance. Thus, efforts to improve anaerobic digester performance have resulted in several new or modified reactor designs for the high-rate anaerobic biodegradation of solid wastes. New designs were developed based on enhanced retention of active biomass by separating solid retention time (SRT) from hydraulic retention time (HRT), which was an essential factor for the high-rate digestion and could be achieved using sequencing batch operation (Dugba and Zhang, 1999). To achieve good effluent quality, a staging configuration should be incorporated to improve biomass activity. If the plug-flow-like pattern is established by staging and adequate biomass retention could be achieved in the individual compartments, biomass that is optimally adapted to the specific conditions in the individual reactor stage is possible to be cultivated (Speece, 1996; van Lier *et al.*, 2001). Also, it has been reported that the temperature-phased anaerobic digestion system, a special case of staging, was possible to achieve much higher bioconversion and methane production rates than the existing high-rate single-stage mesophilic anaerobic systems due to enhanced hydrolysis/acidogenesis and higher activity of thermophilic microorganisms (Van Lier, 1996; Welper *et al.*, 1997; Han *et al.*, 1997).

The scattered technologies mentioned above have their own unique target waste or wastewater. If two or more unique technologies were combined properly, there could be a better access for the solid waste management. Accordingly, this research was performed to improve the low efficiency of each anaerobic digestion of sewage sludge and food waste using the optimized unification of temperature-phased digestion, sequencing batch operation, and co-digestion.

Materials and methods

Feedstock

Sewage sludge was sampled from a local municipal wastewater treatment plant (WWTP). Food waste, collected from a dining hall, was crushed by an electrical blender. All the substrates were filtered through a stainless steel sieve (U.S. Mesh No. 10 with corresponding sieve openings of 2.00 mm). The characteristics of the feedstocks are summarized in Table 1.

Seed microorganism

The seed sludge was taken from a conventional egg-shaped anaerobic digester in the same WWTP. The digester was operated at 35 °C and a HRT of about 30 days by feeding a thickened mixture of primary and waste activated sludge. The pH, alkalinity, volatile suspended solids (VSS) and VSS/TSS of the seed sludge were 6.5～7.0, 567～611 mg/L as $CaCO_3$, 14.8 g/L and 0.75, respectively.

Table 1 Characteristics of substrates

Item	Physical characteristics				Chemical characteristics		
	TS[a] (g/L)	VS[b] (g/L)	VS/TS	Moisture Content (%, w/w)	C (%, w/w)	N (%, w/w)	C/N
Sewage sludge	21.2 ± 8.2	12.9 ± 4.6	0.62 ± 0.11	97.9 ± 0.8	39.2	6.0	6.5
Food waste	225.7 ± 32.1	215.2 ± 31.6	0.95 ± 0.01	81.6 ± 2.2	50.1	3.6	13.9

[a]TS: total solids
[b]VS: volatile solids

Experimental set-up and operating procedures

The seed sludge for a thermophilic reactor was acclimated at 55 °C for about one month at the organic loading rate (OLR) of about 0.5 g VS/L/d. A unified high-rate anaerobic digestion (UHAD) system and a control system (mesophilic two-stage anaerobic digestion) were operated continuously to compare their performances depending on OLR. The UHAD system consisted of two cylindrical type reactors. Each reactor with a working volume of 4 L has an electrical agitator in the head. The first-stage thermophilic reactor was directly connected to the second-stage mesophilic reactor in series. The control system had the same configuration other than the temperature conditions of the first-stage (35 °C). In sequencing batch operation, one cycle of each reactor comprised four sequences – fill (1 h), react (17 h), settle (5 h), and draw (1 h). The sequences were operated by controlling motors and peristaltic pumps with several timers on a control panel.

Batch tests

To examine the effects of major components in food waste on the enhanced methane yields of the UHAD system, batch experiments were conducted in duplicate using sewage sludge and food waste. Serum bottles with a working volume of 200 mL were filled with nutrient solutions which have enough essential minerals, trace metals and alkalinity for the growth of thermophilic microorganisms. Sewage sludge was added to be 2.0 g VS/L as a substrate. Dried powders of grains, vegetables and meats were added separately to be 0.7 g VS/L depending on the previous study (Kim *et al.*, 2003). After 20 mL of seed sludge was added, all the bottles were purged with N_2 gas before sealing. Those bottles were incubated in a rotary shaker to provide better contact of substrates, nutrients and microorganisms. The volume of biogas was determined using glass syringes of 5∼50 mL according to Owen *et al.* (1979).

Analysis

The contents of methane and carbon dioxide in the biogas were analyzed by a gas chromatograph (Gow Mac series 580) equipped with a thermal conductivity detector (TCD) and a 2 m × 2 mm stainless-steel column packed with Porapak Q (80/100 mesh). Individual volatile fatty acids (VFA) concentrations were determined by a high performance liquid chromatograph (Spectra Physics P2000) equipped with an Aminex HPX-87H (300 × 7.8 mm) column and a UV (210 nm) detector. Chemical composition of substrates was analyzed by Elemental Analyzer (Fisons, EA-1110) equipped with a dynamic flash combustion oxidation chamber and TCD. The analytical methods for TS, VS, chemical oxygen demand (COD), TSS, and VSS were determined according to *Standard Methods* (APHA, 1998).

Results and discussions

Methane production rate

Figure 1 illustrates the methane production rate (MPR) of the two systems depending on OLR. In the first-stage, the methane contents of the UHAD system and the control system were measured to be 53–64% and 51–64%, respectively, under steady state. The average MPR of the UHAD system linearly increased from 0.21 to 0.60 L CH_4/L/d depending on the increase of OLR. The UHAD system always showed higher MPR than the control system. Although the MPR increased up to the OLR of 4.3 g VS/L/d, stable high-rate operation of the UHAD system was maintained and the instant decrease of the MPR was rapidly recovered. In the effluent quality of the first-stage thermophilic reactor, pH, total

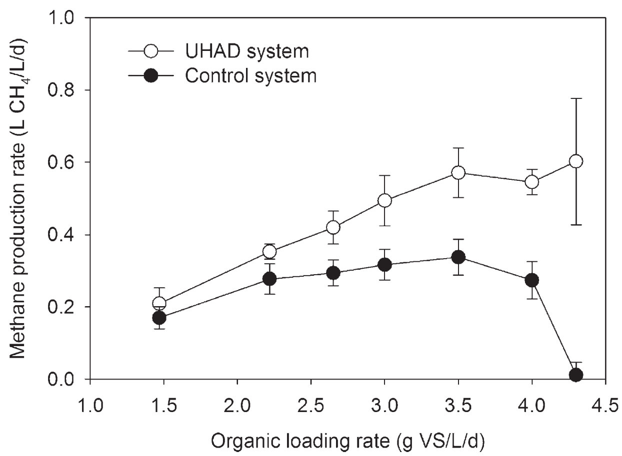

Figure 1 Methane production rate (MPR) of the UHAD system and the control system depending on organic loading rates (OLR)

alkalinity and VFA concentrations were kept to be 6.8~7.5, 2,600~3,200 mg/L as $CaCO_3$ and 710~1,280 mg COD/L, respectively.

On the other hand, the maximum average MPR of the control system was 0.34 L CH_4/L/d at the OLR of 3.5 g VS/L/d, which was only 59.1% of the UHAD system. It was observed that most biogas of both systems was produced in the first-stage. It indicated that the thermophilic reactor of the UHAD system played a very significant role in obtaining higher MPR. It has been reported that the application of thermophilic digestion has distinct advantages in rapid hydrolysis and accelerated biological conversion (Van Lier, 1996; Veeken and Hamelers, 1999). The decrease of MPR in the control system was due to the accumulation of VFAs. A drastic pH drop to 4.7 must have inhibited the activity of methanogens and there was little biogas production when the OLR was further increased to 4.3 g VS/L/d.

Methane recovery

Methane recovery was calculated with the ratio of experimental methane production to average biochemical methane potential (BMP). The BMP values were previously determined to be 0.39 L CH_4/g VS_{added} for thermophilic biomass and 0.34 L CH_4/g VS_{added} for mesophilic biomass by anaerobic batch tests using the same co-substrate.

Figure 2 illustrates the methane recovery efficiency of the UHAD system and the control system. The methane recovery of the UHAD system was between 69.1 and 82.4%

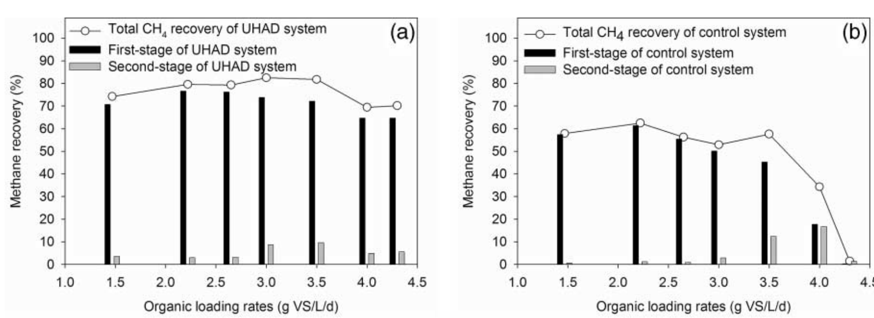

Figure 2 Methane recovery of the UHAD system (a) and the control system (b) depending on organic loading rates

depending on OLR. On the other hand, the control system showed lower methane recovery ranging from 52.8 to 62.5% up to 3.5 g VS/L/d, and then the recovery efficiency sharply decreased at above 3.5 g VS/L/d. As demonstrated in the vertical bars, most methane was recovered at the first-stage of the UHAD system. Beyond the OLR of 3.0 g VS/L/d, the methane recovery of the first-stage in the UHAD system decreased about 10% and the remaining methane potential was recovered in the second-stage mesophilic reactor as a post-treatment. It indicated that the following mesophilic second-stage efficiently removed the remaining or slowly biodegradable substances in the thermophilic effluent, such as VFAs and suspended solids, as pointed out by Welper *et al.* (1997).

Similar trends were observed in the control system as well. When OLR increased from 3.5 to 4.0 g VS/L/d, the methane recovery of the second-stage increased from 12.4 to 16.7%. However, at the OLR of 4.3 g VS/L/d, pH drop occurred in the second-stage because lots of acidified substrates in the first-stage were transferred, which was the main cause of the failure of the control system.

Methanogenic activity

The specific methanogenic activity (SMA) tests on individual biomass of the UHAD system and the control system were conducted using acetate, propionate and butyrate as precursor substrates of methane. In the SMA tests on thermophilic biomass of the UHAD system, the average SMA of acetate was 102 mL CH_4/g VSS/d, which was always higher than that of butyrate (85 mL CH_4/g VSS/d) and propionate (42 mL CH_4/g VSS/d). Figure 3(a) and (b) shows the SMA of acetate and butyrate in each stage of the systems depending on the OLR. The SMA of acetate on thermophilic biomass was maintained relatively constant and higher than that on other biomasses. Low SMA of acetate in the second-stage of the UHAD system indicated that the role of the mesophilic second-stage was merely a post-treatment guaranteeing further stabilization of untreated or remaining organics such as VFA, odorous substances, etc.

There was only a little difference between the first-stage and the second-stage of the control system in the SMA of acetate (63∼92 mL CH_4/g VSS/d) and butyrate (67∼103 mL CH_4/g VSS/d) when OLR was less than 3.5 g VS/L/d. However, at OLR of 4.0 g VS/L/d, the SMA of acetate and butyrate in each stage of the control system decreased about 21∼64% and finally methanogenic activity was fully inhibited at the OLR of 4.3 g VS/L/d in both stages of the control system.

Enhanced methane yield

The calculated average methane yields of the UHAD system and the control system were 0.30 and 0.23 L CH_4/g VS_{added}, respectively, when OLR was less than 3.5 g VS/l/d. From

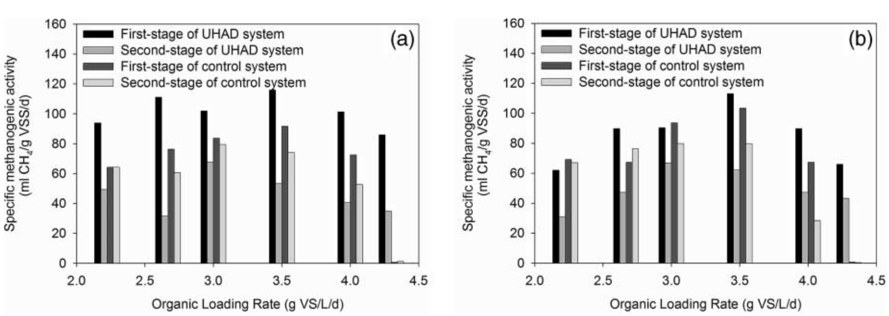

Figure 3 Specific methanogenic activity (SMA) of acetate (a) and butyrate (b) in each stage of the UHAD and the control system depending on organic loading rates

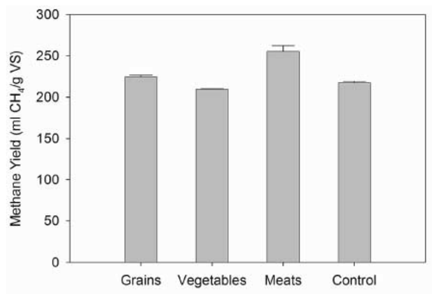

Figure 4 Methane yields in the BMP tests using major components of food waste

the results mentioned above, it was clear that the enhanced performance of the UHAD system resulted from the thermophilic reactor of the first-stage. Relatively rapid reaction rates in hydrolysis, acidogenesis, and methanogenesis led to the enhanced average CH_4 yield (30%) in the UHAD system.

The co-substrate, food waste and sewage sludge, consisted of complex compounds. Between them, food waste has abundant readily biodegradable substances to overcome rate-limiting hydrolysis under thermophilic conditions (Del Borghi *et al.*, 1999; Kim *et al.*, 2003). To investigate the reasons for the enhanced CH_4 yield, a batch test on thermophilic co-digestion was designed in duplicate to investigate the contribution of major components in food waste. As shown in Figure 4, when meats were added as a sole co-substrate, they generated higher methane yield in the thermophilic co-digestion than grains and vegetables. This indicated that protein degradation under thermophilic conditions was preferable. Harris and Dague (1993) and Orlygsson *et al.* (1994) reported that thermophilic conditions could lead to higher destruction of protein and higher levels of alkalinity as OLR increased. This means that higher degradation of meats in thermophilic conditions could prevent pH drop and contribute to stable operation of the UHAD system at high OLRs.

Figure 5 illustrates the methane production rates at various substrate utilization rates. The methane production rate of each system was calculated based on the COD equivalent (4 g COD/g CH_4) of each gram of methane. The substrate utilization rate was calculated based on the average unit COD equivalent (1.3 g COD/g VS) of co-substrate. The slope indicated that, of all the substrate utilized as COD, 29.6% and 23.3% was converted to methane in the UHAD system and the control system, respectively. The rest of the COD presumably remained in the effluent as stabilized solid residues or soluble by-products.

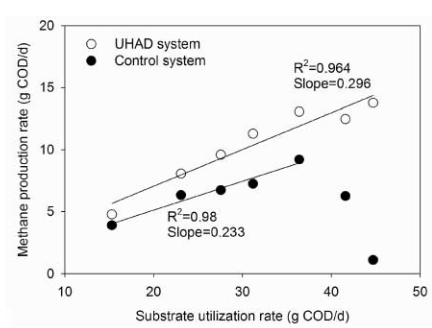

Figure 5 Methane production rates vs substrate utilization rates

Conclusions

It was demonstrated that the UHAD system for the co-digestion of sewage sludge and food waste resulted in higher methane recovery and methane production rate based on the optimized unification of sequencing batch operation, temperature-phased digestion, and co-digestion. The enhanced performance could be attributed to longer retention time of active biomass, faster hydrolysis, higher CH_4 conversion rate, and balanced nutrient condition of co-substrate. Above all, the thermophilic reactor of the UHAD system played a very significant role in obtaining higher performance in the co-digestion of sewage sludge and food waste. It was found that meats, one of the major components of food waste, could contribute to higher methane yield and system stability in the thermophilic first-stage of the UHAD system. The role of the mesophilic second-stage was to guarantee the good quality of the final effluent as a polishing stage. Consequently, this optimized unification could be a viable option for the simultaneous treatment of two types of OFMSW with high stability.

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