Improved anaerobic biodegradation of biosolids by the addition of food waste as a co-substrate

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Abstract. The temperature phased anaerobic digestion (TPAD) process was applied to to increase the performance of anaerobic treatment of biosolids. Previously obtained results indicate that this system showed the advantages of thermophilic and mesophilic anaerobic digestion process. By comparing the performance of each reactor of the system, it was illustrated that the main stage of methane production was the thermophilic reactor which has faster microbial metabolism. However, the result revealed that substrate characteristics of low VS/TS limited the system performance. Therefore, to evaluate the effect of food waste as a co-substrate for improving anaerobic biodegradability, biochemical methane potential (BMP) tests were conducted in thermophilic conditions with biomass of thermophilic reactor. It was confirmed that the co-digestion of sewage sludge mixed with food waste had a distinct improvement on biodegradability. The most significant advantages were the preferable environment provided by food waste for the growth and activity of anaerobes and the mutual assistance between biosolids and food waste.
Key words: anaerobic digestion, biosolids, co-substrate, co-digestion, food waste

Introduction

In many countries, large portion of biosolids have been generally treated by landfill, ocean dumping, incineration, etc. Those disposing methods, however, has historically been expensive because of the extremely large volumes in which they are produced (Rivard *et al.*, 1998a). Therefore, the roll of anaerobic digestion before disposal steps is more and more recognized as an indispensable and important technology. During past decades, various researches have been made for the higher biosolids treatment efficiency. The obvious objective is to attain higher digester performance and to further reduce the organic content of the biosolids for the purpose of increasing the potential to dewater and reducing both the pollution potential and pathogen load of the biosolids (Rivard *et al.*, 1998a; Miron *et al.*, 2000). Though anaerobic digestion is a cost-effective technology due to its high energy recovery and low environmental impact (Mata-Alvarez *et al.*, 2000), conventional anaerobic digestion processes in most biosolids treatment plants still suffer from unreliable performance. This is because of the fact that anaerobic biological waste treatment is a complex microbiological process involving many types of bacteria working like an assembly-line fashion. Thus, reliability depends mainly on the control of governing factors for achieving optimum operation of digesters (Parkin and Owen, 1987). Among the general governing factors of biosolids treatment, feed characteristics and nutrient concentration could be the one of major trouble makers to sound performance of digesters.

The popular concepts of phase separation have been contributed to the development of various types of staged anaerobic processes (Fox and Pholand, 1994). Among them, researches on temperature-phased anaerobic digestion (TPAD) process, which has advantages of both the thermophilic and mesophilic process, reported several successful results. In most cases, the TPAD process showed not only higher biogas recovery and VS removal efficiency, but also higher organic loading rate (OLR) at relatively shorter hydraulic retention time (HRT) (Han and Dague, 1997; Han *et al*, 1997; Oles *et al.*, 1997).

Increasing the solids concentration within the reactor would be particularly beneficial because a decreased reactor volume is possible while the same solids-loading rate and retention time are maintained (Rivard *et al.*, 1998b). At the same time, the biodegradability of solid wastes is another important factor. Increased amount of readily biodegradable matters could be the basis of improving digester performance. In that sense, it has high potential for MSW recycling streams and source separation programs to use organic fraction of municipal solid waste (OFMSW) as a co-substrate. Some experiences have reported the technical effectiveness of co-digestion with biosolids and various OFMSW (Cecchi *et al.*, 1989; Kiely *et al.*, 1997; Converti *et al.*, 1997; Gallert and Winter, 1997; Borghi *et al.*,1999, Stroot *et al.*, 2001). The synergistic effect of co-digestion includes the supply of deficient nutrient, the dilution of toxic materials, the improvement of biodegradability and the stimulation of microbial activity (Griffin *et al.*,1998; Mata-Alvarez *et al.*, 2000). Eventually, co-digestion of OFMSW and biosolids may be an attractive alternative for the management of two separate waste streams that are produced in every community (Griffin *et al.*, 1998). Among various OFMSW produced in Korea, food waste is the major source of decay, odor, and leachate in collection and transportation due to the high VS (80~90%) and moisture content (75~85%). Thus, food waste, consolidated in landfills with other wastes, has resulted in serious environmental problems including odor emanation, vermin attraction, toxic gas emission, groundwater contamination, etc. Moreover, the landfill of food waste will be prohibited in the near future.

However, if it is used as a co-substrate in anaerobic digestion of biosolids, food waste could improve nutrient balance and biodegradability. The biosolids could also give a dilution effect to inhibitory materials of food waste such as volatile fatty acids (VFA), ammonia, sodium ions, etc (Mata-Alvarez *et al.*, 2000). Therefore, this study was attempted to verify the feasibility of the TPAD system and to evaluate the performance of food waste addition as a co-substrate.

Materials and methods

Seed and substrate

Seed microorganisms and biosolids were taken from an anaerobic digester in D city wastewater treatment plant (WWTP). The total suspended solids (TSS) and volatile suspended solids (VSS) concentrations of the seed sludge were 23.6 and 14.1 g/l, respectively. Biosolids was sampled from the sludge thickener of primary and waste activated sludge in D city WWTP. All the substrates were filtered through a stainless steel sieve (U.S. Mesh No. 10 with corresponding sieve openings of 2.00 mm). Food waste, collected from a dining hall, was pretreated by an electrical blender and diluted to 50% (v/v) with liquid from food waste to keep original characteristics. The average characteristics of substrate were summarized in Table 1.

Table 1. Characteristics of substrate

Item	Unit	Food waste	Biosolids
Physical characteristics			
TS	g/l	42.5	30.7~23.7
VS	g/l	41.1	20.3~11.9
VS/TS		0.97	0.49
Chemical Characteristics			
Carbon (C)	%	45.7	24.4
Nitrogen (N)	%	2.2	3.4
Hydrogen (H)	%	6.7	3.9
Sulfur (S)	%	-	0.7
C/N		20.8	7.2

Operation of reactor system

A laboratory-scale TPAD system, combining 5 l of 1st stage CSTR and 15 l 2nd stage CSTR, was operated in mesophilic conditions (35±1°C). A thermophilic reactor equipped with water bath circulator (Jeio Tech, RBC-30) was controlled to 55±1°C. Schematic diagram of the reactor system was illustrated in Figure 1. A conventional mesophilic reactor (20 l, CSTR) was operated as a control. HRT of those reactor system were varied from 30 to 14 days, corresponding OLR was from 0.4 to 2.1 g VS/l/d.

Biochemical methane potential (BMP) tests

Thermophilic and mesophilic biomass were taken to measure methanogenic activity from each reactor of the system. Also, BMP tests for co-substrates were conducted with thermophilic and mesophilic biomass. In the tests, 160 ml serum bottles were used with a working volume of 100 ml. The bottles were operated in mesophilic (35±1°C) and thermophilic (55±1°C) conditions. The various mixtures of food waste and biosolids were added to each serum bottle. Their initial concentrations were all set to 2 g VS/l. After filling all the bottles to 80 ml with anaerobic medium and enough buffer solutions, 25 ml of seed biomass taken from the TPAD system was added to individual serum bottles. All the bottles were purged with N_2 gas before sealing. Then, the bottles were incubated in a rotary shaker to provide better contact of substrates, nutrients and microorganisms. All other procedures were performed according to Owen *et al.* (1979).

Analytical methods.

The contents of methane and carbon dioxide in the biogas were analyzed by a gas chromatograph (GC, 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). During the experiments, 1ml of sample was collected at a proper time with a syringe. The samples were immediately filtered through 0.45 μm cellulose nitrate membrane filters (Whatman) and then stored at 4°C for analysis. For the analyses of individual volatile fatty acid (VFA) concentrations, HPLC (Spectra Physics P2000) was used with an Aminex HPX-87H column and a UV (210 nm) detector. The chemical composition of substrates was analyzed by Elemental Analyzer (Fisons, EA-1110) equipped with a dynamic flash combustion-oxidation chamber and TCD. The elemental analytical methods for total solids (TS), VS, TSS, VSS were determined according to Standard Methods (APHA, 1998).

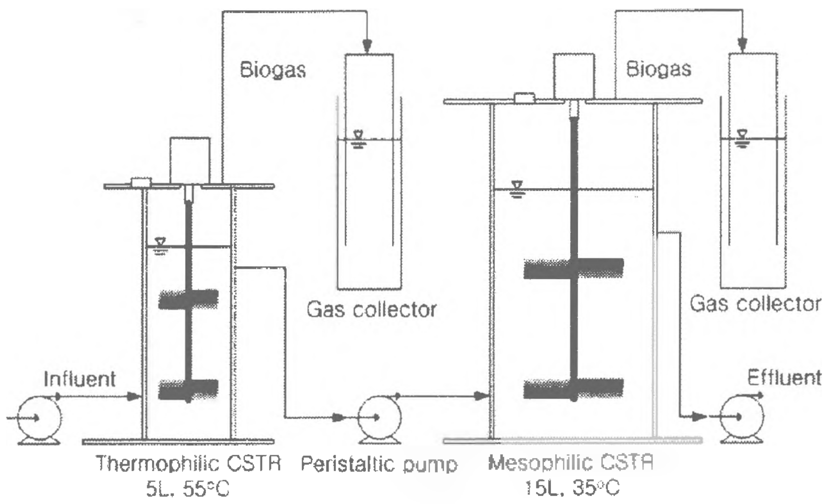

Figure 1. Schematic diagram of TPAD system

Results and discussions

VS removal efficiency and biogas production

Average VS removal efficiencies were evaluated with varying OLR from 0.4 to 2.0 gVS/l/d. As shown in Figure 2(a), the removal efficiency of the TPAD system showed relatively higher values of 48.5~30.9% than that of the control reactor, 40.0~26.2%, regardless of the OLR. Due to relatively low VS/TS of D city WWTP biosolids, VS removal efficiency was rather low than the previous results. Accordingly, TS concentration of biosolids were adjusted to about 4% after OLR 1g VS/l/d. Figure 2(b) shows the variations of methane production rate (MPR) per unit volume of each system. After increase of TS concentration of biosolids, MPR gradually improved as OLR increased. The disappeared initial fluctuation of MPR after increase of substrate concentration indicates that the proper increase of solid concentration level is beneficial for methane recovery.

In the TPAD system, majority of biogas was produced in the thermophilic reactor which had only 25% of total system volume as illustrated in Figure 3 (a). MPR was increased to 0.35 l/l/d and it could be able to increase higher value. In case of the second stage mesophilic reactor, MPR was less than 0.1 l/l/d. This trends demonstrated that the main reactor of methane production was the thermophilic reactor which has relatively faster microbial metabolism. And the roll of second stage was just a post treatment guarantying complete stabilization of thermophilic effluent which is notorious for high concentration of VFAs and offensive odor problem. These were similar with previous works of Han and Dague (1997), Han *et al.* (1997) and Oles *et al.* (1998).

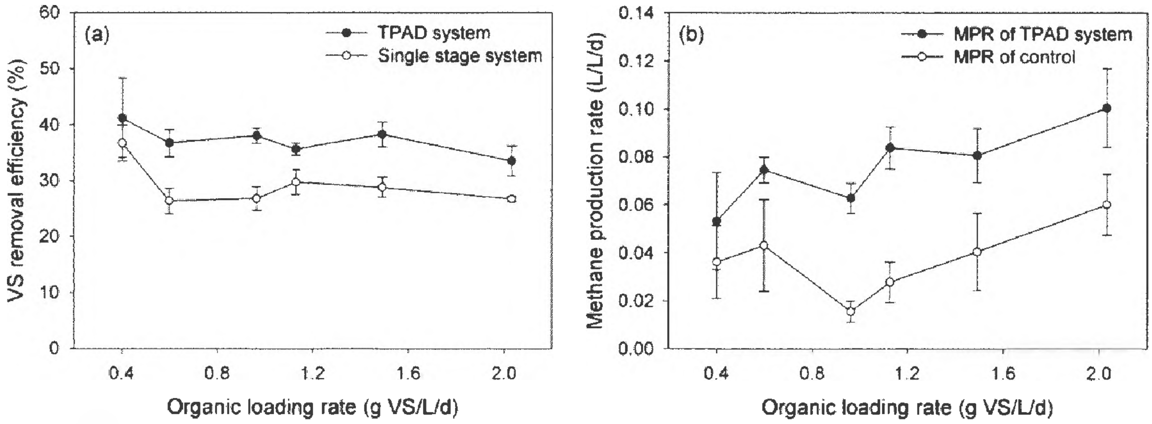

Figure 2. Variations of VS removal efficiency (a) and MPR (b) depending on OLR of TPAD and control system.

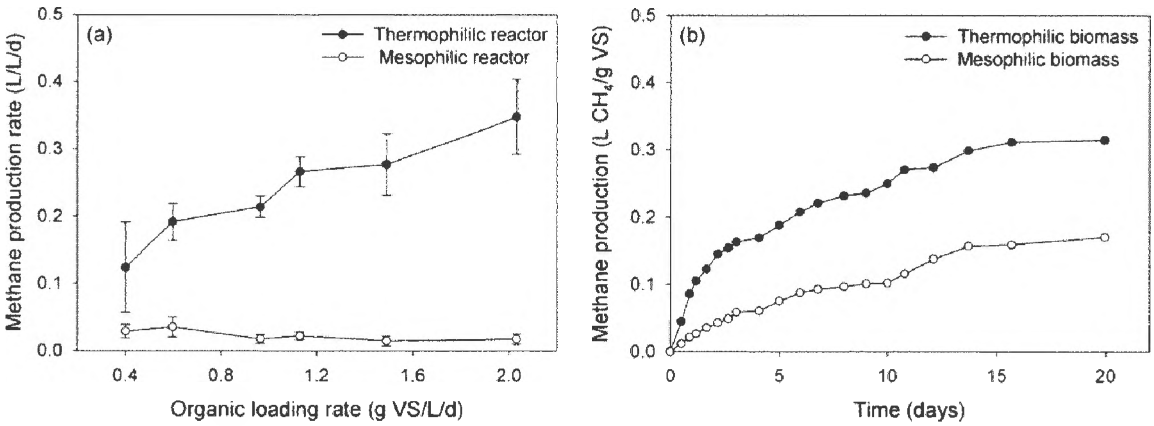

Figure 3. (a) Variations of MPR per unit reactor volume in each reactor of TPAD system; (b) Variations of methane production of thermophilic and mesophilic biomass

Methane yields of thermophilic and mesophilic biomass

Methane yields of thermophilic and mesophilic biomass of the TPAD system were evaluated. Each biomass was taken from the sampling port of thermophilic and mesophilic reactor when the TPAD system was operated at OLR of 1.49 g VS/l/d (HRT 14 days). The amount of thermophilic and mesophilic inoculum were 0.20 and 0.34 g VSS, respectively, per each serum bottle. The concentration of biosolids substrate, composed of primary and waste activated sludge, was 13.29 g VS/l. As shown in Figure 3 (b), there were two points of inflection due to the different biodegradability of organic fractions such as carbohydrates, proteins, lipids and so on. In this result, specific methane production rates of thermophilic and mesophilic biomass were 0.032 and 0.019 l CH_4/gVSS/d at the first inflection point (day 3). The methanogenic activity of thermophilic biomass was about two times higher than that of mesophilic one. After day 3, trends of two biomass were almost same. This means that thermophilic biomass was superior in converting readily biodegradable substances such as sugars or carbohydrates.

Biochemical methane potential of co-substrate

In this study, the overall performance of the TPAD system was much lower than other previous works. This is because typical Korean biosolids has a low VS/TS values. Therefore, using co-digestion strategy could be a preferable solution to increase low VS concentration and be a cost-effective technology due to the treatment two types of OFMSW at the same time. Hence, it was needed to evaluate the effect of food waste addition as a co-substrate on anaerobic digestion of biosolids. BMP tests were tried for the evaluation of feasibility. Four serum bottles were operated in thermophilic conditions with different mixtures of food waste and biosolids using thermophilic seed sludge from the TPAD system. Another four serum bottles were tested As a control in mesophilic conditions. As a result, in spite of same substrate concentration, 2 g VS/l, there were significant differences in BMP values depending on the proportion of food waste. As the proportions of food waste increased, cumulative CH_4 production drastically increased from 32.5 to 77.0 ml as illustrated in Figure 4 (a). All the estimated MPR values of thermophilic reactors at the first inflection point were superior to those of mesophilic ones. However, in contrast with BMP values, MPR decreased when the mixing ratios of food waste was higher than 50% of total VS regardless of temperature conditions. This phenomenon could be explained by the variations of VFA concentration. Since the high soluble organics contained in food waste were rapidly converted to VFA as shown in Figure 2, a drastic pH drop must have inhibited the activity of methanogens as pointed out by Cho *et al.* (1995). Also, as the loading rate increased, VFA accumulation led methanogenesis to a rate-limiting step instead of hydrolysis (Shin *et al.*, 2000). To clarify the influence of food waste addition on methane production rates, regression lines of quadratic form was illustrated in Figure 4 (b). In thermophilic conditions, 50% addition of food waste on a VS basis showed the highest MPR.

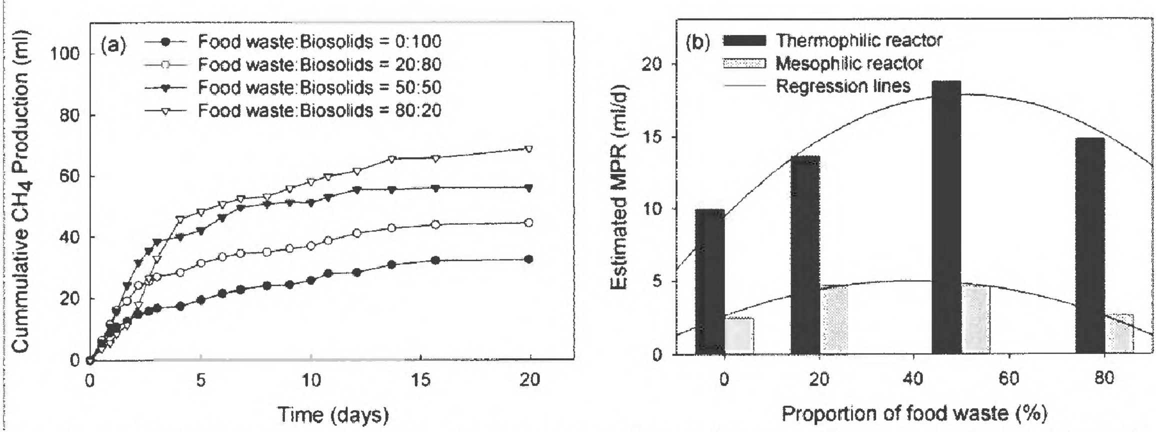

Figure 4. (a) Variations of cumulative methane production of thermophilic co-digestion; (b) Variations of MPR depending on the proportion of food waste in thermophilic and mesophilic co-digestion

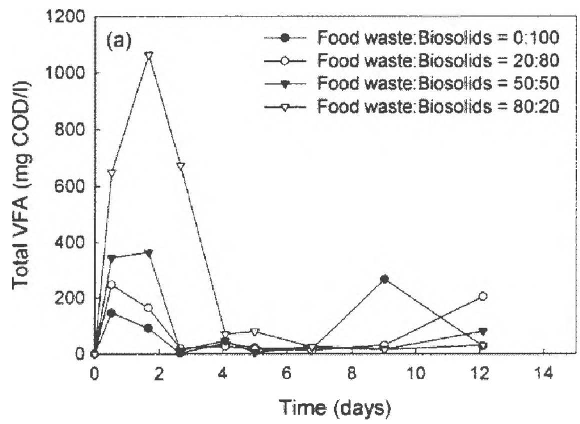

Figure 5. Variations of total VFA in thermophilic co-digestion

The results obtained in this study suggested that co-digestion of food waste and biosolids could be a good alternative for improving the low performance of conventional anaerobic digestion of biosolids. Previous studies reported that it was feasible to digest nutrient-deficient MSW with other co-substrate (Stroot *et al.*, 2001), but it was found to be also feasible to digest nutrient-rich MSW with other co-substrate containing high amount of readily biodegradable substances. However, the C/N ratio of typical Korean sewage sludge was just 7 due to the old combined sewer system. Thus, if food waste is added as a co-substrate, the C/N ratio becomes higher to be more appropriate for anaerobic digestion. It indicates that the addition of food waste plays an important role in providing organic carbon to biosolids. Moreover, food waste has substantially a high hydrolytic kinetic constant (Vavilin *et al.*, 1999). Although the elemental substances of food waste such as carbohydrates, proteins and lipids have different hydrolytic kinetic constants (Christ *et al.*, 1999), fast acidogenesis and methanogenesis can be possible by the enhancement of rate-limiting hydrolysis. Therefore, the balanced anaerobic environment led to the increased MPR and methane yield of anaerobic biomass.

Conclusions

The feasibility of high-rate TPAD system was tested for higher performance of anaerobic digestion of biosolids. Also, the performance of food waste addition as a co-substrate was evaluated to get rid of the substrate limitation. The results of this study showed that using co-digestion with high-rate anaerobic digestion technology could be a promising alternative for energy recovery and beneficial reuse of stabilized biosolids.

1. The maximum VS removal efficiency of the TPAD system was 46 ~ 32 %, which was due to the low VS/TS and the lack of readily biodegradable matter in typical Korean biosolids.
2. After concentrated substrate usage, the system performance of the TPAD system improved because the proper increase of solid concentration of substrate was beneficial for methane recovery.
3. The main stage of methane production was the thermophilic reactor which has faster microbial metabolism. The role of second stage was a post-treatment guarantying complete stabilization of thermophilic effluent which is notorious for high concentration of VFAs and offensive odor problem. The methane yield of thermophilic and mesophilic biomass was 0.32 and 0.27 l CH_4/g VS, respectively.
4. The important factor for the enhanced performance was nutrient balance. Additional carbon source supplied by food waste provided preferable environment for the growth and activity of anaerobes.

Acknowledgement

This research was supported by a grant from Korea Ministry of Science and Technology, through the National Research Laboratory Program.

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