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Single-Stage Anaerobic Codigestion for Mixture Wastes of Simulated Korean Food Waste and Waste Activated Sludge

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Abstract

Korean food waste was treated with a single-stage anaerobic codigester (SSAD) using waste activated sludge (WAS) generated from a municipal wastewater treatment plant. The stability and performance of the system was analyzed. The C/N ratio was improved with increasing food waste fraction of feed mixture. The pH, alkalinity, and free ammonia nitrogen concentration were the parameters used to evaluate the digester's stability. The experimentally determined values of the parameters indicated that there were no methane inhibitions in the digester. Digester performance was determined by measuring the total chemical oxygen demand TCOD), volate solids (VS) removal, methane content in biogas, methane production rate (MPR), and specific methane productivity. Methane content in biogas and MPR were significantly dependent on hydraulic retention time (HRT) and ratio of food waste to WAS. The methane content in biogas decreased at shorter HRT or higher organic loading rate (OLR) with increased food waste fraction. Concerning the performance of the codigester, the optimum operating condition of the SSAD was found to be at an HRT of 10 d with a feed mixture ratio of 50% food waste and 50% WAS. A TCOD removal efficiency of 53.6% and a VS removal efficiency of 53.7% were obtained at an OLR of 5.96 kg of TCOD/(m^3·d) and 3.14 kg of VS/(m^3·d), respectively. A maximum MPR of 1.15 m^3 CH_4/(m^3·d) and an SMP of 0.37 m^3 CH_4/kg of VS_{feed} were obtained at an HRT of 10 d with a methane content of 63%.

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Index Entries: Alkalinity; ammonia nitrogen; anaerobic codigestion; food waste; methane; volatile fatty acids; waste activated sludge.

Introduction

In 2000, Korea generated about 46,438 t/d of municipal solid waste (MSW). Korean food waste (KFW) constitutes approx 25% of MSW *(1)*. Most of the food waste is disposed by landfill (45.4%) and incineration (9.5%), and the rest is recycled as feedstuff, composting, or anaerobic digestion *(1)*. Food waste is difficult to treat or recycle because it contains high levels of sodium salt and moisture and is mixed with other collected wastes *(2,3)*. In 2005, landfilling of food waste, which causes various problems such as a foul odor and ground and surface contamination by leachate, will be prohibited.

Therefore, for KFW, anaerobic digestion has been considered as a feasible alternative to reduce waste volume and recover renewable energy as methane. Presorted KFW with 15–30% of total solid (TS) has a high volatile solid (VS) content (88–92% of TS), and the methane potential of KFW is estimated to be about 0.44–0.47 m^3 of CH_4/kg of VS_{feed} *(4,5)*. A characteristic of food waste that contains highly soluble organics is that it is converted rapidly to volatile fatty acids (VFA) in the early stage of digestion. A drastic drop in pH corresponding to VFA accumulation may lead to irreversible acidification of the digester, owing to poor buffering capacity *(4–6)*. Therefore, anaerobic digestion is often a two-phase system in order to separate acid and methane-forming phases *(4,5,7)*.

One of the most interesting options for improving biogas yield and reducing the volume of organic solid wastes is anaerobic codigestion, i.e., codigestion of the organic fraction of municipal solid wastes (OFMSW) together with sewage sludge *(8–12)*. Cecchi et al. *(13)* and Mata-Alvarez et al. *(14)* described the codigestion of OFMSW with sewage sludge in existing digesters and the advantages of codigestion. The advantages include dilution of potential toxic compounds coming from wastewater or cosubstrate, improved balance of nutrients, synergistic effects of microorganisms, increased organic loading of biodegradable matter, and better methane gas yields per unit of digester volume. In addition, using existing anaerobic digesters to treat OFMSW together with sewage sludge in municipal wastewater treatment plants could reduce capital and operating costs *(15–19)*.

In Korean municipal wastewater treatment plants, the existing anaerobic digesters conventionally are two-stage anaerobic digesters operated at mesophilic temperature (33–37°C); they do not operate properly because the actual loading rate is much less than the design loading rate. Therefore, using the extra capacity by adding OFMSW to existing municipal wastewater treatment plants anaerobic digesters may be a good alternative, especially for treating KFW and it may be possible to enhance the operating efficiency of anaerobic digesters. The present study was performed in a single-stage anaerobic codigester (SSAD) at 35°C, with feed mixture ratios of simulated KFW (SKFW):WAS of 10:90, 30:70, and 50:50. The objectives of this study were to evaluate the feasibility of anaerobic codigestion of KFW and waste activated sledge (WAS) and to investigate the stability and performance of the codigester.

Materials and Methods

Experimental Apparatus

This study used an SSAD—a semicontinuously fed and mixed reactor—made of Plexiglas. The effective volume of the digester was 3.5 L and four SSADs were arranged in a water bath. Each digester was mechanically stirred at 80 rpm with stainless steel paddles on a central shaft by an electric motor with a speed controller. The digestion system was operated with a fill-and-draw method. The water bath was maintained at 35°C by circulating water through a water jacket by a temperature-controlled circulator (Haake, Karlsruhe, Germany). The biogas produced was collected in Tedlar bags, and the volume was measured three times per week by a wet gas meter (Sinagawa, Tokyo, Japan).

Feedstock and Feed Mixtures

To simulate KFW, a traditional Korean food called Bibimbab—SKFW, which has a similar composition to the food waste, was used. It had a TS of 15–20% and a moisture content of 80–85%. Bibimbab consists of boiled rice (10–15%), vegetables (65–70%), and meat and eggs (15–20%). The SKFW was broken down to 2–4 mm using a cook mixer, and the final concentration of TS was controlled to 8 ± 0.5% by adding tap water. A considerable fraction of the soluble organics of SKFW was solubilized reducing the particle size. WAS was collected from the secondary clarifier in municipal wastewater treatment plants located in Daejon, Korea. The WAS sample was thickened using a centrifuge and adjusted to TS of 3%, which is typical of thickened sludge (TS of 2 to 3%) from gravity thickener in municipal wastewater treatment plants. The feed mixture ratios of SKFW:WAS were 10:90, 30:70, and 50:50 on the basis of VS contents of two solid wastes, respectively. Each feed mixture was made once per week and stored in a refrigerator at 4°C; however, partial hydrolysis and acidogenesis of the feed mixture was observed. Table 1 gaves the chemical characteristics and elemental analysis of the inoculum used as the initial seed, SKFW, WAS, and three feed mixtures.

Operating Conditions

The inoculum was used for a quick start-up without preacclimation to feed mixtures, in which the microorgnisms were well adapted to the mixture waste of KFW with thickened sludge (WAS plus primary sludge) was obtained from the mesophilic (35°C) SSAD at the Korea Institute of Energy Research. All experiments were conducted with three feed mixtures as a function of hydraulic retention time (HRT). The start-up periods of each feed mixture were 50 d, and the HRT of four digesters was maintained from 10 d to 13, 16, and 20 d.

Table 1
Chemical Characteristics and Elemental Analysis
of Inoculum, SKFW, WAS, and Three Feed Mixtures[a]

	Inoculum	SKFW	WAS	Feed Mixtures (g SKFW : g WAS)		
				10:90	30:70	50:50
TCOD (g/L)	23.8	100 (10)	36 (2.0)	44.3 (1.0)	45.4 (1.39)	58.5 (2.17)
SCOD (g/L)	0.31	43.0 (3.8)	0.3 (0.2)	2.77 (0.51)	4.01 (0.93)	10.8 (0.77)
TS (g/L)	21.7	80.0 (5.0)	30 (1.0)	31.6 (0.40)	33.1 (0.70)	37.6 (1.10)
VS (g/L)	14.2	75.0 (5.0)	18.5 (0.5)	23.7 (0.60)	26.0 (0.60)	31.4 (0.90)
pH	7.4	4.50 (0.5)	6.8 (2.0)	6.08 (0.15)	5.26 (0.24)	4.09 (0.26)
Alkalinity as CaCO (g/L)	3.65	0.15 (0.1)	0.8 (0.2)	0.95 (0.13)	0.51 (0.13)	—
NH_4^+ (g/L)	0.81	0.29 (0.1)	0.03 (0.01)	0.16 (0.04)	0.12 (0.04)	0.16 (0.02)
VFA (g/L)[b]	0	0.75 (0.15)	0	0.37 (0.13)	0.53 (0.32)	0.68 (0.16)
Elemental analysis (% TS)						
C		45.76	30.05	30.92	34.02	36.43
H		6.68	5.10	3.4	4.22	5.21
O		38.80	20.94	24.55	25.55	29.09
N		2.84	5.03	4.44	4.34	4.13
S		0.24	0.97	0.94	0.89	0.78
C/N ratio		16.11	5.97	6.97	7.84	8.82

[a] Numbers in parenthesis are the SD about the mean.
[b] VFAs: C_2–C_6.

Analytical Methods

The pH and temperature were monitored. Chemical oxygen demand (COD), TS, VS, alkalinity, and NH_4^+ of the samples were determined according to standard methods (APHA, AWWA & WEF, 1998) and were analyzed three times per wk during the start-up. In particular, the sample for the analysis of soluble chemical oxygen demand (SCOD), NH_4^+, and VFA was prepared by filtration using a 0.45-μm cellulose acetate membrane after centrifugating at 15,000 rpm for 15 min. Elemental composition of the sample was analyzed with an elemental analyzer (CHN-1000; Leco) and a sulfur analyzer (SC-432DR; Leco).

The percentage of methane and carbon dioxide was analyzed using a gas chromatograph (HP-5890A GC) equipped with a thermal conductivity detector and a 6-ft stainless column packed with Hayesep Q (80/100 mesh). The injection and detector temperatures were 120 and 150°C, respectively, and the column oven operated isothermally at 60°C. Helium was used as the carrier gas at a flow rate of 30 mL/min. The concentration of VFA was determined using the same gas chromatograph equipped with a flame ionization detector and a capillary column (25 m × 0.2 mm × 0.33-μm; Hewlett Packard-FFAP), with helium as the carrier gas (flow rate of 0.8 mL/min). The injection and detector temperatures were 200 and 220°C, respectively. The initial temperature of the column oven was 80°C and increased gradually by 13°C/min, reaching a final temperature of 180°C.

Results and Discussion

Typical WAS has the following composition: 33% carbohydrates, 28% protein, and 28% lipid *(20)* and is characterized by a low C/N ratio of 5.9 *(21)*. On the other hand, food waste is reported to have the following composition: 78% carbohydrates, 6.5% protein, and 0.6% lipid *(20)*. The anaerobic codigestion of OFMSW with sewage sludge result in a better balance of nutrients and higher C/N ratio in organic wastes, which are the prerequisites for a stable process performance. In other words, the high concentration of macro- and micronutrients in the sewage sludge could compensate the lack of nutrients in OFMSW, and the low C/N ratio of sewage sludge could be increased by the addition of OFMSW. Therefore, the addition of cosubstrate may improve the process performance and the methane yield owing to the better nutrient balance and C/N ratio.

As shown in Table 1, the C/N ratio of WAS used was similar to the typical value of 5.9, and the C/N ratio of SKFW was nearly three times higher than that of WAS. The C/N ratio of the three feed mixtures used as the substrate was improved with increasing SKFW fraction. During the start-up of each feed mixture, 15–20 d were required to reach the first steady-state condition. Indicators of digester stability, such as pH, alkalinity, NH_4^+ and VFA, were monitored. The COD and VS reduction, methane content of the biogas, MPR, and SMP were investigated for the operating performance of the SSAD.

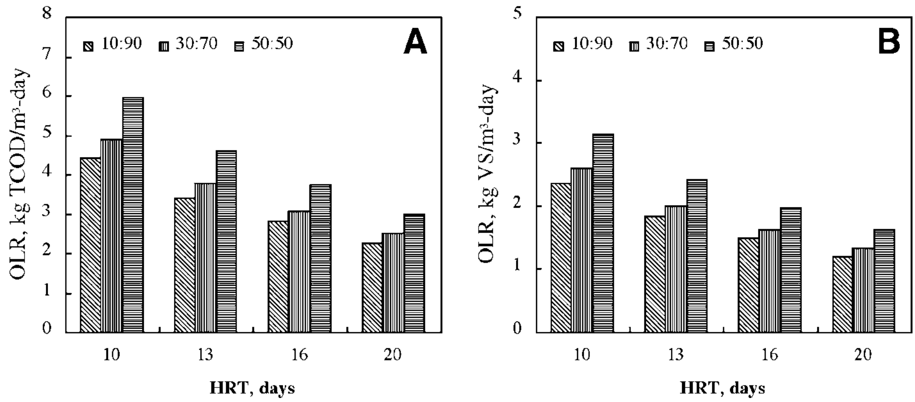

Fig. 1. OLRs of SSAD at different HRTs: **(A)** TCOD basis; **(B)** VS basis.

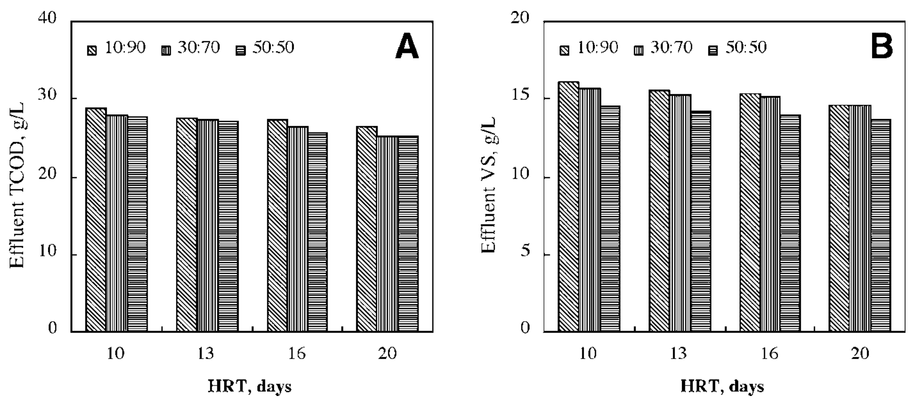

Fig. 2. Effluent TCOD and VS concentrations from SSAD at different HRTs: **(A)** TCOD; **(B)** VS.

Figure 1 presents the organic loading rate (OLR) expressed as total COD (TCOD) and VS on three feed mixtures as the function of HRT. The OLR was gradually increased as the HRT became shorter or the SKFW fraction of the feed mixture increased. Figure 2 shows the TCOD and VS concentration of the effluent; and the levels were nearly similar without the effect of HRT. However, the effluent VS concentration in the mixture ratio of 50:50 feed was the lowest compared with the other feed mixture, in spite of the higher OLR and shorter HRT. This was owing to the high biodegradability of SKFW.

Stability of SSAD System

In the anaerobic digestion process, the parameters that indicate stability are pH, alkalinity, NH_4^+, and VFA concentration in the digester. The pH of the methane bioreactor is usually controlled to a set point within the range of 6.5–7.5 *(22)*. During anaerobic treatment of organic solid wastes, a major pH drop in the digester is owing to the accumulation of VFA produced from the hydrolysis/acidogenesis of organic wastes, especially

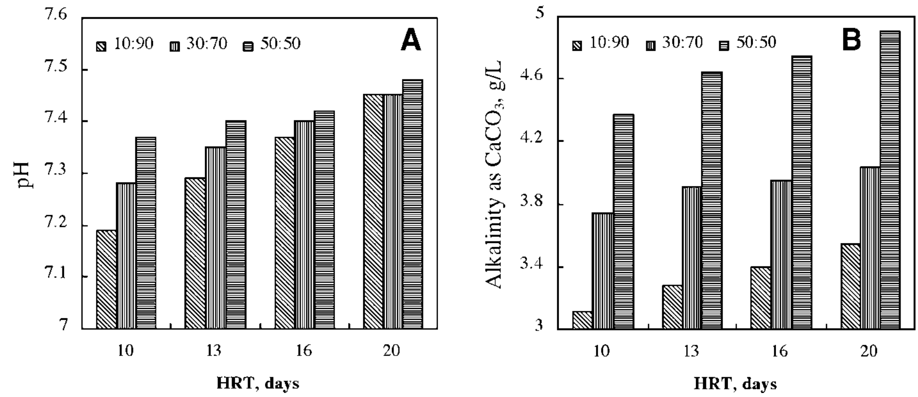

Fig. 3. pHs and alkalinities of SSAD at different HRTs: **(A)** pH; **(B)** alkalinity.

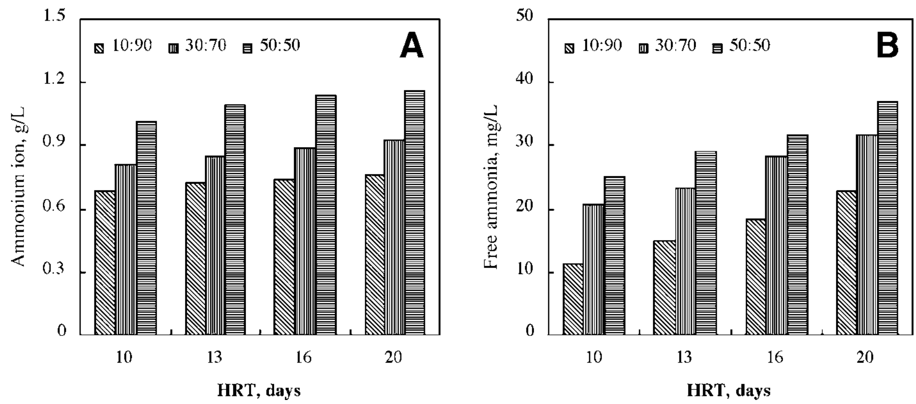

Fig. 4. Ammonium ion and FAN concentrations of SSAD at different HRTs: **(A)** ammonium ion; **(B)** FAN.

during an overloaded condition. Figure 3 shows the digester pH and alkalinity as a function of HRT with three feed mixtures. It is clear that pH and alkalinity of the SSAD proportionally increase as the HRT becomes longer or the OLR at an identical HRT increases. In particular, the alkalinity was compared among three feed mixtures; the maximum alkalinity was 4.91 g/L as $CaCO_3$ for a feed mixture of 50:50. Even at a short HRT of 10 d with an OLR of 5.96 kg of TCOD/(m^3·d), an alkalinity of 4.37 g/L as $CaCO_3$ was maintained. Lay et al. *(23)* reported that the methane production rate in a high-solid sludge digestion was good at a pH range of 6.6–7.8, and the digester may fail if the pH was <6.1 or >8.3. During all the experiments, the digester pH was maintained within the stable range of 7.2–7.5 with sufficient alkalinity ranging from 3.1 to 4.91 g/L as $CaCO_3$. In addition, the accumulation of VFA was not observed in all experiments after reaching the first steady state.

Figure 4 shows the ammonium ion (NH_4^+) and free ammonia nitrogen ([FNA], NH_3) concentration produced from the digester as a function of

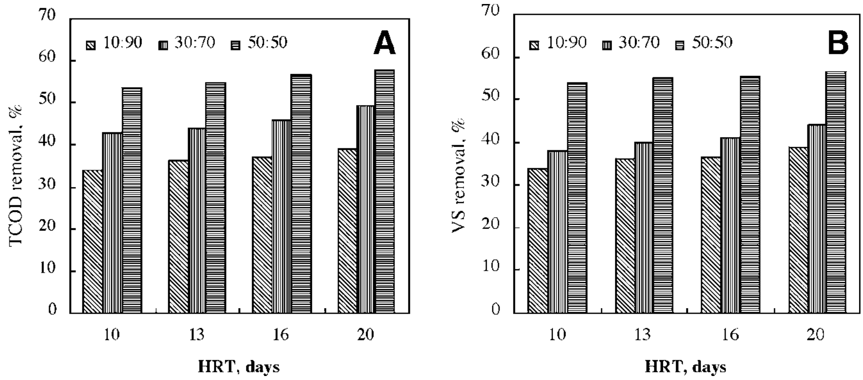

Fig. 5. TCOD and VS removals of SSAD at different HRTs: **(A)** TCOD; **(B)** VS.

HRT on three feed mixtures. The ammonia nitrogen, which is formed by the anaerobic biodegradation of organic nitrogenous compounds such as proteins or amino acids, significantly affects methanogenic activity. The inorganic nitrogen produced, the ammonium ion, and FAN exist in two forms in the liquid phase. In particular, because the FAN concentration depends on pH, it is important to control the pH of an operating digester. Braun et al. *(24)* and Bhattacharya and Parkin *(25)* suggested that the maximum tolerable FAN concentration is 55–80 mg/L for a stable digestion. Lay et al. *(23)* investigated the influence of ammonia nitrogen on methanogenic activity in the wide pH range of 6.5–8.5. The methanogenic activity decreased with increasing NH_4^+ concentration and dropped 10% at a concentration of 1670–3720 mg/L, 50% at 4090–5550 mg/L, and 0 at 5880–6600 mg/L. In the present study, at an HRT of 20 d with a 50:50 feed mixture, the ammonium ion concentration was the highest at 1160 mg/L, and the FAN concentration was 37 mg/L as a function of pH 7.5 at 35°C. Therefore, the FAN concentration was estimated to be below the concentration that inhibits the methanogenic activity mentioned in the literature. The FAN concentration was calculated using Eq. 1, presented by Kayhanian *(26)* as a function of pH at 35°C. Judging from the stability parameters of an SSAD, there was no inhibition of methane production owing to pH drop, insufficient alkalinity, or inhibition by FAN for all the experiments.

$$NH_3(\text{mg/L}) = \frac{\text{TAN} \times (Ka \div [\text{H}])}{(Ka \div [\text{H}]) + 1} \tag{1}$$

in which NH_3 is the free ammonia nitrogen concentration (mg/L), TAN is the total ammonia concentration in solution including ammonium and free ammonia (mg/L), [H] is the hydrogen ion concentration (10^{-pH}), *Ka* is the temperature-dependent dissociation constant (1.097×10^{-9} at 35°C).

Performance of SSAD System

Figure 5 presents the TCOD and VS removal efficiencies of SSAD as a function of HRT on three feed mixtures. For the TCOD and VS removal

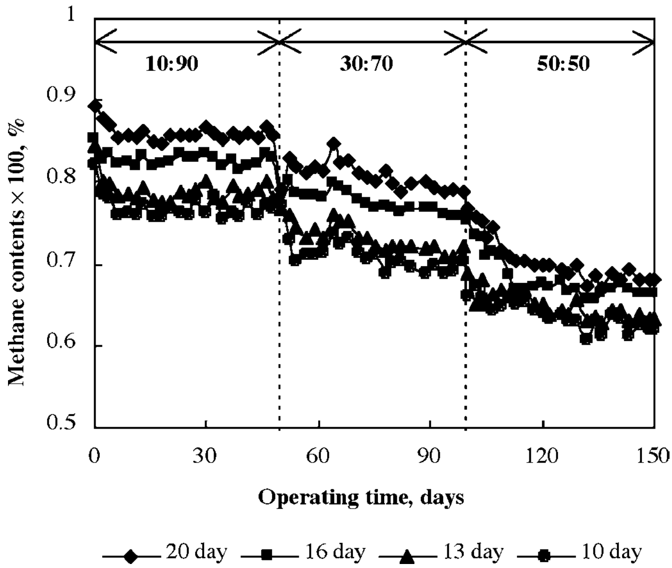

Fig. 6. Methane contents in biogas of SSAD at different HRTs.

efficiencies, the trend was similar and slightly increased as the HRT became longer for the same feed mixture. However, the magnitude of the TCOD and VS removal efficiencies was remarkably different among the three feed mixtures at the same HRT. Therefore, it became clear that the TCOD and VS removal efficiencies were more affected by the SKFW fraction of the feed mixture than the influence of the HRT; that is, their removal efficiencies depended on the biodegradability of the feed mixture. Among three feed mixtures, the TCOD and VS removal efficiencies were the highest at a feed mixture of 50:50. The maximum TCOD removal of 57.9% and VS removal of 56.3% were achieved when the digester was operated at an HRT of 20 d with an OLR of 2.98 kg of TCOD/(m^3·d) and 1.61 kg of VS/(m^3·d), respectively. Even at a shorter HRT of 10 d with an OLR of 5.96 kg of TCOD/(m^3·d) and 3.14 kg of VS/(m^3·d), the TCOD removal was 53.6% and VS removal was 53.7%. These results are comparable to previous research for the anaerobic codigestion of OFMSW and sewage sludge. Mata-Alvarez et al. *(14)* investigated the mesophilic (35°C) anaerobic codigestion of the mixture of 50% OFMSW and 50% sewage sludge. They reported that VS removal was 57% at an HRT of 14.5 d with an OLR of 2.8 kg of VS/(m^3·d). Del Borghi et al. *(11)* investigated the thermophilic (55°C) anaerobic codigestion of a mixture of 50% OFMSW and 50% sewage sludge. The VS removal was 64% at an HRT of 12 d with an OLR of 4.0 kg of VS/(m^3·d).

Figure 6 shows the methane percentage in the biogas. The methane content of biogas produced from all digesters was higher than the usual values of 60% and had significant differences among three feed mixtures.

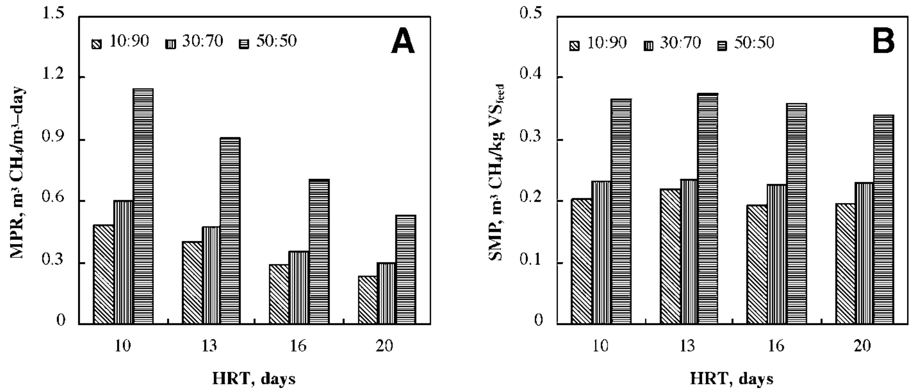

Fig. 7. MPRs and SMPs of SSAD at different HRTs: **(A)** MPR; **(B)** SMP.

As shown in Fig. 6, it became clear that the methane content of biogas gradually decreased as the HRT became shorter or the OLRs increased. The methane content of the digester operated at different HRTs with a mixture ratio of 50:50 was in the range of 63–70%, higher than those of 60 and 50% obtained by Mata-Alvarez et al. *(14)* and Del Borghi et al. *(11)*.

Figure 7 presents the MPR and SMP at different HRTs with three feed mixtures. Two parameters increased with increasing SKFW fraction of the feed mixture owing to the abundant carbohydrate of food waste. MPR was expressed as the methane volume of biogas produced per volume of digester per d. As shown in Fig. 7A, the MPR proportionally increased as the HRT became shorter or the OLR increased; therefore, the MPR was directly related to the OLR applied to the reactor and thus reflects the COD and VS removal efficiency. The maximum MPRs of the three feed mixtures were 0.48 of 10:90, 0.6 of 30:70 and 1.15 m^3 of $CH_4/(m^3 \cdot d)$ of 50:50 ratio at an HRT of 10 d with an OLR ranging from 2.37 to 3.14 kg of VS/$(m^3 \cdot d)$. The SMP is a good parameter to estimate the biodegradability of a substrate added to the digester. The SMP (m^3 of CH_4/kg of VS_{feed}) was expressed as the methane volume of biogas produced per unit mass of VS added to the digester (Fig. 7B). HRT had little effect on SMP of each feed mixture and decreased above an HRT of 13 d. We have already estimated the SMP of three feed mixtures by the batch biochemical methane potential test *(27)*. The SMPs were 0.20, 0.23 and 0.29 m^3 of CH_4/kg of VS_{feed} at the mixture ratios of 10:90, 30:70, and 50:50, respectively. The SMPs obtained in the present study on feed mixtures of 10:90 (0.19–0.22 m^3 of CH_4/kg of VS_{feed}) and 30:70 (0.23–0.24 m^3 of CH_4/kg of VS_{feed}) were similar to the SMPs of the biochemical methane potential test. On the other hand, the SMP (0.34–0.37 m^3 of CH_4/kg of VS_{feed}) of the feed mixture of 50:50 was larger than the SMP obtained in the biochemical methane potential test. However, the maximum SMP of 0.37 m^3 ofCH_4/kg of VS_{feed} is nearly identical to those obtained by Mata-Alvarez et al. *(14)*. Table 2 summarizes the operating conditions, reactor characteristics and digester performances

Table 2
Results of SSAD Operated at Different HRTs with Three Feed Mixtures

Parameter	Mixture ratios of SKFW to WAS											
	10:90 (step 1)				30:70 (step 2)				50:50 (step 3)			
Operating conditions												
HRT (d)	20	16	13	10	20	16	13	10	20	16	13	10
OLR (kg TCOD/[m^3·d])	2.27	2.79	3.42	4.43	2.51	3.07	3.77	4.89	2.93	3.75	4.6	5.96
OLR (kg TVS/[m^3·d])	1.19	1.49	1.83	2.37	1.34	1.63	2.00	2.60	1.61	1.97	2.42	3.14
Reactor characteristics												
TCOD (g/L)	26.4	27.2	27.6	28.7	25.1	26.5	27.4	28.0	25.1	25.8	27.0	27.7
SCOD (g/L)	0.89	0.85	0.85	0.85	0.72	0.75	0.79	0.79	0.74	0.81	0.76	0.76
TS (g/L)	22.1	22.7	22.8	23.5	21.9	22.9	23.0	23.4	20.6	20.8	20.7	20.8
VS (g/L)	14.6	15.3	15.6	16.1	14.6	15.1	15.2	15.7	13.7	14.0	14.2	14.5
pH	7.45	7.37	7.29	7.19	7.51	7.48	7.41	7.38	7.48	7.42	7.40	7.37
Alkalinity as $CaCO_3$ (g/L)	3.54	3.4	3.28	3.11	4.04	3.95	3.91	3.74	4.91	4.75	4.64	4.37
NH_4-N (g/L)	0.76	0.74	0.72	0.68	0.93	0.91	0.91	0.89	1.16	1.14	1.09	1.01
VFAs (g/L)	0	0	0	0	0	0	0	0	0	0	0	0
Digester performance												
TCOD removal (%)	39.1	37.2	36.4	33.9	49.5	45.8	44	42.8	57.9	56.7	54.7	53.6
TVS removal (%)	38.6	36.5	36.1	33.9	43.9	41.1	40.0	38.0	56.3	55.3	54.8	53.7
Methane content (%)	85.7	82.6	78.5	76.5	80.2	77.0	72.5	70.4	69.4	66.8	64.5	63.3
SMP, m^3 CH_4/kg TVS_{feed}	0.194	0.192	0.218	0.202	0.23	0.228	0.235	0.232	0.339	0.359	0.375	0.366
MPR, m^3 CH_4/(m^3·d)	0.230	0.286	0.4	0.48	0.298	0.356	0.471	0.601	0.532	0.708	0.907	1.150

of SSAD to treat the mixture wastes of SKFW and WAS. The data presented are the mean values at the steady-state condition.

Conclusion

The effects of HRT and mixture ratio of SKFW:WAS on the stability and performance of the SSAD were investigated. The SSAD was quite efficient for treating KFW.

Maintaining the proper pH in the digester is important to keep the FAN concentration, a strong inhibitor, low. The digester pH was maintained within the stable range of 7.2–7.5 with sufficient alkalinity ranging from 3.1 to 4.91 g/L as $CaCO_3$. In addition, the accumulation of VFA was not observed in all experiments after reaching the first steady state. Under the investigated operating conditions, there were no inhibitions of the methanogenic activity in the digester.

The optimum operating conditions of the SSAD, concerning the MPR and SMP, was found to be at an HRT of 10 d with a feed mixture ratio of 50% WAS and 50% SKFW. The TCOD removal efficiency of 53.6% and VS removal efficiency of 53.7% were obtained at the highest OLR of 5.96 kg of TCOD/(m^3·d) and 3.14 kg of VS/(m^3·d), respectively. The maximum MPR of 1.15 m^3 of CH_4/(m^3·d) and SMP of 0.37 m^3 of CH_4/kg of VS_{feed} with the methane content of 63% were obtained at an HRT of 10 d. Therefore, the optimum operating conditions in the SSAD, and the corresponding performance of the digester indicate that the anaerobic codigestion of KFW with sewage sludge is a good option for food waste and WAS treatment.

Acknowledgment

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