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Combined mesophilic anaerobic and thermophilic aerobic digestion process for high-strength food wastewater to increase removal efficiency and reduce sludge discharge

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ABSTRACT

In this study, a process that combines the mesophilic anaerobic digestion (MAD) process with thermophilic aerobic digestion (TAD) for high-strength food wastewater (FWW) treatment was developed to examine the removal of organic matter and methane production. All effluent discharged from the MAD process was separated into solid and liquid portions. The liquid part was discarded and the sludge part was passed to the TAD process for further degradation. Then, the digested sludge from the TAD process was recycled back to the MAD unit to achieve low sludge discharge from the combined process. The reactor combination was operated in two phases: during Phase I, 40 d of total hydraulic retention time (HRT) was applied; during Phase II, 20 d was applied. HRT of the TAD process was fixed at 5 d. For a comparison, a control process (single-stage MAD) was operated with the same HRTs of the combined process. Our results indicated that the combined process showed over 90% total solids, volatile solids and chemical oxygen demand removal efficiencies. In addition, the combined process showed a significantly higher methane production rate than that of the control process. Consequently, the experimental data demonstrated that the combined MAD-TAD process was successfully employed for high-strength FWW treatment with highly efficient organic matter reduction and methane production.

Key words | combined biological process, food wastewater, low sludge discharge, mesophilic anaerobic digestion (MAD), methane production, thermophilic aerobic digestion (TAD)

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INTRODUCTION

Food waste accounts for over 26% of total municipal solid waste (MSW) generation (49.150 tons/d) in Korea. Since 2005, the Korean government has prohibited direct landfill of food waste, and about 260 food waste recycling facilities have been installed to treat it appropriately (KMOE 2012). These facilities use composting or washing processes, converting most food waste to feedstuff or fertilizer. However, the demand with regard to these products is very low due to their poor quality. Furthermore, the recycling process (i.e., storage, separation and washing step) produces approximately 9.398 tons/d of food wastewater (FWW), a by-product that contains high-strength organic matter (KMOE 2012). Until 2013, most FWW was discharged by ocean dumping, but this practice was banned by the London Convention 97 protocol in January of 2013 (KMOE 2012). Therefore, finding an appropriate FWW treatment method has become an urgent task in Korea.

Anaerobic digestion (AD) is one practical option for treatment of high-strength FWW, because the organic fraction in FWW can be converted to bioenergy (methane or hydrogen gas). Therefore, AD has become increasingly attractive due to fuel price increase resulting from fossil fuel depletion. In Europe, AD accounts for 25% of the biological waste recycling and has become a preferred option for treatment of the organic fraction of MSW (De Baere & Mattheeuws 2008). The Korean government also plans on installing more AD plants to treat and generate renewable energy from MSW, including FWW (KMOE 2008).

Recently, during the AD of solid wastes various physical, chemical and biological sludge reduction processes have been developed and applied to promote the hydrolysis of the rate-limiting step (Carrère *et al.* 2010). Combined anaerobic and aerobic digestion is a new approach to the treatment of organic wastes; it has attracted attention because only

doi: 10.2166/wst.2014.050

some proportion of the organic component is degraded under anaerobic or aerobic conditions (Novak *et al.* 2003). This combined anaerobic-aerobic process can remove more additional volatile solids (VS) and nitrogen than can the single-stage mesophilic or thermophilic anaerobic process (Kumar *et al.* 2006; Parravicini *et al.* 2008; Novak *et al.* 2011; Tomei *et al.* 2011). However, one major drawback of this sequential process is the relatively slow digestion rate of the aerobic process.

To overcome this drawback, one potentially attractive option is to substitute thermophilic aerobic digestion (TAD) for the aerobic process in the combined anaerobic–aerobic process, because the TAD has several advantages such as self-heat generation, rapid biodegradation rate and low biomass production (Kelly *et al.* 1993; Dumas *et al.* 2010). Although TAD has several obvious advantages, the combination of mesophilic anaerobic digestion (MAD) and TAD processes for treating FWW has never been explored. Thus, the objective of this study is to develop a novel combined process for high-strength FWW treatment with high removal efficiency. To achieve this goal, a laboratory-scale combined MAD-TAD process was developed. In this combined process, all the solid part of the effluent from MAD is separated by a solid/liquid separation unit and then recycled back to TAD for further degradation; then the effluent sludge from TAD is returned to MAD to increase methane production and to discharge low sludge.

METHODS

Preparation of food wastewater

The FWW (Table 1) was collected from a food waste recycling facility in Pohang, Korea. Around 180 tons/d of food waste from various sources is collected and recycled through this facility. During the separation and washing process, approximately 50 tons/d of FWW is generated. Samples from a FWW storage tank were filtered (1.0-mm sieve) to remove large-size inert materials (mainly eggshell, plastic and vinyl), then distributed in 3-L bottles and stored at −25 °C until use.

Reactor set-up and operation

The laboratory-scale experimental setup (Figure 1) consists of a combined process and a control process. The combined process consists of a MAD process (R_1) with a TAD process (R_2). All effluent discharged from R_1 was collected (at 4 °C) and separated daily by centrifugation (8,000 rpm, 20 min) in a solid/liquid separation unit. The liquid part was discarded and the remaining highly concentrated anaerobic sludge was passed to R_2 for additional digestion. Then, the effluent from R_2 was recycled back to R_1 for methane production and further sludge degradation.

The combined process was operated in two phases over 204 days (Table 2): during Phase I (days 0–102) the hydraulic retention time (HRT) was 40 d; during Phase II (days 102–204) it was 20 d; corresponding organic loading rates (OLRs) were 3.5 and 7 kg COD/(m^3 d). For a comparison, a single-stage MAD (control process, R_3) was operated with the same total HRTs of the combined process. All reactors were fed four times a day using a peristaltic pump (Cole-Parmer®) controlled by a timer and relay.

The seed for anaerobic reactors (R_1 and R_3) and for the thermophilic aerobic reactor (R_2) was obtained from an anaerobic sludge digestion plant in Daegu, Korea, and from a successfully operated autothermal thermophilic aerobic

Table 1 | Physical–chemical characteristics of FWW and liquid part of effluent

	Values (average ± standard deviation)		
		Liquid part	
Parameters	FWW	Phase I	Phase II
pH	4.31 ± 0.02	7.43 ± 0.11	7.37 ± 0.01
TS (g/L)	118.49 ± 3.54	8.88 ± 0.21	8.89 ± 0.19
VS (g/L)	106.52 ± 3.41	3.94 ± 0.18	3.98 ± 0.22
VS/TS (%)	90.5 ± 0.69	44.35 ± 0.79	44.75 ± 1.24
TCOD (g/L)	139.58 ± 2.79	9.49 ± 0.58	9.07 ± 0.06
SCOD (g/L)	90.46 ± 1.53	3.43 ± 0.03	4.81 ± 0.11
TN (g/L)	1.94 ± 0.15	–	–
NH_4^+-N (g/L)	0.57 ± 0.03	–	–
TP (g/L)	2.22 ± 0.23	–	–
STP (g/L)	1.58 ± 0.02	–	–
Total organic acid (g COD/L)	69.47 ± 1.46	2.86 ± 0.07	3.28 ± 0.01
Lactic acid (g COD/L)	40.74 ± 1.04	N.D.	N.D.
Acetic acid (g COD/L)	14.35 ± 0.59	1.52 ± 0.01	1.73 ± 0.01
Propionic acid (g COD/L)	3.32 ± 0.31	1.43 ± 0.03	1.55 ± 0.01
Butyric acid (g COD/L)	9.94 ± 0.51	N.D.	N.D.
Succinic acid (g COD/L)	1.12 ± 0.04	N.D.	N.D.

TS: total solids; VS: volatile solids; TCOD; total COD; SCOD: soluble COD; TN: total nitrogen; TP: total phosphorus; STP: soluble total phosphorus; COD: chemical oxygen demand. N.D.: not detected.

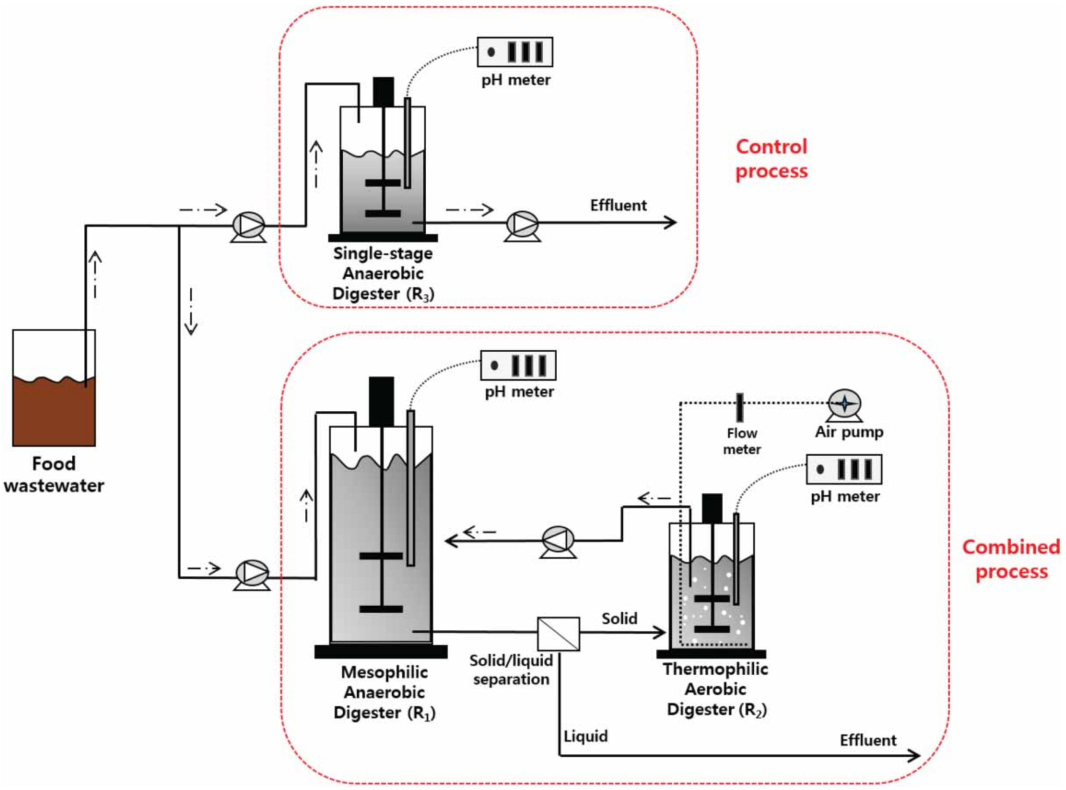

Figure 1 | Overall schematic diagram of a combined process and a control process.

Table 2 | Operating conditions of a combined process and a control process

	Phase I (days: 0–102)			Phase II (days: 102–204)		
Parameter	**MAD (R_1)**	**TAD (R_2)**	**Control MAD (R_3)**	**MAD (R_1)**	**TAD (R_2)**	**Control MAD (R_3)**
Reactor vol. (L)	11	1	6	11	1	6
HRT (d)	22	5	40	13.75	5	20
Total HRT (d)	40		40	20		20

digestion (ATAD) pilot plant in Daejeon, Korea, respectively. To allow seed microorganisms to acclimatize, the reactor was operated in batch mode for 1 week before semi-continuous operation was initiated. R_1 and R_3 were operated at $35 \pm 0.5\,^{\circ}C$ and R_2 was operated at $55 \pm 0.5\,^{\circ}C$. Compressed air was continuously supplied into R_2 at 5 L/min through a fine-pore diffuser to maintain aerobic conditions.

Physical–chemical analysis

Total solids (TS), VS, total chemical oxygen demand (TCOD), total nitrogen (TN), ammonia (NH_4^+-N), total phosphorus (TP) and total alkalinity (TA) were measured using *Standard Methods* (APHA 1998). For soluble COD (SCOD), soluble TP (STP) and organic acid analysis, samples were passed through 0.45 and 0.2-μm pore size filters, respectively. The pH in the reactor was continuously measured using a pH meter (405-DPAS-SC-K85, Mettler Toledo, Switzerland). Organic acids were quantified using a high performance liquid chromatograph (HPLC, Agilent Technology 1100 series, Agilent Inc., USA) equipped with a column (Aminex HPX-87H, Biorad Inc., USA), refractive index detector, and diode array detector. Biogas was detected using a gas chromatograph (Model 6890N, Agilent Inc., USA) equipped with a pulsed discharge detector. Biogas volume was quantified using the water displacement method. The quantified organic acid values were converted to g COD/L by using conversion factors (lactic acid: 1.07, acetic acid: 1.07, propionic acid: 1.51, butyric acid: 1.82, succinic acid: 0.95).

RESULTS AND DISCUSSION

Reactor stability: pH and TA

FWW used in this study had pH around 4.3 (Figure 2(a)). In general, FWW has low pH because partial lactic acid fermentation occurs easily during the recycling process. Typically, overload with feedstock that has a large amount of organic acid or low pH can inhibit growth of anaerobic microorganisms that perform hydrolysis and methanogenesis (Jun *et al.* 2009). Therefore, for the stable process operation, pH and TA were continuously recorded during the entire operating period.

During Phase I the pH was between 7.0 and 7.5 in both R_1 and R_3. During the initial period of Phase II, the pH in R_3 declined from 7.5 to 6.7, but this decline did not reduce methane production because most methanogens have an optimal pH between 6.5 and 7.5. Unlike the anaerobic reactors, pH in R_2 increased to 8.25 during the initial period of Phase I, and then it remained steady during the rest of the operating period. This result is consistent with a previous ATAD experiment (Liu *et al.* 2011) in which pH increased under thermophilic aerobic conditions owing to ammonia and CO_2 stripping caused by continuous aeration.

TA buffers biological processes, and is an important parameter, especially when treating high-strength or low-pH wastewater. TA concentrations in both R_1 and R_3 remained quite stable and were higher than 3 g $CaCO_3$/L during Phase I (Figure 2(b)), but TA in R_3 during the initial period of Phase II declined to 2.23 g $CaCO_3$/L. This phenomenon occurs mainly due to the OLR increase from 3.5 to 7 kg COD/(m^3 d) during Phase II. Even though the TA in R_3 decreased during the initial period of Phase II, relatively sufficient buffer capacity in both anaerobic reactors maintained favourable pH condition for organic matter degradation and methane production during the overall operating period. TA concentration in R_2 was quite stable (around 1.45 g $CaCO_3$/L) because the HRT of R_2 was fixed at 5 d. Also, due to the continuous aeration, R_2 showed lower TA than did both R_1 and R_3.

TS and VS removal

The removal efficiencies of TS and VS were measured at the steady-state condition during Phases I and II (Figure 3). An increase in concentration of solids in the thermophilic aerobic process was observed during the initial digestion period in Phases I and II; however, the solid concentrations in all reactors were quite stable after the reactor reached steady-state conditions (data not shown). In the combined process (R_1–R_2), TS removal was higher than 90% in both phases; these results were 24.3 and 29.4% higher than the TS removal in the control process (R_3) in Phases I (68.2%) and II (63.1%), respectively. The combined process showed the same VS removal efficiencies (96.3%) during Phases I and II; these were 15.7 and 18.7% greater than observed in the control process (R_3) during Phases I (80.6%) and II (77.6%), respectively.

The combined process showed much higher TS and VS removal efficiencies than did the single-stage process. The difference might be due to the fact that recycled sludge

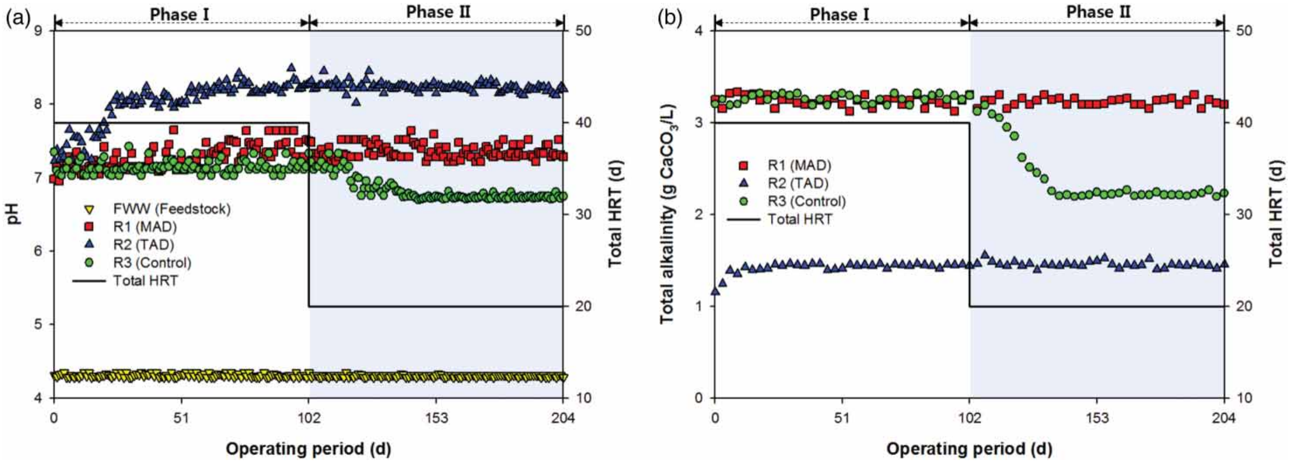

Figure 2 | Variations of (a) pH and (b) TA in the reactor and FWW during the overall digestion.

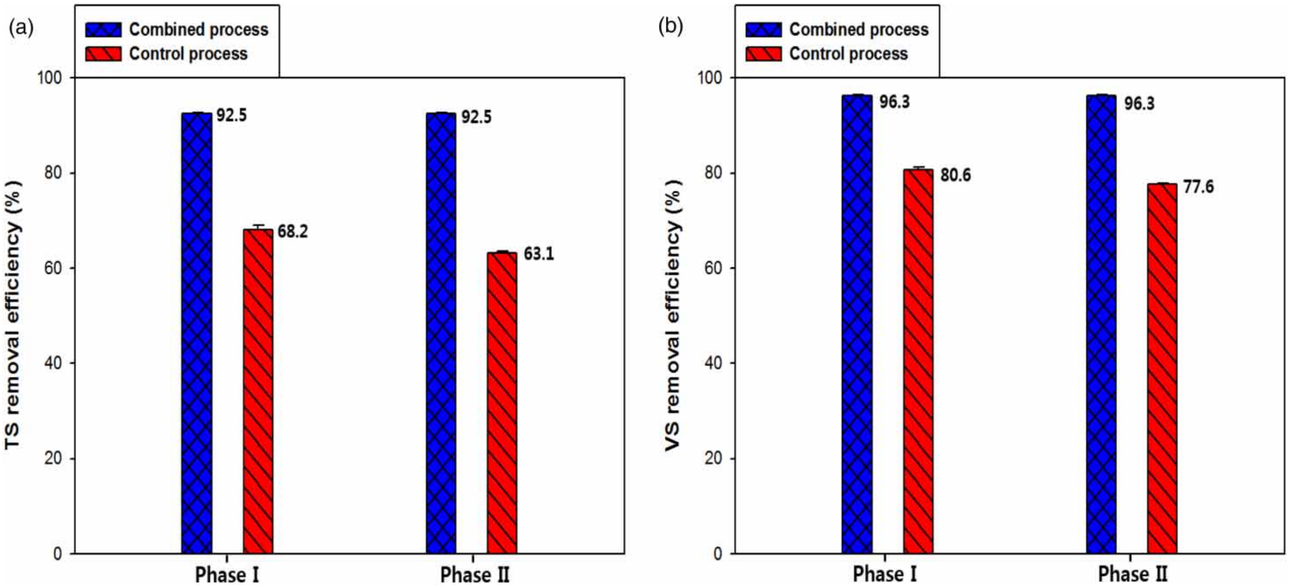

Figure 3 | Removal efficiencies of (a) TS and (b) VS at the steady-state condition of Phases I and II.

from R_1 can be further digested efficiently in the R_2. This possibility is supported by a previous report that fewer temperature-tolerant cells can be easily degraded under thermophilic conditions (Liu *et al.* 2010). In addition, Miah *et al.* (2005) reported that lytic enzymes excreted by thermophilic aerobic bacteria enhanced the solid degradation rate in the following AD. Thus, we infer that a combination of mesophilic anaerobic and thermophilic aerobic conditions provide a more suitable environment for high-strength FWW digestion than does a single-stage MAD.

COD and organic acid removal

Removal efficiencies of TCOD and volumetric removal rate (VRR) were recorded at steady-state condition in Phases I and II (Figure 4). TCOD removal in the combined and control process was very similar to the TS and VS removal patterns (Figure 3). TCOD removal efficiencies of 93.2 and 93.5% were achieved during Phases I and II, respectively in the combined process; these were higher than the corresponding efficiencies (78.5 and 71.1%) in the control

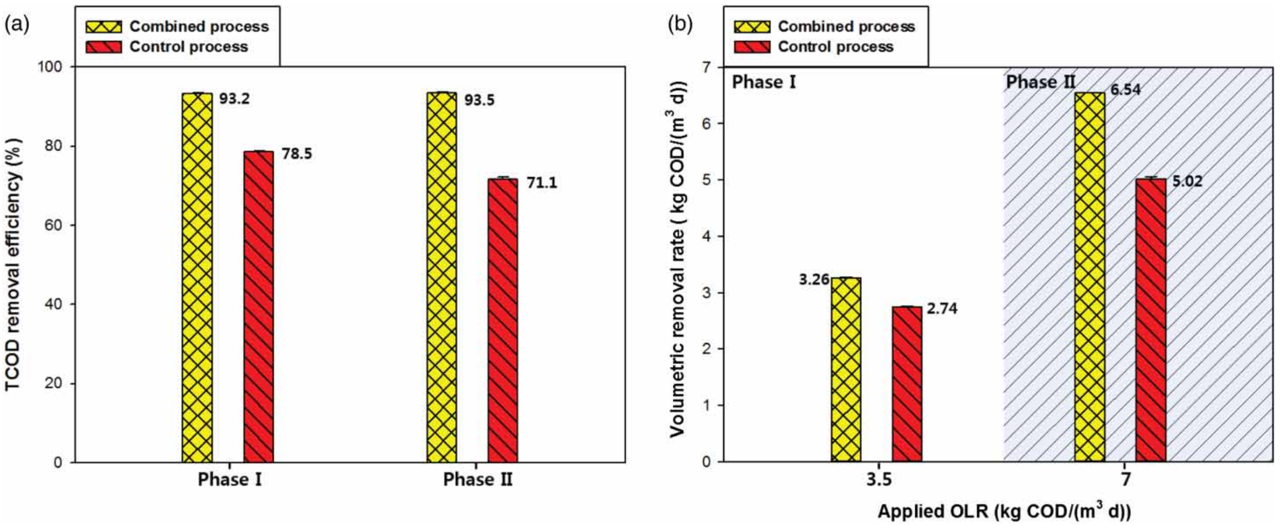

Figure 4 | Removal efficiencies of (a) TCOD and (b) VRR at the steady-state condition of Phases I and II.

Table 3 | Values of organic acids operated in different reactors under steady-state condition of Phases I and II (average ± standard deviation)

	Phase I (days: 0–102)			**Phase II (days: 102–204)**		
Parameter (g COD/L)	**MAD (R_1)**	**TAD (R_2)**	**Control MAD (R_3)**	**MAD (R_1)**	**TAD (R_2)**	**Control MAD (R_3)**
Total organic acid	2.86 ± 0.07	–	0.89 ± 0.01	3.28 ± 0.01	–	1.99 ± 0.05
Acetic acid	1.52 ± 0.01	–	0.89 ± 0.01	1.73 ± 0.01	–	1.24 ± 0.03
Propionic acid	1.43 ± 0.03	–	–	1.55 ± 0.01	–	0.75 ± 0.01

process. The VRRs in the combined process were higher than those of the control process at all applied OLRs; VRR increased from 3.26 to 6.54 kg COD/(m^3 d) when the applied OLR increased from 3.5 to 7 kg COD/(m^3 d) in the combined process. This result implies that the TAD process significantly increased COD removal by rapid degradation of the highly concentrated anaerobic sludge.

As shown in Table 1, FWW contained considerable quantities of organic acids (e.g., lactic, acetic, propionic, butyric and succinic acid), and total organic acid concentrations (converted to g COD/L) in the FWW account for over 76% of SCOD. In contrast, only two organic acids (acetic and propionic acid) were detected in the anaerobic reactors (Table 3). According to previous research, organic acid can be produced at the condition of short HRT in TAD (Chu *et al.* 1994), but organic acids were not detected in R_2, possibly because 5-d HRT is sufficient for consumption of all organic acids produced in R_2.

During Phase I, R_1 and R_3 showed total organic acid concentrations of 2.86 and 0.89 g COD/L, respectively. The lower total organic acid concentration in R_3 can be attributed to the fact that it was operated with relatively longer HRT than that of R_1 (Table 2). During Phase II, total organic acid concentration in R_1 and R_3 increased to 3.28 and 1.99 g COD/L respectively, due to the decrease of HRT. Interestingly, propionic acid was not detected in R_3 during Phase I, but it was detected during Phase II. This observation is consistent with earlier results which show that propionic acid can be accumulated at short HRT because bacteria that consume propionic acid have a slow growth-rate (Shin *et al.* 2010). Taken together, the experimental results showed that high rates of organic acid consumption were observed in all reactors, even though FWW contained a considerable quantity of organic acids, especially lactic acid.

Methane production

To compare methane production rate (MPR) between the combined process and control process, biogas production was continuously recorded. Stable MPRs (1.05 and 0.63 L/(L d) in R_1 and R_3, respectively) were observed at Phase I in both anaerobic reactors (Figure 5). The MPR in both anaerobic reactors increased greatly during the initial period of Phase II (applied OLR increased from 3.5 to 7 kg COD/(m^3 d)). During Phase II, MPR in R_1 increased from 1.05 to 1.77 L/(L d) and in R_3 MPR increased from 0.63 to 1.19 L/(L d).

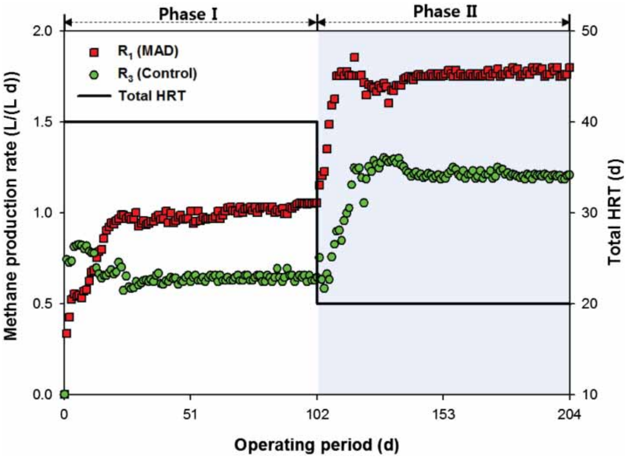

Figure 5 | Changes in MPR during the overall digestion.

Although similar variation patterns of MPR were observed in both anaerobic reactors, MPRs were approximately 66 and 49% higher in R_1 than in R_3 during Phases I and II, respectively. Methane content was also higher in R_1 (66.2–68.4%) than in R_3 (59.4–63.1%) during the overall digestion (data not shown). Therefore, the contribution of TAD in the combined process might increase both biodegradability of sludge and microbial activity, resulting in an increase in organic matter removal and methane production in R_1.

CONCLUSIONS

This study was conducted to evaluate the feasibility of the combined MAD-TAD process for treating high-strength FWW. The combined process shows relatively stable operation and TS and VS removal efficiencies both over 90%. In addition, higher TCOD removal (over 93%) and VRR (6.54 kg COD/(m^3 d)) were achieved in the combined process than in the control process during the overall digestion. As a result of the high ability to biodegrade organic matter and of the synergy between the MAD and TAD processes, the combined process shows higher MPR than that of the control process. The combined MAD-TAD process is therefore an attractive and practical option for high-strength FWW treatment; it not only attained high solid and organic matter removal but also increased methane production.

ACKNOWLEDGEMENTS

This research was supported by a grant from the Marine Biotechnology Program funded by the Ministry of Land, Transport and Maritime Affairs of the Korean Government and an Advanced Biomass R&D Center (ABC) of Korea grant funded by the Ministry of Education, Science, and Technology (ABC-2013059453). The research was partially supported by the WCU (World Class University) program through the National Research Foundation of Korea, funded by the Ministry of Education, Science, and Technology (R31-30005) and the Manpower Development Program for Marine Energy funded by Ministry of Land, Transportation and Maritime Affairs (MLTM) of the Korean government. This research was also supported by POSCO and a Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government Ministry of Knowledge Economy (No. 2012A095).

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First received 5 November 2013; accepted in revised form 14 January 2014. Available online 21 February 2014