Thermophilic anaerobic digestion of sewage sludge with high solids content

Feng Wang, Taira Hidaka, Tsutomu Uchida and Jun Tsumori

ABSTRACT

The treatment performance of thermophilic anaerobic digestion (AD) of sewage sludge with high solids content was investigated with two laboratory-scale thermophilic anaerobic reactors (R1 and R2) with a feeding of pre-centrifuged sewage sludge. Reactor R1 was fed with sludge of 3.7% total solids (TS). The volatile solids (VS) removal ratio and methane yield in the stable state were 54.9% and 0.29 NL CH_4/g VS_{added}, respectively. For reactor R2, when the TS content of fed sludge was 7.4%, the VS removal ratio and methane yield in the stable state were 73.2% and 0.38 NL CH_4/g VS_{added}, respectively. When the TS content was increased to 9.5%, the VS removal ratio and methane yield slightly decreased to 69.3% and 0.32 NL CH_4/g VS_{added}, respectively, but the reactor was stably operated. An increase of ammonia concentration was observed, but it was in the safe range without severe inhibition on the methane production. The result indicated that thermophilic AD could support sewage sludge with high TS content (9.5%) without abrupt deterioration of the treatment performance. The high-solids AD process is an economical method for centralized sewage sludge treatment with lower transport cost.

Key words | anaerobic digestion, high solids content, sewage sludge, thermophilic

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INTRODUCTION

The amount of sludge generated in wastewater treatment plants (WWTPs) is expected to continuously increase for several reasons, including high population growth, rapid urbanization, construction of new WWTPs, and upgrading of existing plants to meet stricter local effluent regulations. One of the most widely used processes to reduce the amount of sludge is anaerobic digestion (AD), which has been successfully used for the treatment of agricultural wastes, organic fraction of municipal solid waste, and sewage sludge (Verstraete *et al.* 2005; Guendouz *et al.* 2008). AD can destroy organic matter and recover methane gas as a renewable energy source.

Many small-scale facilities treating sewage and waste are scattered in local areas. In recent decades, there has been a trend for the small towns and cities to merge together for more effective utilization of the infrastructure, including sewage and waste treatment facilities in Japan (Hidaka *et al.* 2013). The sewage and waste from such local cities can be treated in a new facility built to serve as a regional treatment system. Another choice is to use an existing WWTP with an anaerobic digester to accept sewage sludge from other WWTPs which have no digesters. Under this circumstance, high-solids sewage sludge is more acceptable, because the energy and cost for the transportation of sludge from the dispersed WWTPs to the centralized one can be cut to a great extent. In Japan, most sewage sludge used for AD has a total solids (TS) concentration of less than 3%, and in a few cities it is around 5% (JSWA 2013). If higher TS of sewage sludge could be feasible for AD, such as 10%, the volume of sewage sludge would be reduced to one third or half of the original one with the result of saving the cost for the transportation process.

Although AD of high-solids sewage sludge has not been widely used, it has been regaining attention recently. Dohanyos *et al.* (1997) investigated the enhancement of AD with thickened activated sludge and obtained an improvement of methane yield ranging from 8.1 to 86.4% depending on the sludge quality. Duan *et al.* (2012) reported that mesophilic AD of high-solids sewage sludge with TS up to 20% could support organic loading rate (OLR) as high as four to six times a conventional low-solids system and obtain similar methane yield at the same solids retention time (SRT). Dong *et al.*

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(2012) used dewatered-sewage sludge with TS up to 23% for mesophilic AD and obtained an average methane yield of 0.869 L g/VS$_{\text{removal}}$. Abbassi-Guendouz *et al.* (2012) evaluated the role of TS on AD in batch conditions and found that the methane production could be kept stable with only a slight decrease when the TS was increased from 10 to 25%.

Compared with mesophilic digestion, thermophilic systems with higher reaction rate can support higher OLR (Zabranska *et al.* 2002). De la Rubia *et al.* (2006) evaluated the SRT effect on the thermophilic AD using sewage sludge with volatile solids (VS) content up to 3.5%. However, there have been few reports on the long-term thermophilic AD of sewage sludge with a high TS content (approx. 10%). In this study, the thermophilic AD of sewage sludge with TS content of 4, 7.5 and 10% was evaluated and the effect of substrate TS on the treatment performance was evaluated. In full-scale AD, the viscosity that affects mixing performance is of concern and the effect of substrate TS on the viscosity of digested sludge was also discussed.

MATERIAL AND METHODS

Experimental set-up

The operation conditions and substrate characteristics are summarized in Tables 1 and 2, respectively. Two single-run completely stirring tank reactors (CSTR) with the working volume of 10 L, named R1 and R2, were operated under thermophilic conditions (55 °C). The seeding sludge was collected from a reactor operated under mesophilic conditions. Sewage sludge used as substrate was collected in a municipal WWTP in Japan and it was a mixture of raw primary sludge and waste activated sludge. The original TS content was in the range of 1–2%, and before the experiment it was centrifuged at 3,000 rpm for 10 min. The volume of supernatant discarded was adjusted to make the TS content the desired value. The feeding of substrate and the discharge of digested sludge were conducted once every working day.

Table 1 | Operation conditions

	R1		R2			
	Run 1	**Run 2**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Day	0–67	68–340	0–32	33–60	61–270	271–403
Substrate	I	I	I	II	II	III
SRT (d)	70–25	21	70–35	70–58	42	42
Average OLR (g VS/L d)	1.0	2.1	0.7	1.4	2.0	2.6

Table 2 | Substrate characteristics (average ± SD)

Substrate	I	II	III
pH (–)	7.4 ± 0.2	7.5 ± 0.3	7.4 ± 0.2
TS (%, w/w)	3.7 ± 0.4	7.4 ± 0.8	9.5 ± 1.0
VS (%, ww)	3.0 ± 0.4	6.0 ± 0.7	7.9 ± 0.8
VS/TS (–)[a]	0.81	0.80	0.83
COD (mg/L)	44.4 ± 7.87	93.5 ± 12.6	125 ± 17.3
Protein (mg/L)	10.6 ± 0.1	20.4 ± 0.1	26.9 ± 1.7
C (%-TS)	39.5 ± 0.3	40.6 ± 0.1	–
H (%-TS)	6.15 ± 0.26	6.20 ± 0.04	–
N (%-TS)	4.76 ± 0.74	4.60 ± 0.04	–
C/N(–)[a]	8.3	8.8	–

[a]Calculated by the average values.

In the initial period of the experiment, the SRT of the reactors was set as 70 d to allow the microbes a relatively long time to adapt to the temperature switch from the mesophilic range to the thermophilic range. For R1, sewage sludge (substrate I) with a TS content of 3.7% was fed throughout the experimental period. The SRT was gradually decreased from the initial value of 70 to 25 d until 67 d after the beginning of the experiment. From day 68, the SRT was set as 21 d until the end of the experiment. For R2, four different runs were conducted. During Run 1, the SRT was decreased from 70 to 35, and the substrate was the same as that fed into R1. In Run 2, substrate II with a TS content of 7.4% was fed and the SRT was kept in the range of 58–70 d. In the following Runs 3 and 4, the SRT was kept constant at 42 d and two substrates, substrate II and substrate III, were used to evaluate the effect of the substrate TS and VS contents on treatment performance.

Chemical analysis

The TS and VS contents of the influent and effluent were determined according to the standard method (APHA

2005). Chemical oxygen demand (COD) was measured with Hach COD Reagent, TNTplus kits TNT 822 (Hach, USA). Organic acid was measured with Hach Volatile Acids TNTplus Reagent Set TNT 872 (Hach, USA). NH_4-N was measured with a TRAACS2000 autoanalyzer (BRAN LUEBBE, Germany). A 3 mol/L NaOH solution was used to completely adsorb the CO_2 in the generated biogas, and the methane gas was collected by gas bag and its volume was measured with a wet gas meter. The viscosity of the sludge was measured by a viscotester (VT-04, Rion Co., Ltd, Japan) under room temperature. The measurement was conducted once a week throughout the experimental period.

The VS and COD removal ratio is calculated by the following equations:

$$\text{VS remobal ratio}(\%) = \frac{\text{VS}_{\text{in}} - \text{VS}_{\text{out}}}{\text{VS}_{\text{in}}} \times 100 \qquad (1)$$

$$\text{COD remobal ratio}(\%) = \frac{\text{COD}_{\text{in}} - \text{COD}_{\text{out}}}{\text{COD}_{\text{in}}} \times 100 \qquad (2)$$

where VS_{in} (%) and COD_{in} (g/L) are the VS and COD concentration of substrate, VS_{out} (%) and COD_{out} (g/L) are the VS and COD concentration of digested sludge. The free ammonia concentration (FAN) of the digestion sludge is calculated by the following equation (Hansen *et al.* 1998):

$$\text{FAN} = \text{TAN} \times \left(1 + \frac{10^{-\text{pH}}}{10^{-\left(0.9018 + \frac{2729.92}{T(K)}\right)}}\right)^{-1} \qquad (3)$$

where TAN is the total ammonia concentration (mg N/L) and T(K) is the Kelvin temperature.

RESULTS AND DISCUSSION

Treatment performance under stable operational period

The pH of the two reactors is summarized in Figure 1(a). In R1, the pH was stable at around 7.4 up to day 120, and then decreased to almost 7.0, and after 1 month it increased to the original level without alkaline addition. In R2, the pH increased from 7.0 to 7.5 in the start-up period, then decreased after day 120 and increased to over 7.5 after another 60 d. Throughout the experimental period, the pH in the two reactors remained in the range of 7 to 8 and no violent fluctuation was observed, confirming the stability of the thermophilic AD process. The pH of R1 in Run 2 was 7.4 ± 0.2, while those of R2 in Runs 3 and 4 were 7.5 ± 0.2 and 7.7 ± 0.1, respectively. This higher pH might be due to the higher ammonia concentration, which can increase the buffering capacity of the digestion system.

The organic acids concentrations in the two reactors are summarized in Figure 1(b). The accumulation of organic acids in the anaerobic reactor is another inhibitor for AD (Wang *et al.* 1999). From day 100 to 250, there was an accumulation of organic acids in both reactors. The highest organic acids concentration in R1 was almost 3,000 mg HOAc/L, while that in R2 was over 5,000 mg HOAc/L. The high organic acids concentrations caused a decrease of pH in both reactors, and when the organic acid concentration decreased, the pH recovered without addition of alkali solution. When the TS content of the substrate was increased to 9.5% in R2, the organic acids concentration showed a slight increase. Considering that the same behavior of organic acids was observed in R1 whose operational conditions were constant, the evolution in Run 4 of R2 might be due to not only a change in solids content but also a change in substrate characteristics.

The TS and VS contents of the influent and effluent in the two reactors are shown in Figure 2. In R1, the average TS and VS contents of the feeding sludge were 3.7% and 3.0, respectively. The TS and VS contents of the digested sludge increased synchronously up to day 120, then remained stable at 2.2 and 1.5%, respectively. In R2, the TS content of the digested sludge increased to around 4% up to day 120, then remained at this level for one month, and then decreased to around 2.6%. The VS of the digested sludge increased to about 3.0% up to day 120, and after day 180, it decreased to about 1.8%. In Run 4 of R2, the TS and VS of the digested sludge increased to around 3 and 2%, respectively. It took around 4 months for the two reactors to get a stable state as indicated by stable methane production and VS content in the reactor. This is four times longer than that of Bouskova *et al.* (2005), who reported the temperature change from mesophilic to thermophilic conditions. This could be due to the different characteristics of the feed sludge and longer SRT by higher TS in the present study.

The treatment performance of the two reactors is summarized in Table 3. In each run, the data during the stable state were selected for the calculation of the VS removal ratio, the COD removal ratio, and the methane yield. The VS and COD removal ratios in Run 2 of R1 were 54.9 ± 7.0% and 53.7 ± 5.0%, respectively. The methane yield was 0.29 ± 0.04 NL CH_4/g VS_{added}. In Run 3 of R2, the VS and COD removal ratios were 73.2 ± 3.2% and 69.5 ± 5.3%,

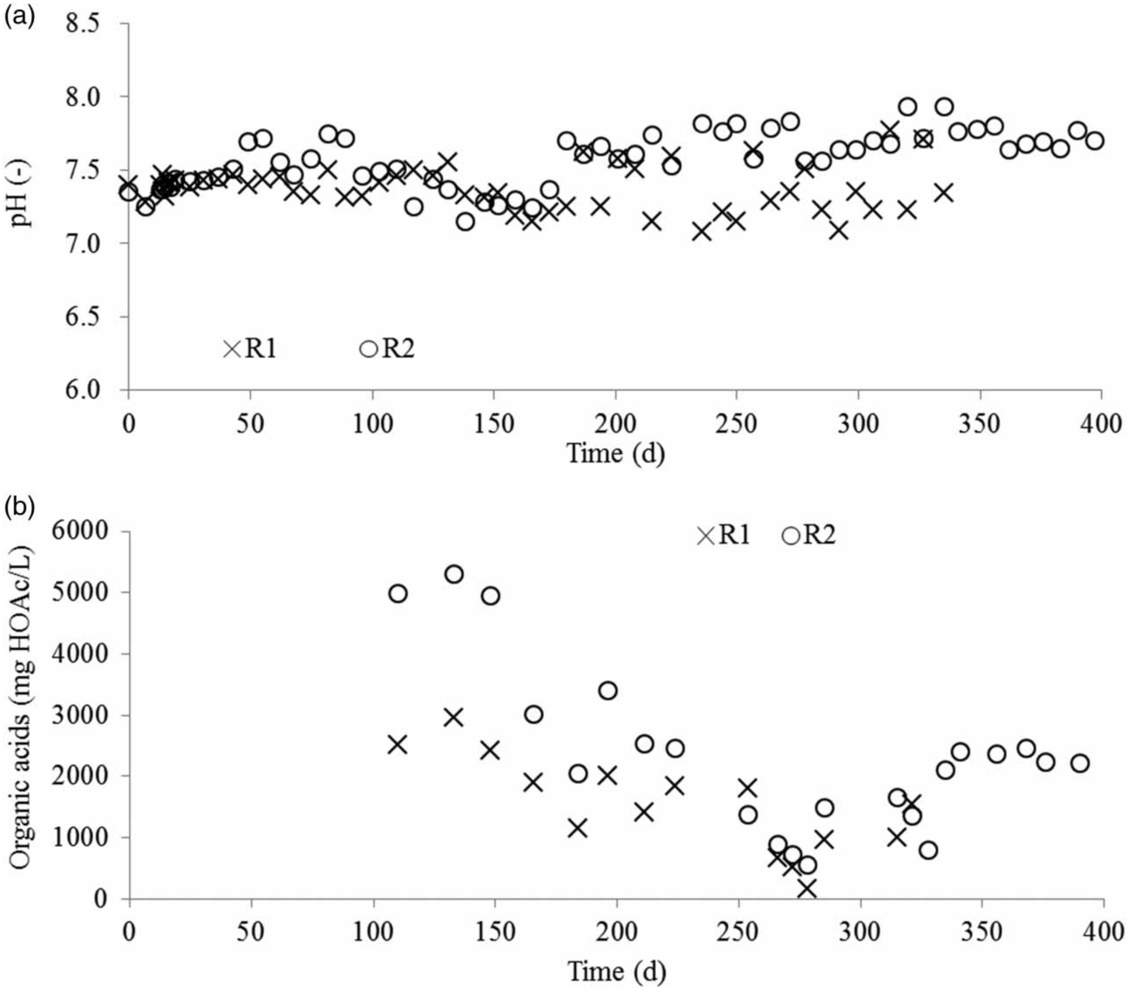

Figure 1 | pH (a) and organic acids (b) profile.

respectively. The methane yield was 0.38 ± 0.05 NL CH_4/g VS_{added}. The performance in Run 3 of R2 was better than that in Run 2 of R1. Lee *et al.* (2011) investigated the effects of SRT on methanogenesis in mesophilic AD and found that the COD and VSS removal ratios increased with the SRT. Considering that the substrate used in the two runs was derived from the same sewage sludge, the improvement of the treatment performance in Run 3 of R2 was caused by the longer SRT. In Run 4 of R2, the VS and COD removal ratios were 69.3 ± 3.4% and 62.8 ± 5.9%, respectively, which were lower than those in Run 3 and the methane yield decreased to 0.32 ± 0.04 NL CH_4/g VS_{added}. The decrease in the treatment performance might be caused by the higher OLR and solids content of the substrate including protein which increased ammonia after digestion, as discussed below. But still they were higher than those in Run 2 of R1.

Ammonia concentration and methane production

Figure 3(a) shows the TAN and FAN concentrations in the two reactors. Throughout the experimental period, the TAN concentration in R2 was higher than that in R1. The TAN concentration in R1 was stable at around 1,000 mg N/L. In R2, the TAN concentration increased rapidly at the start of the experiment and reached 2,500 mg N/L, then decreased to around 2,000 mg N/L and remained at this level until the end of Run 3. In Run 4, the TAN concentration increased up to around 2,500 mg N/L again corresponding to the increase in the solids concentration of the substrate. Ammonia is one inhibitor for the AD process. Compared with mesophilic AD, the thermophilic AD process is more easily inhibited and FAN is usually thought to be the actual inhibitor instead of TAN (Hansen *et al.* 1998; Fujishima *et al.* 2000; Martinez-Sosa *et al.* 2008). Figure 3(b)

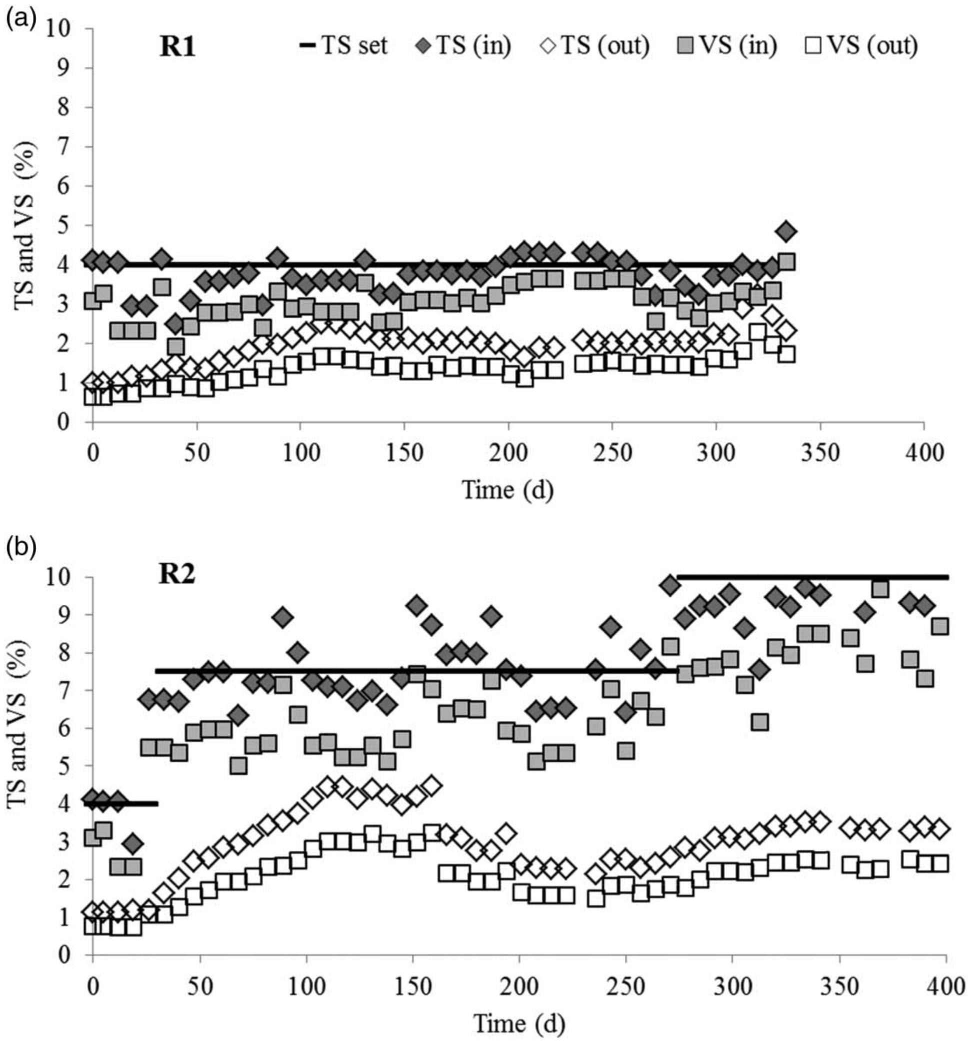

Figure 2 | TS and VS contents of the influent and effluent in the two reactors.

Table 3 | Long-term treatment performance of the two reactors

	Run 2 of R1	**Run 3 of R2**	**Run 4 of R2**
Period for calculation	Day 138–305	Day 180–270	Day 292–403
Set influent TS content (%)	4	7.5	10
Actual influent TS content (%)	3.8 ± 0.4	7.5 ± 0.9	9.6 ± 1.1
Effluent TS content (%)	2.0 ± 0.1	2.5 ± 0.3	3.4 ± 0.2
Influent VS content (%)	3.2 ± 0.4	6.1 ± 0.7	8.1 ± 0.9
Effluent VS content (%)	1.4 ± 0.1	1.7 ± 0.2	2.5 ± 0.1
VS removal ratio (%)	54.9 ± 7.0	73.2 ± 3.3	69.3 ± 3.4
Influent COD content (g/L)	48.6 ± 4.8	101.4 ± 4.7	112.0 ± 11.4
Effluent COD content (g/L)	22.4 ± 2.9	30.7 ± 4.7	41.1 ± 2.6
COD removal ratio (%)	53.7 ± 5.0	69.5 ± 5.3	62.8 ± 5.9
Methane yield (NL CH_4/g VS_{added})	0.29 ± 0.04	0.38 ± 0.05	0.32 ± 0.04

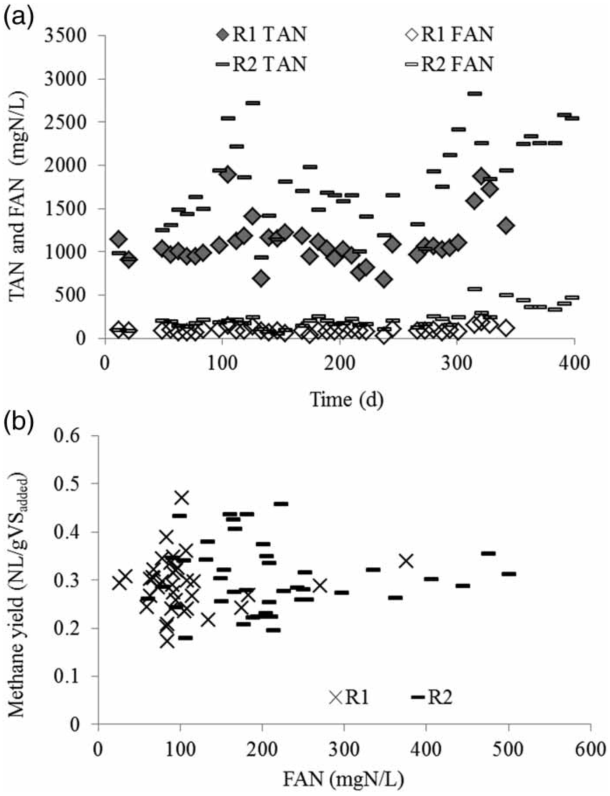

Figure 3 | Ammonia profile (a); and relationship between FAN and methane yield (b).

shows the relationship between FAN and methane yield in the two reactors. In Run 2 of R1, the average FAN was 92 mg N/L, while the FAN in Run 3 and Run 4 of R2 was 168 and 336 mg N/L, respectively. Comparing Run 2 of R1 and Run 3 of R2, the methane production was not affected by the FAN because the latter achieved a higher methane yield under almost the same OLR. This indicated that R2 could support a higher FAN concentration for a long operation period, which may be attributed to the acclimation of microbes to the high ammonia concentration caused by protein decomposition. For R1, when the FAN was over 100 mg N/L, a decrease of methane yield was observed, while for R2, the threshold value was 200 mg N/L. The difference of the threshold in the two reactors also indicated that R2 showed a better acclimation to the ammonia. Previous research showed a 50% inhibition of methanogenesis when the FAN concentration was 600 mg N/L under thermophilic conditions (Sung & Liu 2003). In the present research, the FAN in R2 was lower than 600 mg N/L and almost in the range of 100–300 mg N/L. For the high-solids AD process, it is important to keep the ammonia concentration in a safe range to prevent the inhibition effect.

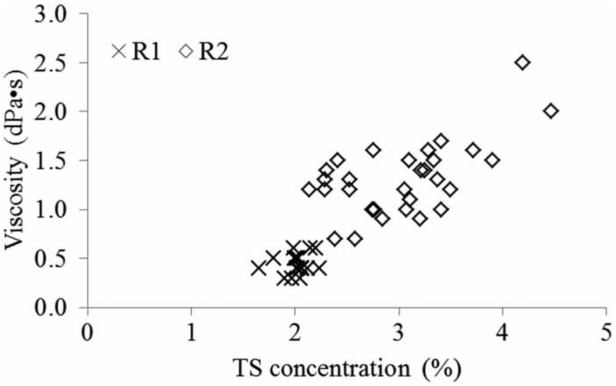

Figure 4 | Relationship between TS of the digested sludge and viscosity.

Viscosity of digested sludge

The viscosity of the digested sludge in the two reactors is summarized in Figure 4. The value was stable at around 0.5 dPa s in R1, while it was much higher in R2. It reached the highest value of 2.5 dPa s at day 160. After that, the viscosity decreased gradually to less than 1.5 dPa s, but this was still three times as high as that in R1. When the TS content of the digested sludge increased after day 277 in R2, a synchronous increase of viscosity was observed. The viscosity of the digested sludge was related to the TS content in the reactor. The viscosity of the digested sludge in R2 increased to 2.5 dPa s when the sludge TS was over 4%. A high viscosity is of great concern for mixing in full-scale operation. It requires higher mixing speed and energy level in the reactor (Wu 2010). For high-solids AD, it is important to focus on the viscosity of the digested sludge to optimize the benefits of the whole treatment process.

CONCLUSIONS

In this study, AD of sewage sludge with different TS contents (3.7, 7.4 and 9.5%) was investigated with laboratory-scale CSTR reactors under long-term thermophilic conditions. The reactors remained in a stable condition without abrupt deterioration when the TS content of the sewage sludge was increased to 9.5%. The high-solids digestion system could support higher OLR and obtain similar VS and methane yields compared with the low-solids system. This makes it possible to increase the OLR. For the AD treatment of sewage sludge generated from small WWTPs, feeding substrate with a high-solids concentration brings economic benefits because the volume of sludge transported to a centralized AD plant can be cut significantly.

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REFERENCES

Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenes, J. P., Steyer, J. P. & Escudie, R. 2012 Total solids content drives high solid anaerobic digestion via mass transfer limitation. *Bioresour. Technol.* **111**, 55–61.

APHA, AWWA, WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. APHA, AWWA, WEF, Washington, DC, USA.

Bouskova, A., Dohanyos, M., Schmidt, J. E. & Angelidaki, I. 2005 Strategies for changing temperature from mesophilic to thermophilic conditions in anaerobic CSTR reactors treating sewage sludge. *Water Res.* **39** (8), 1481–1488.

De la Rubia, M. A., Perez, M., Romero, L. I. & Sales, D. 2006 Effect of solids retention time (SRT) on pilot scale anaerobic thermophilic sludge digestion. *Process Biochem.* **41** (1), 79–86.

Dohanyos, M., Zabranska, J. & Jenicek, P. 1997 Enhancement of sludge anaerobic digestion by using of a special thickening centrifuge. *Water Sci. Technol.* **36** (11), 145–153.

Dong, B., Liu, X., Dai, L. & Dai, X. 2012 Changes of heavy metal speciation during high-solid anaerobic digestion of sewage sludge. *Bioresour. Technol.* **131**, 152–158.

Duan, N., Dong, B., Wu, B. & Dai, X. H. 2012 High-solid anaerobic digestion of sewage sludge under mesophilic conditions: Feasibility study. *Bioresour. Technol.* **104**, 150–156.

Fujishima, S., Miyahara, T. & Noike, T. 2000 Effect of moisture content on anaerobic digestion of dewatered sludge: ammonia inhibition to carbohydrate removal and methane production. *Water Sci. Technol.* **41** (3), 119–127.

Guendouz, J., Bufflere, P., Cacho, J., Carrere, M. & Delgenes, J. P. 2008 High-solid anaerobic digestion: comparison of three pilot scales. *Water Sci. Technol.* **58** (9), 1757–1763.

Hansen, K. H., Angelidaki, I. & Ahring, B. K. 1998 Anaerobic digestion of swine manure: Inhibition by ammonia. *Water Res.* **32** (1), 5–12.

Hidaka, T., Wang, F., Togari, T., Uchida, T. & Suzuki, Y. 2013 Comparative performance of mesophilic and thermophilic anaerobic digestion for high-solid sewage sludge. *Bioresour. Technol.* **149**, 177–183.

JSWA 2013 *Annual Report on Sewerage System in Japan*. Japan Sewage Works Association, Tokyo.

Lee, I., Parameswaran, P. & Rittmann, B. E. 2011 Effects of solids retention time on methanogenesis in anaerobic digestion of thickened mixed sludge. *Bioresour. Technol.* **102**, 10266–10272.

Martinez-Sosa, D., Rafrafi, Y., Torrijos, M., Bernet, N., Buitron, G., Bosque, F. & Delgenès, J. P. 2008 Anaerobic digestion of gelatinous water at laboratory and pilot scale and nitrogen inhibition. *Water Sci. Technol.* **57** (11), 1735–1741.

Sung, S. W. & Liu, T. 2003 Ammonia inhibition on thermophilic anaerobic digestion. *Chemosphere* **53** (1), 43–52.

Verstraete, W., Morgan-Sagastume, F., Aiyuk, S., Waweru, M., Rabaey, K. & Lissens, G. 2005 Anaerobic digestion as a core technology in sustainable management of organic matter. *Water Sci. Technol.* **52** (1–2), 59–66.

Wang, Q., Kuninobu, M., Ogawa, H. I. & Kato, Y. 1999 Degradation of volatile fatty acids in highly efficient anaerobic digestion. *Biomass Bioenerg.* **16** (6), 407–416.

Wu, B. X. 2010 CFD simulation of mixing in egg-shaped anaerobic digesters. *Water Res.* **44**, 1507–1519.

Zabranska, J., Dohanyos, M., Jenicek, P., Zaplatilkova, P. & Kutil, J. 2002 The contribution of thermophilic anaerobic digestion to the stable operation of wastewater sludge treatment. *Water Sci. Technol.* **46** (4–5), 447–453.

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