Anaerobic co-digestion of sewage sludge and primary clarifier skimmings for increased biogas production

S. Alanya, Y. D. Yilmazel, C. Park, J. L. Willis, J. Keaney, P. M. Kohl, J. A. Hunt and M. Duran

ABSTRACT

The objective of the study was to identify the impact of co-digesting clarifier skimmings on the overall methane generation from the treatment plant and additional energy value of the increased methane production. Biogas production from co-digesting clarifier skimmings and sewage sludge in pilot-scale fed-batch mesophilic anaerobic digesters has been evaluated. The digester was fed with increasing quantities of clarifier skimmings loads: 1.5, 2.6, 3.5 and 7.0 g COD equivalent/(L·d) (COD: chemical oxygen demand). Average volatile solids reduction of 65% was achieved in the scum-fed digester, compared with 51% in the control digester. Average 69% COD removal was achieved at highest scum loading (7 g COD eq/(L·d)) with approximate methane yield of 250 L CH_4/kg COD fed (4 ft^3/lb COD fed). The results show that scum as co-substrate in anaerobic digestion systems improves biogas yields while a 29% increase in specific CH_4 yield could be achieved when scum load is 7 g COD eq/(L·d). Based on the pilot-scale study results and full-scale data from South East Water Pollution Control Plant and Northeast Water Pollution Control Plant the expected annual energy recovery would be approximately 1.7 billion BTUs or nearly 0.5 million kWh.

Key words | anaerobic digestion, co-digestion, primary clarifier skimmings (scum), sewage sludge

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INTRODUCTION

Anaerobic digestion has been recognized as an established technology for treatment of various organic wastes, offering a high degree of stabilization, reduction of waste volume and energy production. One major benefit of anaerobic digestion is that the technology enables conversion of organic matter to bioenergy in the form of biogas, mainly composed of methane (CH_4) and carbon dioxide (CO_2), which is a source of domestic renewable energy (Speece 1996; Lema & Omil 2001; McCarty 2001). The anaerobic digestion process is advantageous because it is suitable for treating considerably high organic loading rates (3.2–32 kg/(m^3.d)) and enables production of 12×10^6 BTU (3,515 kWh) as methane per 1,000 kg of chemical oxygen demand (COD) destroyed (Speece 1996).

Co-digestion of organic wastes has recently been receiving increased interest mainly in order to increase biogas production and provide a beneficial reuse of waste material by combining its treatment with renewable energy production (Murto et al. 2003; Duran & Tepe 2004). There are numerous studies in the literature on application of co-digestion using various wastes as substrate, such as organic solid waste, animal manure and fat, oil and grease for increased biogas production (Ahring et al. 1992; Edelmann et al. 2000; Bailey 2007; Li et al. 2009).

Clarifier skimmings, also referred to as scum, are composed of various quantities of fats, grease, oils and floating debris. Scum is highly biodegradable and thus has a high specific CH_4 generation potential. Thus, its co-digestion with the wastewater biosolids may potentially increase the overall CH_4 yield. In fact, triglycerides, glycerol esters of fatty acids, available in scum have the potential to generate a synergistic effect on anaerobic digestion of biosolids (Keefer & Kratz 1931). Although inhibition due to the presence of long chain fatty acids, and low solubility and adsorption have been listed as causes of several operational problems in anaerobic treatment systems receiving wastes with high lipid content (Rinzema et al. 1994), there are a number of successful cases in the literature (Suto et al. 2006; Bailey 2007; Kabouris et al. 2008).

A study by Fernandez et al. (2005), investigated co-digestion of the organic fraction of municipal solid waste with animal- and vegetable-originated fats using mesophilic anaerobic digestion. They observed over 88% fat reduction with methane yield of 0.5 m^3 CH_4 per kg of total volatile solids degraded, suggesting the anaerobic digestion process as an efficient technology for treatment of fats (Fernandez et al. 2005). Another study indicated the positive effect of co-digestion of fats, oil and grease with sludge resulting in increased biogas production without excessive sludge production, while achieving a more than four-fold increase in CH_4 production over sludge alone (Kabouris et al. 2008).

The objective of this study is to investigate the effect of scum co-digestion with sewage sludge on biogas production and digestion performance, and to determine optimal loading in order to achieve increased biogas production.

MATERIALS AND METHODS

Waste characteristics

Scum samples were collected from the surface of the primary settlers as well as from the scum concentration tank in the Northeast Water Pollution Control Plant (NEWPCP) operated by Philadelphia Water Department (PWD). Scum samples were collected, characterized and kept refrigerated at 4 ± 2 °C until used. Results of the scum characterization tests are presented in Table 1. As expected, scum has a high COD content, 1.18 g COD/g scum when skimmed off the primary clarifiers and 1.40 g COD/g scum in the samples obtained from the scum concentration tank. Similarly, scum samples have high total solids (TS) content, 28.7 and 62.7%, respectively. Interestingly, the solids were nearly completely volatile, with volatile solids (VS) contents of 97 and 98% of the TS, respectively.

NEWPCP has eight 'pancake' type anaerobic digesters each with 7,570 m^3 (2 MG) capacity treating domestic and pretreated industrial wastewater. The mixed anaerobic culture obtained from the anaerobic digesters of NEWPCP was used as the seed in the study. The feed sludge, collected from the settling tanks (primary sludge or PS) and from the waste activated sludge (WAS) concentration units were collected separately, characterized and then stored at 4 ± 2 °C in a refrigerator to avoid degradation of sludge. The average TS content of PS was 4.4%, of which 68% was VS. The TS of concentrated WAS, on the other hand, was 3.6% with 77% VS content. The feed sludge to the reactors was prepared in the laboratory by mixing PS and WAS in a 1:1 (by mass) ratio. The feed was prepared daily to minimize the effects of change in feed sludge composition. Both feed sludge and scum were mixed continuously before feeding to reactors.

Inoculum

The inoculum used in the experiment was sewage sludge obtained from the full-scale mesophilic anaerobic digesters of NEWPCP. The seed sludge contained 1.72% TS, of which 55% was volatile.

Experimental design

Two bench-scale anaerobic mesophilic digesters with approximately 13 L (3.4 gallons) liquid volume were used in the study. The digesters were housed in a temperature-controlled environmental room with operating temperature of 35 ± 2 °C. The study was carried out in fed-batch operation with a once a day draw–fill feeding schedule. The feed volume, 1 L per day, was the same as the decanted volume. Reactors were fed daily and were mixed continuously during the feeding and decanting process while being mixed intermittently (10 min every hour at 300 rpm). Reactor 1 (R1), the control, received the feed sludge only and Reactor 2 (R2) received feed sludge along with increasing amounts of scum.

Biogas from both digesters was analyzed for its CH_4 and CO_2 content via gas chromatography. Total gas from both

Table 1 | Characteristics of scum samples[a]

Parameter	Scum sample From primary settlers	From skimmings concentration tank
Total solids (TS), mg/L	287,000 (13,900)	627,000 (1,710)
Volatile solids (VS), % of TS	97 (1.22)	98 (1.69)
Chemical oxygen demand (COD), g/g scum	1.18 (0.084)	1.40 (0.065)

[a]Values in parenthesis represent standard deviations of triplicate samples.

digesters was monitored continuously. In addition, pH, alkalinity, and short-chain volatile fatty acids (VFAs) up to four carbons were measured in the effluent from the pilot-scale digesters, as VFAs are excellent indicators of anaerobic digester performance.

Prior to introducing the scum to the active digester both R1 and R2 were operated under the identical conditions, for a 15-day period, to establish that performance in both digesters was the same when they are operated under identical conditions. During this 'background' data collection period, only total biogas production from each digester was monitored and compared. In the following 78 days of operation period, four different scum loadings were applied to R2: Phase 1 with 1.5 g COD eq/(L·d) (18 days), Phase 2 with 2.6 g COD eq/(L·d) (7 days), Phase 3 with 3.5 g COD eq/(L·d) (11 days), and Phase 4 with 7.0 g COD eq/(L·d) (20 days). The organic load of the feed sludge applied to both reactors was around 4.0 g COD/(L·d) ($\pm$0.2) during the operation. Intermittent scum loading was applied during the initial three weeks of operation. During that period, at least 80% of the expected CH_4 recovery was achieved before another dose of 1.5 g COD eq/L scum was added. The conservative feeding strategy prevented a potential inhibitory effect while giving the anaerobic microbial consortium ample time to acclimate to scum. Once 80% or greater CH_4 recovery was observed daily, semi-continuous scum loading, daily fill–draw, started.

Analytical methods

For TS and VS analyses, Standard Methods Section 2540 B-E was followed (APHA 1995). Total COD analyses were conducted according to the closed reflux colorimetric method as described in Standard Methods Section 5220 D (APHA 1995). The volume of the total gas produced in pilot-scale digesters was monitored continuously by wet-test gas meters (Rebel Point Wet-Tip Gas Meter Co., Nashville, TN, USA). Biogas composition of the reactors was analyzed for CH_4 and CO_2 by a Hewlett Packard™ Model 6890 gas chromatograph equipped with a thermal conductivity detector. Pure gases (Micromat™ – 14 Cylinder from Matheson Tri- Gas®, Alltech Associates, Inc. Deerfield, IL, USA) were used to develop calibration curves for CH_4 and CO_2. In addition, pure samples (10% methane) were run periodically as the quality check of the calibration. Samples were run for 2 min at 75 °C. CH_4 percentages were calculated by assuming other components were negligible. It is important to note that gas volumes reported throughout this article are at 35 °C temperature and 1 atm pressure.

RESULTS AND DISCUSSION

Co-digestion performances

During the 'background' data collection period, total biogas production from each digester was monitored for 15 days. ANOVA test results showed that there was no statistically significant difference in biogas production between two digesters within a 95% confidence level.

As mentioned earlier and shown in Figure 1, four scum loadings applied during the co-digestion study were Phase 1 with 1.5 g COD eq/(L·d), Phase 2 with 2.6 g COD eq/(L·d), Phase 3 with 3.5 g COD eq/(L·d), and Phase 4 with 7.0 g COD eq/(L·d). During the initial periods of operation, intermittent loading was applied. Figure 1(a) presents the daily
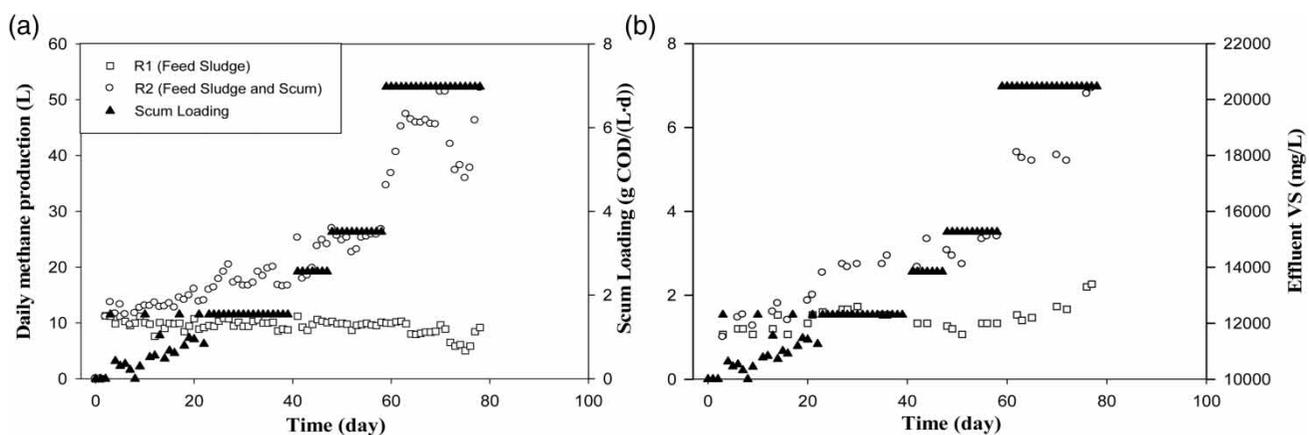

Figure 1 | (a) Daily CH_4 production in R1 and R2; (b) Daily effluent VS in R1 and R2 during digestion period.

Table 2 | Methane yield from scum co-digestion under various COD loading rates[b]

COD loading rate (g COD/(L·d))		CH$_4$ yield (L CH$_4$/d)		Specific CH$_4$ yield (L CH$_4$/kg COD)	
Scum and feed	Scum only[a]	Scum and feed	Scum only	Scum and feed	Scum only
5.6	1.5	17.4 (1.8)	7.7 (1.4)	238.4 (24.8)	105.1 (18.8)
6.7	2.6	22.6 (3.4)	12.6 (2.8)	257.7 (39.2)	143.5 (32.1)
7.6	3.5	25.9 (3.1)	16.2 (2.9)	262.2 (31.6)	163.9 (29.8)
11.0	7.0	44.1 (5.1)	35.9 (4.4)	308.4 (35.9)	251.3 (30.5)

[a]CH$_4$ production from 'scum only' was calculated by taking the difference in CH$_4$ generation from R1 and R2.
[b]Values in parenthesis represent standard deviations of triplicate samples.

CH$_4$ production in R1 and R2, and it shows that the daily CH$_4$ production in R2 increased steadily as higher scum loads were applied. The data indicate that scum does not have an inhibitory effect on primary and WAS digestion. Figure 1(b) depicts the daily effluent VS concentration from R1 and R2. Effluent VS concentration in R1 remained constant at an average of 12,170 mg/L throughout the study. Effluent VS concentration in R2, on the other hand, increased as the scum loading increased, reaching approximately 20,000 mg/L at the highest scum loading, 7 g COD eq/(L·d). It is important to note that the effluent VS concentration in R2 might have increased further if that scum loading continued, allowing the digester to reach a quasi steady state. Nevertheless, the higher VS concentrations in the effluent of R2 in comparison with those of R1 are most likely due to accumulation of the non-biodegradable fraction of scum.

To further compare the biodegradability improvement the average CH$_4$ yield from 'scum and feed' as well as 'scum only' was identified, and is presented for each COD loading in Table 2. In addition to increasing daily CH$_4$ production rates, the specific CH$_4$ yields increased with the increase in scum loading applied. The co-digestion with 11 g COD/(L·d) total (sludge and scum) loading obtained the highest CH$_4$ yield. This could be attributed to the effects of the acclimation of the biomass to scum.

Figure 2 presents the substrate utilization rates, which are calculated from CH$_4$ generation using the standard 395 L CH$_4$ per 1 kg COD destroyed according to Duran & Tepe (2004), as a function of COD loading to R2. Substrate utilization rate in R2 increases linearly with increasing scum load and reaches 8.59 kg COD/(m^3·d) from 3.38 COD/(m^3·d) when load increased from 5.6 to 11 g COD/(L·d). When the Michaelis–Menten model for substrate utilization is considered (Bailey & Ollis 1986), the data suggests that the scum concentrations tested were not high enough for anaerobic biomass to reach maximum substrate utilization rate. This could explain the increasing
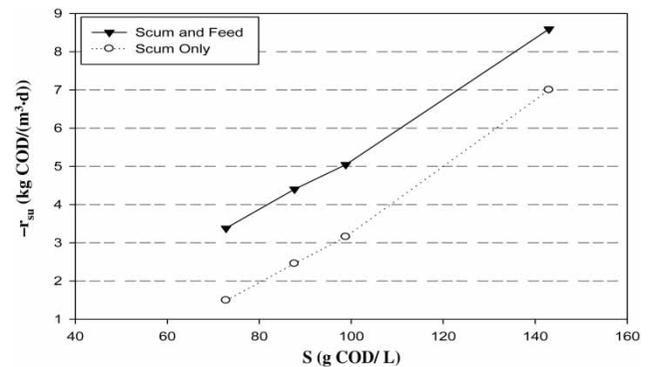

Figure 2 | Substrate utilization rates (−r$_{su}$) for feed sludge and scum, and scum only, as a function of substrate (COD) loading.

specific CH$_4$ yield as scum loading increases. Therefore, it is safe to say that the increase in specific CH$_4$ recovery rate reported in Table 2 is due to an increase in the substrate utilization rate, according to the Michaelis–Menten model.

There is a close relationship between COD and VS reduction and biogas yield (Speece 1996); therefore percent COD and VS removals were calculated. Percent COD removal in R1 and R2 is presented in Figure 3(a), and VS removal, as a percentage of influent VS, in Figure 3(b). Percent COD removal has a similar trend in both reactors during low scum loading while there is a slight decrease in percent COD removal in R2 at higher scum loadings. Percent VS reduction in R2 is slightly higher than R1. As expected, VS removal in the control, R1, was consistently around 50%, an average of 51% with a 2.06 standard deviation. This is consistent with full-scale VS removal rates at the PWD NEWPCP. The VS removal in R2, on the other hand, increased steadily as higher scum loadings were applied. The overall average VS removal rate was 65% with a 5.55 standard deviation. It is not possible to determine whether the greater VS destruction in R2 is a result of a synergistic effect of scum on feed sludge digestion or
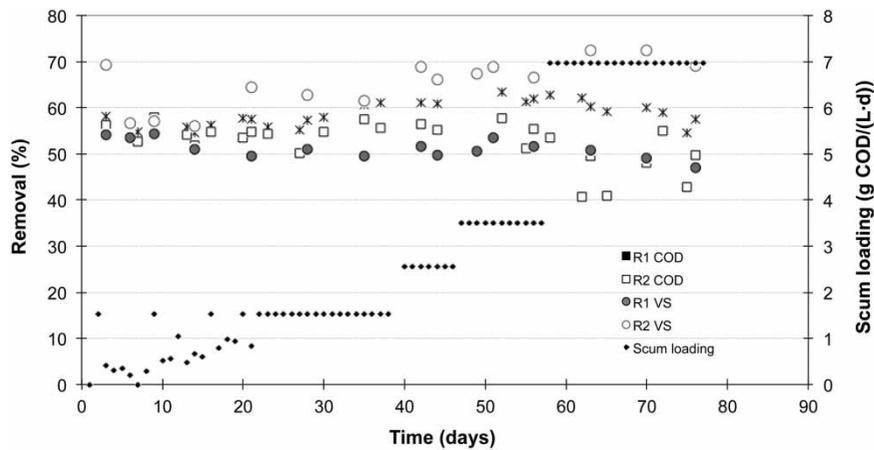
Figure 3 | Daily COD and VS removal in R1 and R2.

is due to increased scum destruction under increasing scum loading. Nevertheless, the increasing VS removal in R2 supports the hypothesis that the scum loadings studied are below the non-limiting substrate range, and the maximum substrate utilization rate is not reached under such substrate concentrations.

During the pseudo steady-state operation, daily CH_4 generation from the control digester, R1, was 9.2 L under an average of 24.7 g VS/day load. The average VS destruction was 51% and average CH_4 yield was 730 L CH_4/kg VS destroyed (11.7 ft^3 CH_4/lb VS destroyed). The CH_4 yield observed in this study closely mimics full scale digester operation at the NEWPCP (average yield at full–scale is approximately 659 L CH_4/kg VS destroyed based on the NEWPCP data between September 2008 and March 2009) as well as the pilot-scale digesters operated during an earlier 'digester optimization' study, 739 L CH_4/kg VS destroyed.

Weekly alkalinity measurements show that there was no significant difference in average alkalinity in R1 and R2, 6,280 and 6,170 mg/L as $CaCO_3$, respectively. Similarly, no significant concentrations of VFAs were observed in either digester, with the exception of a sharp increase in acetic acid concentration in R2 due to high scum loading, 7 g COD eq/(L·d). It is important to realize that acetic acid concentration in R2 might have reached inhibitory levels if 7 g COD eq/(L·d) scum loading had continued. Nevertheless, 7 g COD eq/(L·d) is approximately three times the expected scum load at full scale and such a high load is highly unlikely to occur.

Based on full-scale data (South East Water Pollution Control Plant, or SEWPCP, scum concentration tank cleaning for 2006, 2007, and 2008), there is approximately 600 wet tons of scum disposed of annually from the scum concentration tank at the SEWPCP. Extrapolating that to South West Water Pollution Control Plant (SWWPCP) and NEWPCP, based on each plant's average flow, we estimated that the total combined annual scum generation at the PWD plants is approximately 3,000 US tons. Our previous analysis indicated that the COD content of scum from the concentration tank at the NEWPCP is 1.4 kg COD eq/kg scum. Thus, the expected COD load from scum is approximately 4,200 US tons of COD per year. The expected load would be the same whether the scum that is fed to a full-scale digester is collected from the surface of the primaries or from the concentration tanks, although the COD of the scum collected from the surface of the primaries (the scum used in this study) is 1.18 kg COD eq/kg wet scum.

Assuming that the scum would be fed to the digester, one at the NEWPCP, the COD to the reactor would then be 3,810,235 kg COD/year, which translates into a daily scum load of 10,440 kg COD/day. Assuming an effective 1.5 MG digester volume, the expected daily scum load to the digester then would be 1,840 mg COD eq/L. Based on the pilot-scale study results, the expected CH_4 at that loading would be 117 L CH_4/kg COD eq at 35 °C (see Table 2). Then the overall expected daily CH_4 would be 1,221,480 L (43,156 ft^3). Assuming 630 BTU energy content per cubic feet of CH_4, the annual expected energy recovery would be nearly 10 billion BTUs or 2.9 million kWh.

CONCLUSIONS

As mentioned earlier, previous research demonstrated that using scum as co-substrate in anaerobic digestion systems

improves biogas yields through positive synergism while it does not show any inhibitory effect on anaerobic microbial consortium or anaerobic digestion. The data reported herein support those findings in the case of PWD. The average VS reduction in the scum-fed digester was 65% over the course of this study while it was 51% in the control digester. Scum is highly co-digestible even at high volumetric loadings up to 7,000 mg COD eq/(L·d). At the highest loading studied, 7,000 mg COD eq/(L·d), the specific CH_4 yield from anaerobic co-digestion of scum is approximately 250 L CH_4/kg COD fed (4 ft^3/lb COD fed). Based on the measured COD/VS ratio of scum (4.23 g COD per g VS) and an average 69% COD removal at that particular loading, co-digestion of one pound of VS equivalent scum will yield 1.02 m^3 (36.11 ft^3) CH_4, more than three times the typical yield from feed sludge co-digestion. It would be more beneficial, at full-scale application, if scum is fed to the least possible number of digesters to create the highest possible scum loading, as specific CH_4 yield increases with the increasing concentration. Based on full-scale data provided by PWD and the results of this study, full-scale co-digestion of scum is expected to increase annual CH_4 by approximately 2.7 million ft^3 (76,455.485 m^3), nearly 1.7 billion BTU equivalent.

REFERENCES

Ahring, B. K., Angelidaki, I. & Johansen, K. 1992 Anaerobic treatment of manure together with industrial waste. *Water Sci. Technol.* **25**, 211–218.

APHA 1995 *Standard Methods for the Examination of Water and Wastewaters*, 19th edn. American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, D.C.

Bailey, R. S. 2007 Anaerobic digestion of restaurant grease wastewater to improve methane gas production and electrical power generation potential. In: *Proceedings of the Water Environment Federation*, WEFTEC, Session 81 through Session 90, pp. 6793–6805.

Bailey, J. E. & Ollis, D. F. 1986 *Biochemical Engineering Fundamentals*, 2nd edn. McGraw-Hill, Inc., Boston, Massachusetts, USA.

Duran, M. & Tepe, N. 2004 Co-digestion with waste activated sludge for improved methanogenesis from high solids industrial waste. *Environ. Technol.* **25**, 919–927.

Edelmann, W., Engeli, H. & Gradenecker, M. 2000 Co-digestion of organic solid wastes and sludge from sewage treatment. *Water Sci. Technol.* **41**, 213–221.

Fernandez, A., Sanchez, A. & Font, X. 2005 Anaerobic co-digestion of a simulated organic fraction of municipal solid wastes and fats of animal and vegetable origin. *Biochem. Eng. J.* **26**, 22–28.

Kabouris, J. C., Tezel, U., Pavlostathis, S. P., Engelmann, M., Todd, A. C. & Gilette, R. A. 2008 The anaerobic biodegradability of municipal sludge and fat, oil, and grease at mesophilic conditions. *Water Environ. Res.* **80**, 212–221.

Keefer, C. E. & Kratz, H. 1931 The digestion of scum from preliminary settling tanks. *Sewage Works J.* **3**, 50–53.

Lema, J. M. & Omil, E. 2001 Anaerobic treatment: a key technology for a sustainable management of wastes in Europe. *Water Sci. Technol.* **44**, 133–140.

Li, X., Li, L., Zheng, M., Fu, G. & Lar, J. S. 2009 Anaerobic co-digestion of cattle manure with corn stover pretreated by sodium hydroxide for efficient biogas production. *Energy Fuels* **23**, 4635–4639.

McCarty, P. L. 2001 The development of anaerobic treatment and its future. *Water Sci. Technol.* **44**, 149–156.

Murto, M., Bjornsson, L. & Mattiasson, B. 2003 Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. *J. Environ. Manage.* **70**, 101–107.

Rinzema, A., Boone, M., van Knippenberg, K. & Lettinga, G. 1994 Bactericidal effect of long chain fatty acids in anaerobic digestion. *Water Environ. Res.* **66**, 40–49.

Speece, R. E. 1996 *Anaerobic Biotechnology for Industrial Wastewaters*. Archae Press, Nashville, Tennessee, USA.

Suto, P., Gray, D. M. D., Larsen, E. & Hake, J. 2006 Innovative anaerobic digestion investigation of fats, oils, and grease. In: *Residuals and Biosolids Management Conference Proceedings*, Water Environment Federation, pp. 858–879 (22).