Anaerobic Degradability of Pinellas County Sludge & FOG at Mesophilic & Thermophilic Temperatures

John Kabouris, Spyros Pavlostathis, Ulas Tezel, Mike Engelmann, Jim Dulaney, Allen Todd, and Bob Gillette

The potential for an increase in methane production by 100 percent or more through the co-digestion of FOG with municipal sludge has been demonstrated in a laboratory study (Kabouris et al., 2008a); however, long-chain fatty acids (LCFAs) low solubility, adsorption, and inhibition of anaerobic microorganisms have been listed as the cause for operational problems in the anaerobic treatment of waste streams with relatively high lipid content, and acid-methane phased digestion has been used to reduce the risk of toxicity from lipids.

A two-phase system successfully treated a synthetic wastewater that contained a mixture of LCFAs at loading rates up to 1.72 kg LCFA-COD/m^3-day (Kim et al., 2004). In addition to reducing the potential for lipid toxicity, acid-methane phased digestion has the potential to accelerate reaction rates and improve stability by providing the optimal environment for the growth of acid- and methane-producing organisms.

Significant improvement in volatile solids (VS) destruction, associated methane production, and process stability has been reported as a result of phase separation. Andryszak et al. (2004) conducted a side-by-side, full-scale evaluation of a 55/45 percent (TS basis) PS/WAS sludge digestion and reported that the VS destruction increased in magnitude and decreased in variability, changing from a median value of 48 percent (90 percentile from 26 to 57.5 percent) with conventional mesophilic digestion to 58 percent (90 percentile from 52.5 to 62 percent) with phased digestion.

The municipal sludge and FOG used in this study was provided by Pinellas County, which operates the South Cross Bayou Water Reclamation Facility, permitted at an average daily flow of 33 million gallons per day (mgd). In order to increase biogas production and provide a beneficial reuse for FOG, in addition to the South Cross Bayou facility's sludge, the county has been feeding the facility's egg-shape digesters partially dewatered FOG from the county's off-site FOG receiving facility.

Traditionally the primary clarifiers at the South Cross Bayou facility have been partially bypassed. In combination with the operation of a long solids retention time (SRT), modified Lutzack-Ettinger (MLE) activated sludge process with alum addition prior to the secondary clarifiers, the result is a sludge that is relatively difficult to degrade and a 20/80 percent (TS basis) PS/WAS sludge mix (Kabouris et al., 2007).

When the samples for this study were collected, the South Cross Bayou facility was operated at an SRT of about 18 to 22 days. The county's FOG dewatering facility receives FOG obtained from grease traps associated with, among others, restaurants, hospitals, schools, assistant living facilities, and catering services. The facility uses a FOG dewatering process based on polymer addition and gravity water drainage to generate partially dewatered FOG.

The objective of this study was to assess and quantify the anaerobic biodegradation of municipal sludge when co-digested with large quantities of FOG under completely mixed, semi-continuously fed, mesophilic acid phase, followed by mesophilic and thermophilic methane phase digestion. Such information is very valuable for establishing the feasibility and associated cost savings from the co-digestion of municipal sludge and dewatered FOG.

To provide baseline data, ultimate degradability batch digestion testing was used for the sludge and FOG components, along with mesophilic and thermophilic semi-continuous feed methane phase digestion of sludge without and with FOG.

Materials and Methods

Samples

Three samples were obtained from the South Cross Bayou facility:

- Primary sludge (PS)
- Thickened waste activated sludge (TWAS)
- Polymer-dewatered FOG (FOG)

The sludge and FOG samples were shipped to the laboratory at Georgia Tech overnight and upon delivery they were stored at 4°C. Since the primary sludge was relatively dilute (1.2 percent TS, 0.9 percent VS), it was stored at 4°C for two days, and then the supernatant was decanted, creating two subsamples: primary supernatant and primary concentrate. Details on the analytical methods are described in Kabouris et al (2008b).

John Kabouris, Ph.D., P.E., is a project manager in the Sarasota office of Carollo Engineers. Spyros Pavlostathis, Ph.D., is a professor of civil and environmental engineering at the Georgia Institute of Technology. Ulas Tezel is a graduate research assistant at the Georgia Institute of Technology. Mike Engelmann, P.E., is a senior engineer with Pinellas County Utilities. Jim Dulaney is manager of the South Cross Bayou Water Reclamation Facility. Allen Todd, P.E., BCEE, and Bob Gillette, P.E., BCEE, are partners with Carollo Engineers. This article was presented as a technical paper at the 2008 Florida Water Resources Conference in May.

Batch Biodegradability Test

A batch biodegradability test was performed with the PS, TWAS, and FOG separately, as well as combinations of these components (PS + TWAS; PS + TWAS + FOG) using 160-ml serum bottles. Seed for this test was mixed liquor, obtained from the South Cross Bayou facility's mesophilic anaerobic digesters, which was then pre-digested under batch conditions for 90 days (Kabouris et al., 2007).

PS and TWAS were tested separately at a VS concentration of 3 g/L (= kg/m^3). The FOG VS concentration was 2.39 g/L because of an initial underestimation of the TS and VS content of this sample. The combined PS + TWAS sample had a VS concentration of 1.16 and 1.84 g/L, respectively (3 g VS/L total), and the combined PS + TWAS + FOG sample had a VS concentration of 1.16, 1.84, 0.48 g/L, respectively (3.48 g VS/L total). Incubation was carried out in the dark at 35°C, and the bottles were shaken manually once a day.

Digestion System

The complete digestion system included two mechanically mixed 4-L and two 1-L glass reactors. All reactors had a water jacket and their temperature was controlled with water recirculation, using two heated water circulating baths. One 4-L reactor was maintained at 35°C (mesophilic) and the other 4-L

Continued on page 40

Table 1: Results of sludge and FOG sample analysis and characterization[a, b]

Parameter	PS Super-natant	PS Con-centrate	PS Mix	TWAS	FOG
pH	5.49	5.63	5.55	6.61	4.03
TS, g/kg wet sample[c]	3.9±0.1[d]	58.2±0.4	25.0	67.0±1	424.0±8
VS/TS, %	59.0	80.8	78.8	65.7	96.5
Total COD, g/kg wet sample	11.6±0.2	96.8±9.3	44.8	85.4±1.2	1,211±31
Soluble COD, g/L	4.4±0.1	4.8±0.4	4.56	2.5±0.1	13.7±1.3
VFAs, mg COD/L	1,295	1,566	1,400	567	3,473
Total COD/VS, g/g	5.04	2.06	2.27	1.94	2.96
Carbohydrate, g/kg wet sample (% of VS)			7.6 (39)	21.2 (48)	60.1 (15)
Protein, g/kg wet sample (% of VS)			6.0 (30)	20.3 (46)	29.7 (7)
Total fat, g/kg wet sample (% of VS)			6.1 (31)	2.6 (6)	319.3 (78)
Saturated fat, g/kg (% of total fat)[d]			4.6 (75.5)	1.9 (71.6)	121 (37.9)
Polyunsaturated fat, g/kg (% of total fat)[d]			0.1 (2.1)	0.05 (1.8)	23.6 (7.4)
Monounsaturated fat, g/kg (% of total fat)[d]			0.7 (10.9)	0.4 (15.5)	126.1 (39.5)
Trans fat, g/kg (% of total fat)[d]			0.7 (11.5)	0.3 (11.1)	48.5 (15.2)
Total nitrogen, g N/kg wet sample			1.3	3.9	5.4
Total Kjeldahl nitrogen (TKN), g N/kg wet sample			1.2	3.7	5.1
Ammonia, mg N/L	123±2	431±32	243	460±13	356±10
Total phosphorus, mg P/kg wet sample			780	4,910	670
Water soluble phosphorus, mg P/kg wet sample			78	< 10	77

[a] Abbreviations: PS, primary sludge; TWAS, thickened waste activated sludge; FOG, polymer-dewatered FOG.
[b] Primary supernatant and concentrate measured directly; PS mix values are for a mixture of PS supernatant and concentrate (61/39% by volume, respectively), resulting in a mix 2.5% TS; TWAS and FOG samples were diluted (1% TS; see text) and reported values are for the undiluted samples.
[c] 1 g/kg wet sample = 1,000 mg/L
[d] Mean ± standard deviation ($n \geq 3$).

Continued from page 38

reactor was maintained at 52°C (thermophilic).

A 1-L reactor served as the feed reservoir, was maintained at room temperature (22 to 24°C), and was cleaned every one to two days. The other 1-L reactor was used as the acid-phase reactor and was maintained at 35°C.

Wasting and then feeding of the acid-phase reactor was achieved for five minutes every hour with two peristaltic pumps. Both methane-phase reactors were wasted manually once a day by syringe, five minutes before feeding.

Feeding of the two methane-phase reactors was achieved either manually once a day using a 60-mL syringe (Run 1) or with a peristaltic pump for five minutes every three hours (Run 2). The pumps were controlled by an electronic timer.

Gas produced in both the acid-phase and methane-phase reactors was collected in graduated cylinders filled with an acid brine solution. Gas samples were taken directly from the reactors by syringe.

Reactors Start-Up

The mesophilic, methane-phase reactor was started with a mixed liquor sample obtained from the South Cross Bayou facility's mesophilic anaerobic digesters. The digester sample was screened and then kept in a sealed, plastic bottle with minimal headspace volume at room temperature (22 to 24°C) for two months before it was transferred to the mesophilic, methane-phase reactor.

The thermophilic, methane-phase reactor was started following the same procedure as that of the mesophilic reactor with a digester liquor sample obtained from a thermophilic methane phase digester operated by Inland Empire Utilities Agency (IEUA), located in Ontario, California. Both reactors were equilibrated at their respective temperature without any feeding for four days before regular feeding started (see Run 1).

The initial pH, before any feeding, of the mesophilic and thermophilic reactors were 7.4 and 7.6, respectively. The acid-phase reactor was started by transferring 0.5 L of a mix of PS, TWAS, and FOG to this reactor and batch incubating it at 35°C for two days.

Digestion Runs

Continuous testing of PS, TWAS, and FOG under both mesophilic and thermophilic conditions was conducted in two runs. Run 1 was a direct comparison of mesophilic vs. thermophilic digestion; the feed was a mix of PS and TWAS without preacidification in an acid phase reactor (i.e., conventional).

For Run 2, the feed was a mix of PS, TWAS, and FOG and was preacidified by the use of a mesophilic acid-phase reactor. Portions of the acid digester effluent were fed to two side-by-side methane phase digesters operating respectively at mesophilic and thermophilic temperatures.

Results & Discussion

Sample Characterization

The results of the analysis of the sludge and FOG samples are shown in Table 1. All sludge and FOG samples were acidic, with the TWAS sample having the highest pH value of 6.61 and the FOG sample having the lowest value of 4.03. The TWAS sample had the lowest COD/VS value (about 1.94), and the FOG COD/VS value was 2.96.

A significant level of soluble COD and VFAs was found in the liquid portion of all samples, indicating that a degree of sample solubilization and preacidification had taken place during sample transport and/or storage. The PS sample's soluble-COD-to-total-COD ratio was significantly higher compared to that of the TWAS and FOG samples. The VFA-COD-to-soluble-COD ratio for the PS sample was also significantly higher than the ratios for the TWAS and FOG samples.

As expected, the dewatered FOG fat content was very high (78 percent of VS), and its protein content was low (7 percent of VS). The majority of the fat in the FOG sample was saturated and monounsaturated, followed by trans and polyunsaturated fat. Palmitic acid (16:0) was the major component of the FOG saturated fat, followed by stearic acid (18:0) and arachnidic acid (20:0). Oleic acid (18:1) was the major component of the FOG monounsaturated fat, followed by eicosenoic acid (20:1), linoleic acid (18:2W6), and palmitoleic acid (16:1).

All samples had high (above 200 mg/L) ammonia concentrations, consistent with ammonification having taken place during sample transport and/or storage. The TKN-to-VS ratio for FOG was significantly lower compared to the values for PS and TWAS, respectively, consistent with the low protein content of the FOG sample.

All samples had relatively low water-soluble phosphorus content. The TWAS sample had the highest total phosphorus content. The soluble and total phosphorus content is consistent with the full-scale practice of alum addition to the South Cross Bayou facility sludge for P removal to average effluent levels below 1 mg/L.

Ultimate Biodegradability

The biodegradability test was carried out for 120 days. At the end of the incubation, all samples tested had pH values between 6.95 and 7.16 and VFAs were not detected. Other observations have been reported previously (Kabouris et al., 2007).

Table 2 summarizes the results of the batch test for the three individual samples, as well as the two combined samples. The results of the biodegradability test for several additional combinations of sludge and FOG were reported before (Kabouris et al., 2007).

Based on these results, the ultimate biodegradability of the three individual samples follows the descending series FOG, PS, TWAS. The same descending order is applicable to the observed methane yield per unit VS mass added for the three samples.

Based on the ultimate biodegradability (i.e., VS destruction) of each component (i.e., PS, TWAS, and FOG), and taking into account the VS concentration of each component in both the PS_{39}+$TWAS_{61}$ and PS_{33}+$TWAS_{53}$+FOG_{14} combinations, with subscripts indicating VS percentage for each component, the VS destruction in the combined samples was calculated as equal to 36.2 and 41.0 percent, respectively.

These values are almost identical to the measured VS destruction of 36.8 and 39.7 percent, respectively (Table 2), so the presence of FOG and the higher loading used in this combination did not adversely affect the ultimate biodegradability of the sludge components. Similar results were obtained in a previously reported batch test where the co-digestion of PS and TWAS was assessed in combination with increasing amounts of FOG (Kabouris et al., 2008).

Based on the ultimate biodegradability at mesophilic conditions of each component (i.e., PS, TWAS, and FOG), and taking into account the VS and COD loading of each component in the feed, the ultimate VS and COD destruction for the combined PS_{21}+$TWAS_{31}$+FOG_{48} sample was calculated as equal to 52.9 and 57.7 percent, respectively.

Table 2: Batch anaerobic ultimate biodegradability test results[a]

Parameter	PS	TWAS	FOG	PS_{39} + $TWAS_{61}$[b]	PS_{33} + $TWAS_{53}$ + FOG_{14}[c]
PS VS loading, g/L	3			1.16	1.16
TWAS VS loading, g/L		3		1.84	1.84
FOG VS loading, g/L			3		0.48
Total VS loading, g/L	3	3	3	3	3.48
VS destruction[d,e], %	56.7	23.3	70.7	36.8	39.7
COD destruction[d], %	58.5	26.3	70.8	40.0	50
Methane, %	69.2	72.3	75.0	71.5	71.7
Total gas produced, mL @ STP/g component VS added[f]	680	248	1,324	407	573
Methane, mL @ STP/g VS destroyed[f]	830	767	1,404	792	1,034
Methane, mL @ STP/g VS added[f]	470	179	993	291	410

[a] Abbreviations: PS, primary sludge; TWAS, thickened waste activated sludge; FOG, polymer-dewatered FOG.
[b] PS/TWAS mix, 39/61% VS basis.
[c] PS/TWAS/FOG mix, 33/53/14% VS basis.
[d] Seed-corrected, correspond to the individual component or mix of components.
[e] Based on the mass-balance method.
[f] 1 mL/g = 0.01602 ft^3/lb

Table 3: Reactor characteristics for Digestion Runs 1 and 2.

Parameter	Run 1	Run 2	
		Acid Phase	Methane Phase[a]
Volume, L	2.0	0.5	2.0
Retention time, days	12	1	12
Flow rate[b], mL/day	166.7	500	166.7
PS loading, g VS/L-day[b]	0.99	11.1	–
TWAS loading, g VS/L-day	1.46	16.4	–
FOG loading, g VS/L-day	–	25.0	–
Total loading, g VS/L-day	2.45	52.5	4.35[c]

[a] Mesophilic and thermophilic reactors operating in parallel using acid phase reactor effluent.
[b] 1 lb/ft^3 = 16.02 kg/m^3
[c] Nominal, based on feed to acid phase reactor.

Digestion Run 1

This run was conducted to directly compare mesophilic vs. thermophilic digestion of a mix of PS and TWAS. Both reactors were maintained under exactly the same conditions, except their temperature (35 vs. 52°C). The reactors' characteristics during Run 1 are listed in Table 3.

Table 4 shows the feed composition during Run 1. A significant fraction (about 9 percent) of the total feed COD was soluble COD, indicating that a certain degree of sludge acidification had taken place, which is also reflected by the relatively low feed pH of 6.4 and high VFAs of 3,500 mg/L (about 73 percent of the soluble COD), values compatible with those observed in full-scale acid phase digesters (Andryszak et al., 2004). In addition, further acidification may have occurred in the feed vessel that was maintained at room temperature (22 to 24°C) and for 1 to 2 days.

Run 1 lasted for 42 days, which corresponds to 3.5 retention times for both methane-phase reactors. The total gas production in the mesophilic and thermophilic reactors during the entire Run 1 are shown in Figure 1.

Continued on page 42

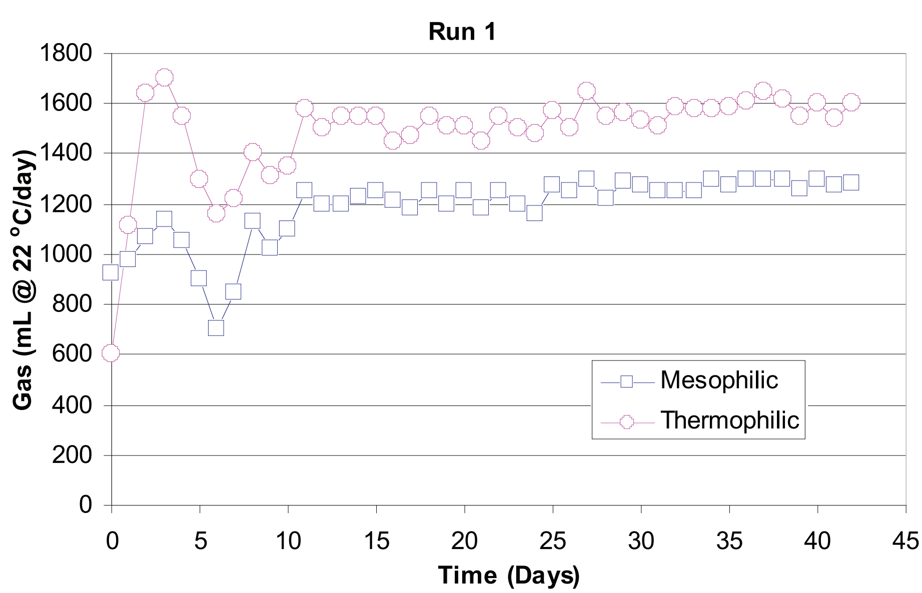

Figure 1: Total gas production in the mesophilic and thermophilic reactors and feed during Digestion Run 1.

Continued from page 41

Following the first HRT of 12 days, the reactors' gas production became significantly more stable and further stabilized following the second 12-day HRT period. A gradual decrease of the pH in the mesophilic reactor was observed, and after about one 12-day HRT period, the pH varied between 6.90 and 7.05. The thermophilic reactor had consistently higher and less stable pH, which varied between 7.24 and 7.42.

The effluent characteristics measured after the two reactors had reached three HRT periods, as well as the reactors' performance data, are shown in Table 4. The thermophilic reactor achieved 30.7 percent VS destruction, compared to only 25.3 percent for the mesophilic reactor.

An excellent agreement between VS and COD destruction was achieved in this run. The higher VS and COD destruction in the thermophilic reactor resulted in a higher methane production by about 24 percent. Both reactors had comparable methane content in the gas produced and very low VFA concentrations. The methane yield was 159 and 197 mL @ STP/g VS added for the mesophilic and thermophilic reactor, respectively.

Effluent ammonia concentrations of 495 and 719 mg N/L, correspond to a net ammonia production of 196 and 420 mg N/L for the mesophilic and thermophilic reactor, respectively, when the feed ammonia concentration of 299 mg/L is subtracted.

The soluble phosphorus concentration remained below 30 mg/L under mesophilic and thermophilic conditions. The relatively low soluble phosphorus could be the result of the alum included in the TWAS. The COD balance, which is based on feed and effluent COD and methane-COD values, indicates a good agreement between these measurements.

A decrease by about 28 and 68 percent in the fat content was observed in the mesophilic and thermophilic reactor, respectively, although saturated fat was the major fat component in both reactors' effluent. The protein reduction in the mesophilic and thermophilic reactor was 11 and 23 percent, respectively (Table 4). Carbohydrate was reduced by about 37 and 24 percent in the mesophilic and thermophilic reactors, respectively.

Table 4: Feed and effluent characteristics and reactors performance for Digestion Run 1.

Parameter	Feed	Methane Phase	
		Mesophilic	Thermophilic
TS, g/L	41.5 ± 0.1[a]	33.8 ± 0.1	32.8 ± 0.1
VS, g/L	29.4 ± 0.1	22.0 ± 0.1	20.4 ± 0.1
VS/TS, g/g	70.8	65.1	62.2
Total COD, g/L	53.1 ± 3.7	39.7 ± 3.4	37.5 ± 1.0
Soluble COD, mg/L	4,820 ± 150	601 ± 9	1,446 ± 106
VFAs, mg COD/ L	3,500 ± 35	50 ± 5	75 ± 7
pH	6.40 ± 0.02	6.95 ± 0.04	7.30 ± 0.04
Carbohydrate, g/L (% of VS)	13.2 (45)	8.4 (38)	10.1 (49)
Crude protein, g/L (% of VS)	11.5 (39)	10.2 (47)	8.8 (43)
Total fat, g/L (% of VS)	4.7 (16)	3.4 (15)	1.5 (7)
Saturated fat, g/L (% of total fat)	3.8 (81)	2.2 (66)	1 (69)
Polyunsaturated fat, g/L (% of total fat)	0.05 (1)	0.2 (5)	0.1 (8)
Monounsaturated fat, g/L (% of total fat)	0.5 (11)	1 (29)	0.4 (24)
Trans fat, g/L (% of total fat)	0.3 (7)	ND[b]	ND
Total Kjeldahl nitrogen, mg N/L [c]	2,130 ± 58	2,130 ± 58	2,130 ± 58
Ammonia, mg N/L	299 ± 16	495 ± 16	719 ± 58
Total phosphorus, mg P/L	2,450	2,490	2,460
Water soluble phosphorus, mg P/L	ND	22	26
Total gas, ml @ 22°C/day		1,274 ± 25	1,577 ± 44
Methane, %		66.1 ± 2.1	66.0 ± 2.8
Methane, ml @ 22°C/day		842 ± 25	1,041 ± 30
VS destruction [c], %		25.2	30.6
Degradable VS destruction [d]		68.5	83.2
Total COD destruction [d], %		25.3	29.4
Degradable COD destruction [e], %		63.3	73.5
COD Balance, %[d]		0.2	-1.6
Biogas, mL @ STP/g VS added[f]		241	298
Methane, mL @ STP/g VS added[f]		159	197
Methane, mL @ STP/g VS destroyed[f]		632	642

[a] Mean ± standard deviation ($n \geq 5$)
[b] ND, not detected
[c] Based on one measurements of feed and mesophilic and thermophilic reactors
[d] Based on the mass balance method
[e] COD Balance: $(COD_{in} - COD_{out} - COD_{CH4}) \times 100/COD_{in}$
[f] 1 mL/g = 0.01602 ft^3/lb

Digestion Run 2

For this run, the acid reactor was started with a mix of primary sludge, TWAS, FOG, and incubated at 35°C for two days before continuous feeding started. The acid phase reactor was operated initially on a semi-continuous feed, stand-alone mode for seven days. Starting on the seventh day, every hour the acid reactor effluent was either fed to the mesophilic or the thermophilic methanogenic reactors or wasted to maintain the desired acid- and methane-phase HRT of one and 12 days, respectively.

Before being used in Run 2, the mesophilic and thermophilic reactors were acclimated to combined sludge and FOG feed for several weeks. Subsequently, the reactors were kept without any feeding for 31 days and maintained at 35 and 52°C, respectively, to allow for degradation of all degradable substrate in them. The three reactors' characteristics during Run 2 are listed in Table 3.

Table 5 shows the feed composition during Run 2. The soluble COD was 4.9 percent of the total feed COD, and the VFAs comprised about 56 percent of the soluble feed COD. Sludge acidification had taken place, which, combined with the low FOG pH value of about 4 (Table 1), resulted in a very low feed pH of 5.6. The feed pH and VFAs were comparable to those observed in full-scale acid phase digesters (Andryszak et al., 2004). In addition, further acidification has likely occurred in the feed vessel that was maintained at room temperature (22 to 24°C) for one to two days.

The protein and fat fraction of the feed VS was 28 and 56 percent, respectively. Saturated and monounsaturated fat were more than 79 percent of the total feed fat. The increase in the monounsaturated fraction of the fat in this feed reflects the fat component distribution in the FOG (Tables 1 and 5).

Run 2 lasted for 36 days—seven days with the acid reactor alone and 29 days with all three reactors. Thus, the acid reactor completed 36 retention times and the two methane phase reactors completed almost 2.5 retention times each. The total gas production and gas composition in the acid phase

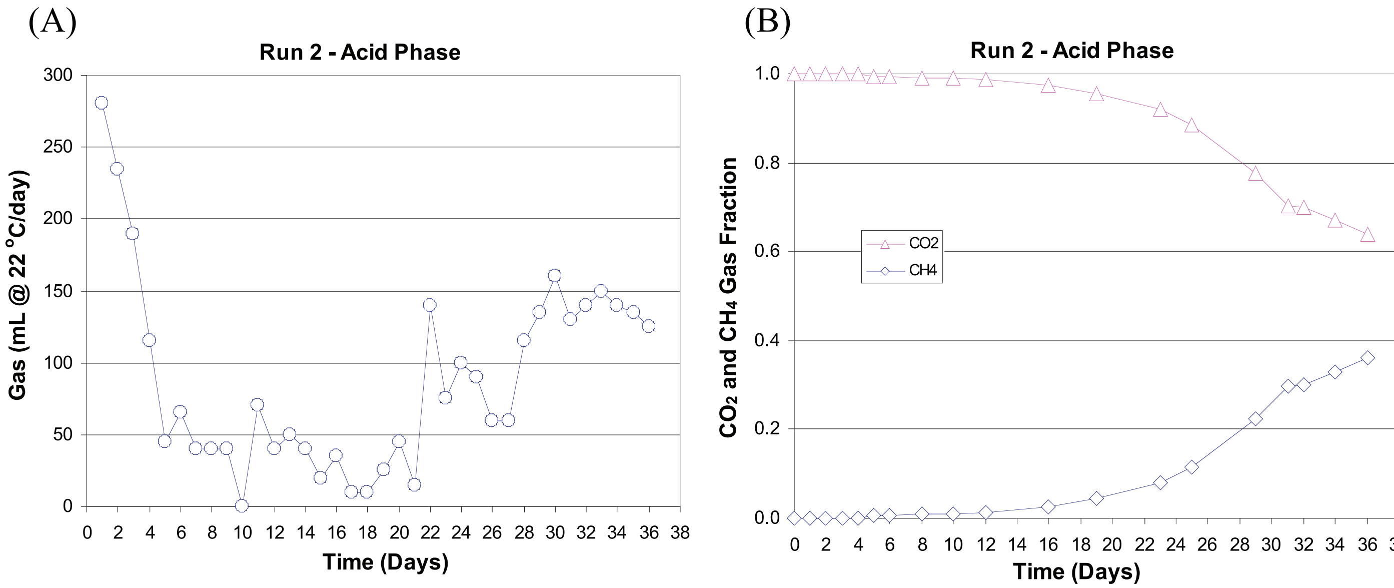

Figure 2: (A) Total gas production, and (B) relative reactor headspace gas composition neglecting H_2 and N_2 in the acid-phase reactor during Digestion Run 2.

reactor during the entire Run 2 are shown in Figure 2.

During the first five days of operation of the acid reactor, the gas production decreased and for about 10 days was below 50 mL/day. After 21 days of operation, the gas production increased rapidly, and during the last six days averaged 137 mL/day.

Initially, the acid reactor headspace was predominantly carbon dioxide, but after 16 days of operation, a gradual decrease in carbon dioxide and an increase in methane were observed. At the end of this run, the reactor headspace relative composition (considering only CO_2 and CH_4) was 64 percent CO_2 and 36 percent CH_4. Upon further investigation of the gas composition at the end of this run, H_2 and N_2 were also found at 10 and 7 percent, respectively. Taking into account all four gas components, the absolute gas composition toward the end of Run 2 was 53 percent CO_2 and 30 percent CH_4.

The feed pH varied between 5.36 and 5.59. The acid reactor pH increased initially from 5.0 to 5.3 and then stabilized to about 5.1. A comparison of the acid phase reactor influent and effluent characteristics shows a minimal decrease in total COD and VS, and an increase of soluble COD, VFAs, and ammonia by about 16, 25, and 20 percent, respectively (Table 5).

Although a modest decrease (about 5 percent) in total fat content of the acid reactor effluent was observed, the saturated fat fraction increased from 40 to 64 percent of the total fat content (Table 5).

The total gas production in the mesophilic and thermophilic reactors during the entire Run 2 is shown in Figure 3. By the 12th day, the gas production became very stable. The pH in both reactors decreased initially, remaining around 7.0 in the mesophilic reactor but increasing in the thermophilic reactor and stabilizing around 7.35 after 15 days of operation.

The effluent characteristics of the two methane phase reactors, measured after they had reached two retention times, as well as their performance data, are shown in Table 5. The thermophilic reactor achieved 5.8 percent higher VS destruction compared to the mesophilic reactor. The calculated COD destruction in this run was about 5.1 and 7.0 percent higher than the VS destruction in the mesophilic and thermophilic reactor, respectively. The methane yield was 473 and 551 mL @ STP/g VS added for the mesophilic and thermophilic reactor, respectively.

The thermophilic reactor resulted in a higher methane production by about 16 percent compared to the mesophilic reactor. Run 2 increased methane yield per g VS added of about 280 to 300 percent compared to Run 1.

Effluent ammonia concentrations of 504 and 728 mg N/L correspond to a net ammonia production of 84 and 308 mg N/L for the

Continued on page 44

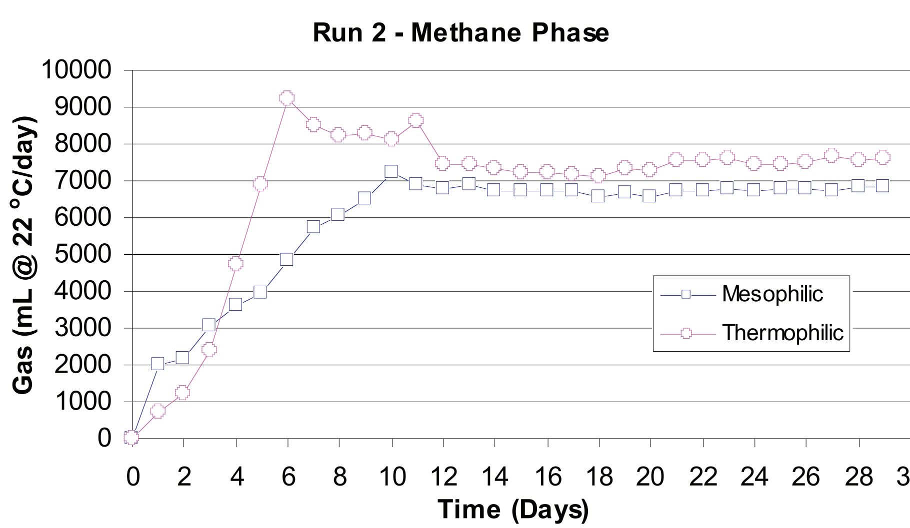

Figure 3: Total gas production in the mesophilic and thermophilic reactors during Digestion Run 2.

Table 5: Feed and effluent characteristics and reactors performance for Digestion Run 2.

Parameter	Feed	Acid Phase	Methane Phase	
			Mesophilic	Thermophilic
TS, g/L	64.8 ± 0.1[a]	64.8 ± 0.3	41.1 ± 0.5	38.6 ± 0.2
VS, g/L	52.5 ± 0.2	52.3 ± 0.9	28.7 ± 0.2	25.7 ± 0.2
VS/TS, g/g	81.0	80.7	69.8	66.6
Total COD, g/L	129.9 ± 8.7	129.5 ± 6.0	64.5 ± 4.2	54.5 ± 1.8
Soluble COD, mg/L	6,340 ± 80	7,372 ± 272	705 ± 85	1,525 ± 60
VFAs, mg COD/ L	3,580 ± 80	4,500 ± 22	20 ± 5	70 ± 5
pH	5.57 ± 0.03	5.12 ± 0.03	7.03 ± 0.02	7.34 ± 0.01
Carbohydrate, g/L (% of VS)	8.3 (16)	10 (19)	8.3 (29)	8.7 (34)
Crude protein, g/L (% of VS)	14.8 (28)	14.4 (28)	13.9 (48)	12.5 (49)
Total fat, g/L (% of VS)	29.4 (56)	27.9 (53)	6.5 (23)	4.5 (18)
Saturated fat, g/L (% of total fat)	12 (40)	18 (64)	5 (70)	3 (67)
Polyunsaturated fat, g/L (% of total fat)	2 (7)	1 (3)	0.13 (2)	0.14 (3)
Monounsaturated fat, g/L (% of total fat)	11 (39)	5 (17)	1 (15)	1 (17)
Trans fat, g/L (% of total fat)	4 (14)	4 (16)	1 (13)	1 (13)
Total Kjeldahl nitrogen, mg N/L [b]	2,725 ± 335	2,725 ± 335	2,725 ± 335	2,725 ± 335
Ammonia, mg N/L	350 ± 10	420 ± 10	504 ± 5	728 ± 15
Total phosphorus, mg P/L	1,780	2,310	2,460	2,540
Water soluble phosphorus, mg P/L	112	33	14	19
Total gas, ml @ 22°C/day		137 ± 9	6,775 ± 43	7,550 ± 73
Methane, %		30.0 ± 3.0	65.8 ± 1.8	68.7 ± 1.2
Methane, ml @ 22°C/day		41.1 ± 3	4,458 ± 40	5,187 ± 50
VS destruction[b], %		0.4	45.1	50.9
Degradable VS destruction [c]			85.3	96.2
Total COD destruction [c], %		0.3	50.2	57.9
Degradable COD destruction [c], %			87	100
COD Balance, %[d]		0.2	- 4.4	- 5.6
Biogas, mL @ STP/g VS added		5	719	802
Methane, mL @ STP/g VS added		2	473	551
Methane, mL @ STP/g VS destroyed[e]		381	1049	1083

[a] Mean ± standard deviation ($n \geq 5$)
[b] Based on one measurements of feed and mesophilic and thermophilic reactors
[c] Based on the mass balance method
[d] COD Balance: $(COD_{in} - COD_{out} - COD_{CH4}) \times 100/COD_{in}$
[e] 1 mL/g = 0.01602 ft^3/lb

Continued from page 43

mesophilic and thermophilic reactors, respectively, based on the acid phase reactor effluent ammonia concentration of 420 mg N/L. The soluble phosphorus concentration remained below 20 mg/L under both mesophilic and thermophilic conditions, likely because of the alum included in the TWAS.

Comparison of Runs 1 & 2 to Batch Mesophilic Digestion

The destruction of the degradable COD under mesophilic batch digestion conditions for PS, TWAS, FOG, and PS_{39}+$TWAS_{61}$ are presented in Figure 4. Simulation of the destruction of the degradable COD and its conversion to methane of the PS, TWAS, and FOG samples based on first-order kinetics resulted in the following rate constants: PS, 0.2 day^{-1}; TWAS, initial 0.10 and then 0.03 to 0.05 day^{-1}; and FOG, from 0.10 to 0.15 day^{-1} (Kabouris et al., 2007). Similarly, the rate constants for the combined samples were: PS_{39}+$TWAS_{61}$, initial 0.15 and then 0.04 to 0.08 day^{-1}; PS_{33}+$TWAS_{53}$+FOG_{14}, initial 0.15 and then 0.06 to 0.10 day^{-1}. Addition of FOG resulted in an overall faster destruction of the composite sample.

The fraction of the ultimately degradable COD that was degraded in Runs 1 and 2 under mesophilic and thermophilic methane phase conditions is also shown in Figure 4. Theoretically, based on first-order degradation kinetics, batch digestion is expected to be about 20 to 25 percent more efficient in terms of COD destruction at an average digestion time of 10 to 20 days, compared to continuous flow digestion (Kabouris et al., 2007). This effect was not observed in our case.

The fractional destruction of degradable COD under the 12-day HRT of the semi-continuous feed mesophilic conditions in Run 1 was about 0.64 and almost equal to the fractional degradable COD destruction obtained under batch conditions for the PS_{40}+$TWAS_{60}$ sample, estimated at about 0.65. This is attributed to the higher loading and associated increased microbial activity in the semi-continuous feed testing and the sample's pre-acidification described previously. The enhanced kinetics under thermophilic conditions during Run 1 resulted in a higher fractional destruction of degradable COD to about 0.74.

An even larger enhancement of COD destruction kinetics was observed in Run 2, which reached a fractional degradable COD destruction of 0.87 under mesophilic methane phase conditions. This performance exceeds the fractional degradable COD destruction obtained under batch mesophilic digestion for 12 days for any of the samples in the mix (i.e., PS, TWAS, FOG).

This enhancement is attributed to the higher loading and associated increased microbial activity in the semi-continuous feed system, as well as to the effect of the acid phase digestion. A further enhancement of the degradation kinetics under thermophilic conditions during Run 2 resulted in complete, within experimental uncertainty, destruction of degradable COD.

Conclusions

The results of this study indicate that a mix of PS, TWAS, and FOG, corresponding to 21/31/48 percent on a VS basis, or 16/28/56 percent on a carbohydrate/protein/fat basis, could get digested efficiently, based on an acid digester operated at a one-day HRT, at 35°C and a loading rate of 52.5 g VS/L-day, with the acid reactor effluent fed to methane phase reactors operated at an HRT of 12 days and at 35°C or 52°C.

The acid reactor stabilized to a biogas production of about 2 mL CH_4 @STP/g VS added, corresponding to a minimal VS destruction of 0.4 percent, and achieved a 43 percent decrease in non-saturated fat and a 16, 26, and 20 percent increase of soluble COD, volatile fatty acids (VFAs), and ammonia, respectively. An acid phase HRT higher than one day could accelerate the establishment of acid phase reactor steady-state under high FOG VS fraction load.

The methane-phase VS destruction in Run 2 was 45 and 51 percent (85 and 97 percent biodegradable VS destruction) at 35°C and 52°C, respectively. Stable gas production and pH level was reached within only one 12-day HRT period at 35°C or 52°C. The methane yield for the methane phase reactors was 473 and 551 mL @ STP/g VS added, at 35°C and 52°C respectively, indicting that operation at 52°C is advantageous in cases when there is a need for near-complete destruction of degradable VS and a higher methane production.

When considering these results, financial and treatment process design considerations should be taken into account because of the increase in released nutrients at the digestion temperature of 52°C, compared to 35°C. This increase is of particular concern for treatment facilities with low effluent nutrient requirements. With reference to Run 1, the addition of FOG and acid-methane phased digestion in Run 2 significantly increased methane production, resulting at a methane gas yield ratio of 3.0 and 3.4 in at 35°C on a VS basis and TS basis, respectively, while at 52°C the methane yield ratio was 2.8 and 3.2 on a VS basis and TS basis.

Acknowledgement

The authors would like to thank Pinellas County Utilities for funding this study and the staff of South Cross Bayou WRF for their assistance during the project.

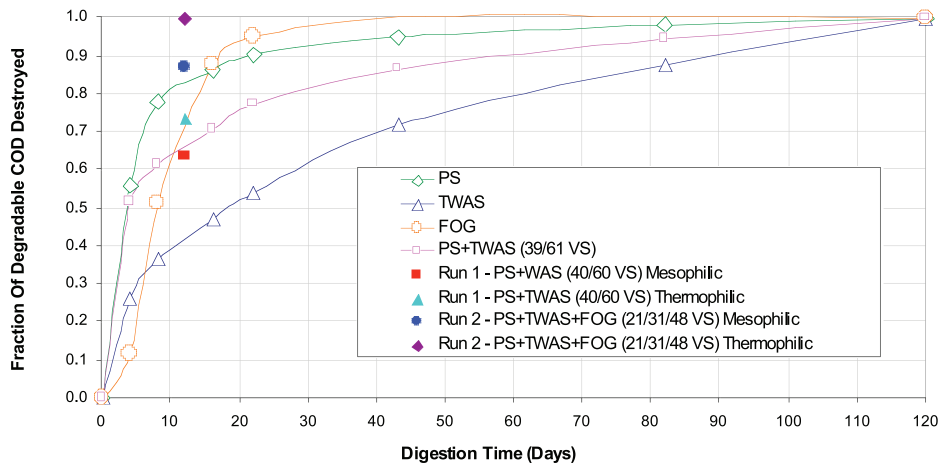

Figure 4: Normalized COD destruction over a 120-day mesophilic batch incubation period with superimposed results of Digestion Runs 1 and Run 2 (12 days HRT).

References

- Andryszak; R.; Fooksman, Y.; Brooks, P. (2004) Evaluation of the Two-Phase Digestion Process for Baltimore's Back River Wastewater Treatment Plant. *Proceedings of the 77th Annual Water Environment Federation Technical Exposition and Conference.*
- Kabouris, J.C.; Tezel, U.; Pavlostathis, S.G.; Engelmann, M.; Dulaney, J.; Gillette, R.A.; Todd, A.C. (2007) The Ultimate Anaerobic Biodegradability of Municipal Sludge and FOG. *Proceedings of the 80th Annual Water Environment Federation Technical Exposition and Conference.*
- Kabouris, J.C.; Tezel, U.; Pavlostathis, S.G.; Engelmann, M.; Todd, A.C.; Gillette, R.A. (2008a) The Anaerobic Biodegradability of Municipal Sludge and FOG at Mesophilic Conditions. *Water Environ. Res.*, **80**, 212.
- Kabouris, J.C.; Tezel, U.; Pavlostathis, S.G.; Engelmann, M.; Todd, A.C.; Gillette, R.A. (2008b) The Mesophilic and Thermophilic Anaerobic Digestion of Municipal Sludge and FOG. *Water Environ. Res.*, submitted for publication.
- Kim, S. H.; Han, S. K.; Shin, H. S. (2004) Two-Phase Anaerobic Treatment System for Fat-Containing Wastewater. *J. Chem. Technol. Biotechnol.*, **79**, 63-71.