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Pilot-scale anaerobic co-digestion of municipal wastewater sludge with restaurant grease trap waste

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ABSTRACT

The maximum feasible loading rate of grease trap waste (GTW) to the municipal wastewater sludge (MWS) was investigated using two 1300 L pilot-scale (1200 L active volume) digesters under mesophilic conditions at a 20 day solids retention time. During the co-digestion, the test reactor received a mixture of GTW and MWS while the control reactor received only MWS. The test digester loading was increased incrementally to a maximum of 280% of the control digester COD loading. The highest feasible GTW loading was determined to be 23% and 58% in terms of its total 1.58 kg VS/(m^3 d) and 3.99 kg COD/(m^3 d) loadings, respectively. This test digester COD loading represented 240% of the control digester COD loading. At this loading, test digester biogas production was 67% greater than that of the control. During the test digester quasi steady state loading period when VS from GTW represented 19% of its total VS loading, the test digester COD and VS removal rates were 2.5 and 1.5 fold those of the control digester, respectively. The test digester biogas production declined markedly when the percentage of VS from GTW in its feed was increased to 30% of its total VS loading. Causes of the reduced biogas production were investigated and attributed to inhibition due to long chain fatty acid accumulation.

1. Introduction

The many advantages of anaerobic digestion make it an attractive alternative for organic waste management and treatment. The widespread application of anaerobic digestion by municipalities is in part due to its environmental and energy benefits (Chen et al., 2008; Li et al., 2011; Nuchdang and Phalakornkule, 2012). It is a reliable and mature technology to stabilize sewage sludge and many organic wastes effectively and economically (Iacovidou et al., 2012). However, anaerobic treatment of organic wastes is not widely used by industry because many of the wastes do not have the proper nutrient balance to ensure stable operation or the wastes are not produced in quantities that could sustain continuous anaerobic digester operation. Conversely, digested sludge at municipal wastewater treatment facilities possesses an excess of nutrients and many of these plants do not fully utilize the on-site anaerobic digestion capacity (Schwarzenbeck et al., 2008). Therefore, there is great interest in co-digesting industrial, commercial and agricultural organic wastes with municipal wastewater sludge. The bioenergy production potential of organic waste anaerobic co-digestion as well as the related research trends and requirements are reviewed in Appels et al. (2011). Additional advantages of co-digestion as a biomass valorization technology are reported by De Meester et al. (2012).

Fats, oils and grease (FOG) wasted from restaurants, commercial kitchens, and food service providers has become a major stream of organic waste in urban areas. Disposal of this waste to landfills is no longer permitted in many jurisdictions and of the alternative disposal methods, anaerobic digestion is an attractive option because greasy wastes have high energy content and methane production potential (Davidsson et al., 2008). Although individual digestion of greasy waste is not viable because of long-chain fatty acid inhibition (Luostarinen et al., 2009) its co-digestion with municipal wastewater sludge has been demonstrated in a number of bench-scale studies and has been implemented at several full-scale facilities. Nevertheless, pilot-scale studies are required to assess several operational parameters.

In this study, pilot-scale anaerobic co-digestion of municipal wastewater sludge (MWS) and grease trap waste (GTW) was investigated to determine the maximum safe GTW loading rate. The effect of GTW addition on volatile solids and total chemical oxygen demand (COD) reduction rates and on biogas production were also determined.

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Nomenclature

$COD_{removed}$	Chemical oxygen demand removed (g/L)
FA	Free ammonia (mg/L)
GTW	Grease trap waste
IA	Intermediate alkalinity (mg/L $CaCO_3$)
LCFAs	Long chain fatty acids
MWS	Municipal wastewater sludge
PA	Partial alkalinity (mg/L $CaCO_3$)
TA	Total alkalinity (mg/L $CaCO_3$)
TAN	Total ammonium nitrogen (mg/L)
TKN	Total Kjeldahl nitrogen (mg/L)
$VS_{removed}$	Volatile solids removed (g/L)

2. Materials and methods

2.1. Substrates

Municipal wastewater sludge consisting of a 3:1 (v/v) mixture of primary treatment scum and sludge (PS) and thickened waste activated sludge (TWAS) was obtained daily from the Gold Bar Wastewater Treatment plant (WWTP) in Edmonton, Alberta. GTW was obtained from a local waste collection company in Edmonton, Alberta. Effluent from full scale mesophilic anaerobic digesters at the Gold Bar WWTP was used as the inoculum's (seed) during digester start-up.

The characteristics of the MWS and GTW varied somewhat during the investigation and are shown in Table 1, which also indicates the nominal COD loadings to the test digester relative to the control digester loadings. The characteristics of the GTW varied primarily because of differing water contents from one batch to another. The COD and VS content of GTW ranged from approximately 737–1510 kg/m^3 and 127.6–256.9 kg/m^3, respectively. The MWS had COD and VS values between 31.2 to 34.3 kg/m^3 and 18.8 to 24.3 kg/m^3, respectively.

2.2. Pilot digesters

Two identical 1300 L (1200 L active volume) complete mix digesters housed in a trailer were received from the King County Wastewater Treatment Division in Washington USA, and modified as required to conduct anaerobic co-digestion testing at the Gold Bar WWTP in Edmonton. Each digester was approximately 91 cm in diameter and 214 cm tall, with a sloped bottom. The digesters were operated in the mesophilic temperature range (36 ± 1 °C), with a solids retention time (SRT) of 20 days. Start-up involved placing 1200 L of full-scale digester effluent sludge in each digester and purging the headspace with nitrogen gas. Each day, 60 L of digested sludge were withdrawn and replaced with an equal volume of MWS (or a mixture of MWS and GTW) to provide a 20 day SRT.

Digester internal temperature was monitored by Type J thermocouples whose output to a programmable logic controller allowed the temperature to be controlled by an external thermal jacket. A top-mounted three bladed digester mixer was operated at a nominal shaft speed of 100 rpm in each digester. Biogas flow rate from each digester was measured by a mass flow meter (Kurz Instruments Model 502FT-6A, Monterey, CA). Each flow meter was provided with a transmitter wired to a digital panel meter (Precision Digital Model # PD690, Natick, MA) which produced an analog output wired to the data collection system. A data collection system logged the digesters' biogas flow rates as well as their internal temperatures and active volumes every 5 min.

2.3. Digester feed and organic loading rate protocols

The loading to the test digester was based on the control digester loading and expressed as a percentage of the control digester COD loading. The study was divided into three stages in terms of the COD loading of the test digester: baseline performance without a co-digestate; quasi steady state co-digestion; and ultimate co-digestate loading determination. The digesters initially received the same amount and type of feed (MWS only) in order to establish the baseline performance of each reactor. This operating mode was continued for a 30-day period. When the equivalence of the digesters' performance was established, the COD loading of the test digester was increased with the addition of a known volume of GTW in addition to the MWS to achieve the desired COD loading. Digester loading rates and their durations of application are shown in Table 2. Because, the MWS was collected daily from the WWTP, the operational changes and variations in plant flow rates and influent quality resulted in variations in MWS feed characteristics throughout the study.

The COD loading to the test digester was increased until it reached 190% relative to the control digester. This 190% loading was maintained for 30 days to allow the system to stabilize. Subsequently, the test digester loading was increased incrementally until the biogas production rate reduced and process instability was observed.

Each day, a volume of MWS sufficient to meet the line flushing and feed requirements for both digesters (approximately 150 L) was obtained from the WWTP sludge blending tank and transferred to the grinder tank to be mixed thoroughly (see Fig. 1). 75 L of the MWS were then transferred to the feed tank. Before feeding, 60 L of digested sludge was drained from each digester to its effluent tank. Samples were collected from the feed and the effluent tanks for subsequent analysis. The control digester feed line was flushed with the MWS and the digester was fed a sufficient amount of MWS (60 L) to return its active volume to 1200 L. Then, feed tank and control digester feed lines were emptied and flushed with clean water. The volume of MWS in the grinder tank was determined, and a quantity of GTW was added to the grinder tank

Table 1
Characteristics of municipal wastewater sludge (MWS) and grease trap waste (GTW).

Nominal COD loading (%)	MWS			GTW		
	COD (kg/m^3)	TS (kg/m^3)	VS (kg/m^3)	COD (kg/m^3)	TS (kg/m^3)	VS (kg/m^3)
100	34.1 ± 4.5[a]	26.5 ± 1.4	20.5 ± 1.3	N/A[b]	N/A	N/A
120	32.6 ± 5.7	26.3 ± 4.0	19.0 ± 2.4	1510.0 ± 55.8	258.4 ± 4.6	256.9 ± 4.3
170	31.2 ± 3.7	30.7 ± 3.8	22.3 ± 1.8	737.0 ± 196	129.0 ± 7.1	127.6 ± 7.2
190	32.5 ± 1.9	31.5 ± 3.3	18.8 ± 2.5	860.0 ± 21.6	155.4 ± 8.7	154.7 ± 8.4
240	33.1 ± 5.8	33.8 ± 4.6	24.3 ± 2.5	1026.0 ± 65.2	179.7 ± 5.5	178.4 ± 6.7
280	34.3 ± 6.2	32.0 ± 3.5	22.3 ± 1.1	1150.0 ± 24.2	178.4 ± 4.0	176.3 ± 4.6

[a] Standard deviation.
[b] Not applicable.

Table 2
Organic loading rate (OLR) at various increments.

Nominal COD loading (%)	Duration of loadings	OLR (kg COD/m^3 d)		OLR (kg VS/m^3 d)	
		Control	Test	Control	Test
100	1–30 (30 days)	1.71 ± 0.2	1.71 ± 0.2	1.03 ± 0.1	1.03 ± 0.1
120	31–55 (25 days)	1.63 ± 0.2	2.00 ± 0.2	0.95 ± 0.4	1.01 ± 0.4
170	56–80 (25 days)	1.56 ± 0.2	2.62 ± 0.2	1.12 ± 0.1	1.26 ± 0.1
190	81–110 (30 days)	1.62 ± 0.1	3.01 ± 0.2	0.94 ± 0.1	1.16 ± 0.1
240	111–135 (25 days)	1.66 ± 0.3	3.99 ± 0.4	1.22 ± 0.1	1.58 ± 0.1
280	136–155 (20 days)	1.72 ± 0.3	4.87 ± 0.3	1.12 ± 0.2	1.60 ± 0.2

in order to achieve the required total COD target (120%, 170%, 190%, 240% and 280% of the control feed). After thorough mixing, the feed was transferred to the feeding tank. 60 L of the feed mixture was then pumped to the test digester to return its active volume to the 1200 L level. Finally, the test digester feed line and all tanks were emptied and flushed with clean water.

2.4. Analytical methods

The percentage of carbon dioxide in biogas was measured using a Fyrite® gas analyzer according to the method specified by the manufacturer (Bacharach Inc., 2010). Total chemical oxygen demand of influents and effluents were measured with the closed reflux (5220C) method (APHA, 2005). Because GTW is a lipid-rich material with no affinity to dissolve in distilled (DI) water, GTW samples were saponified using a known volume of 19 mmol/L NaOH solution. This dilution of the GTW sample was taken into account when calculating its COD. Total solids and volatile solids also were quantified using methods 2540C and 2540E, respectively (APHA, 2005).

Samples were centrifuged at 1018 × g for 10 min and the supernatants were analyzed according to Standard Method 2320B (APHA, 2005) to determine alkalinity. The titration end point for partial alkalinity was pH 5.75 and that for total alkalinity was pH 4.30. All the above measurements were performed in triplicate. Intermediate alkalinity was calculated as the difference between total and partial alkalinity values.

Volatile fatty acids (VFAs) in the effluents were analyzed by the on-site laboratory staff using a Metrohm Peak ion chromatograph by an internally developed method based on the Metrohm Peak Method, Application Note #0–15. Total Kjeldahl nitrogen (TKN) and total ammonia nitrogen (TAN) were measured by the EPCOR laboratory staff at Gold Bar WWTP according to the Alberta Research Council (1996) Code 235 (Semi-automated block digestion, phenate colorimetric method).

3. Results and discussion

The daily biogas production per unit digester active volume is shown in Figure S-1 of the Supplementary Data. The evaluation of reactor performance parameters was based on sampling performed during the final 10 days of each test digester loading level, and the mean performance of the test digester was compared to that of the control during each period.

The variability of the test and control digester effluents is shown graphically and statistically in terms of COD and VS in the Supplementary Data. True steady state conditions could not be achieved in the digesters because of day-to-day variability in the blended MWS used as feed. Unlike bench-scale studies, which involve smaller feed volumes that can be stored under conditions that preserve their characteristics, the larger volumes of sludge used in the pilot-scale study (approximately 150 L per day including the piping hold-up) required that fresh feed be obtained daily from the on-site sludge blend tank. The control digester was operated throughout the 155 day study at a constant volumetric loading rate and with the same source of feed (sludge from the full-scale plant blend tank). Because of the varying characteristics of the blended sludge, comparisons are made between the test and control digester on an on-going basis. Quasi steady state was deemed to prevail when coefficients of variation of effluent COD and VS daily measurements over a 10 day period were less than 5%.

3.1. Baseline operation

Baseline operation was conducted to assess the equivalence of the performance of the two digesters. The mean values of the six parameters monitored during this stage are listed in Table 3. Paired two tailed *t*-tests performed on the data indicated that the parameter means were not significantly different for the two digesters as shown by the *p*-values given in Table 3. This indicates that equivalent performance had been established in the digesters.

As shown in Table 3, volatile solids destruction in the two digesters was not significantly different during the baseline loading when the control and test digesters achieved 47% and 45% VS removals, respectively. These values represent VS removal rates of 0.49 and 0.46 kg VS/(m^3 d) in control and test digesters, respectively. The digesters' behaviors in terms of COD removal also did not differ significantly during this period. Percent COD removals of 60%

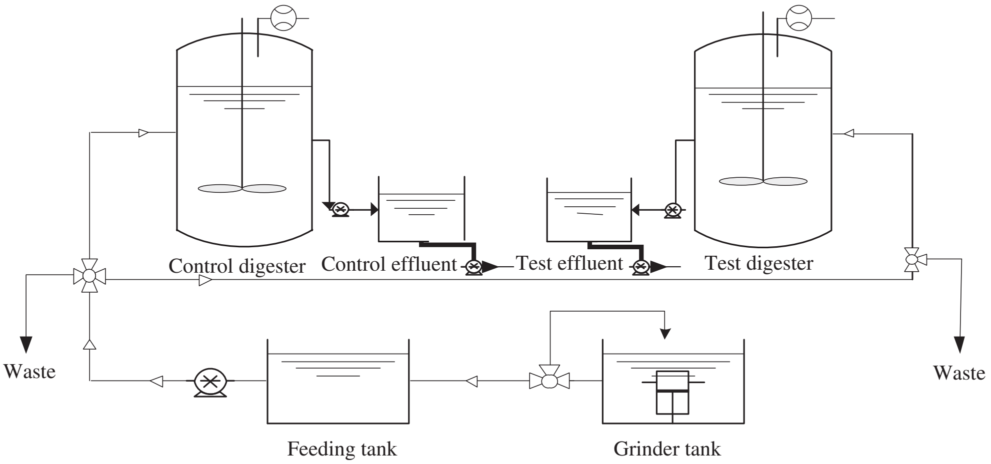

Fig. 1. Schematic of the pilot scale anaerobic digester setup.

Table 3
Comparison of digester performance during baseline operation.

Parameter	Mean value ± standard deviation			p-value
	Feed	Control effluent	Test effluent	
COD (g/L)	34.1 ± 4.5[a]	13.4 ± 1.7	14.1 ± 1.1	0.40
VS (g/L)	20.5 ± 1.3	10.8 ± 0.4	11.3 ± 0.4	0.44
Biogas production (m^3/d)	N/A[b]	1.1 ± 0.2	1.0 ± 0.1	0.39
pH	6.0 ± 0.2	7.2 ± 0.1	7.2 ± 0.1	0.34
PA (mgCaCO$_3$/L)	N/A	2577 ± 92	2535 ± 85	0.27
TA (mg CaCO$_3$/L)	1520 ± 8.5	3656 ± 139	3599 ± 95	0.30
IA (mg CaCO3/L)	N/A	637 ± 152	669 ± 130	0.29

[a] Standard deviation.
[b] Not applicable.

and 58% corresponding to COD removal rates of 1.03 and 1.00 kg COD/(m^3 d) were achieved in the control and test digesters, respectively.

3.2. Overall digester performance

When equivalence of digester performance had been established, increasing proportions of GTW were added to the test digester MWS feed to progressively increase its COD loading rate relative to that of the control digester. The control digester continued to receive only MWS as before. The mean digester loading levels and their durations are shown in Table 2.

Biogas production declined in the control digester from the 190% test digester COD loading period onward (data not shown). This was due to a leak in the gas collection system that was not located until the end of the testing period. The control digester biogas production per unit COD removal (m^3 biogas/kg COD removed) was calculated for the 100–170% test digester loading periods. An ANOVA test performed on the resulting mean values indicated no significant difference (p-value = 0.33). The overall mean control digester biogas production rate per unit mass of COD removed was calculated to be 1.02 m^3 biogas/kg COD removed for the period up to and including the 170% test digester loading. This value was applied to control digester COD removals measured during the 190–280% test digester loading periods in order to estimate control digester biogas production during this period. Biogas production by the two digesters is shown in Fig. 2. This figure also indicates the percentage of the volatile solids in the test digester feed that was due to GTW. As shown in Fig. 2, test digester biogas production increased with increasing loading. GTW additions amounting to 19% and 23% of the total 1.16 and 1.58 kg VS/(m^3 d) loadings resulted in 63% and 67% increases in biogas generation relative to the control, respectively. The maximum test digester biogas production rate of 1.84 m^3/d (1.53 m^3/m^3 d) was attained at the 240% COD loading (23% GTW VS). Increasing the test digester COD loading to 280% relative to the control resulted in a rapid reduction of biogas generation.

Enhanced biogas production during GTW co-digestion has been reported in a number of bench-scale studies. A comparison of the results from other studies to those obtained from the present study is shown in Table 4. Silvestre et al. (2011) co-digested greasy sludge from a WWTP dissolved air flotation unit with blended WWTP sludge. Biogas production was reported to increase by 128% during co-digestion of a mixture in which VS from grease represented 23% of the total 1.6 kg VS/(m^3 d) loading. Luostarinen et al. (2009) co-digested grease trap sludge from a meat processing facility with sewage sludge. These researchers reported the biogas production rate to increase by 164% compared to the baseline value when VS from grease represented 46% of the total 3.46 kg VS/(m^3 d) loading. Process instability was observed when the proportion of VS from grease reached 55%.

Enhanced biogas production has been reported to be due to the increased methane potential of the VS in the feedstock as well as the increased VS loading rate. The methane potential of GTW has been reported to range from 0.9 to 1.4 m^3/kg VS removed in previous studies (Davidsson et al., 2008; Luostarinen et al., 2009; Bond et al., 2012). These values are significantly higher than those of the primary sludge (0.47 m^3/kg VS) and waste activated sludge (0.18 m^3/kg VS). Increased methane potential of grease-MWS has been demonstrated by Wan et al. (2011) who studied co-digestion of thickened WAS and GTW. In this work, the organic loading in terms of kg VS/(m^3 d) was held constant, but the proportion of VS from grease was increased to 64% of the total 2.34 kg VS/(m^3 d) loading resulting in a 125% increase in biogas production. Process instability was noted when the proportion of VS from grease reached 74%. Girault et al. (2012) studied the co-digestion of thickened WAS and greasy sludge from a pork processing plant dissolved air flotation unit. In that study, the OLR was held relatively constant at 3.0 kg COD/(m^3 d) but the OLR in terms of VS decreased from 1.9 kg VS/(m^3 d) to 1.0 kg VS/(m^3 d) as the proportion of greasy sludge VS in the feed was increased. Biogas production was reported to increase by 55% during co-digestion of a mixture in which the VS from greasy sludge represented 52% of the total 1.2 kg VS/(m^3 d) loading. Process instability was noted when the proportion of VS from grease reached 74%.

As shown in Fig. 2, test digester biogas production decreased remarkably when the percentage of VS from grease was increased

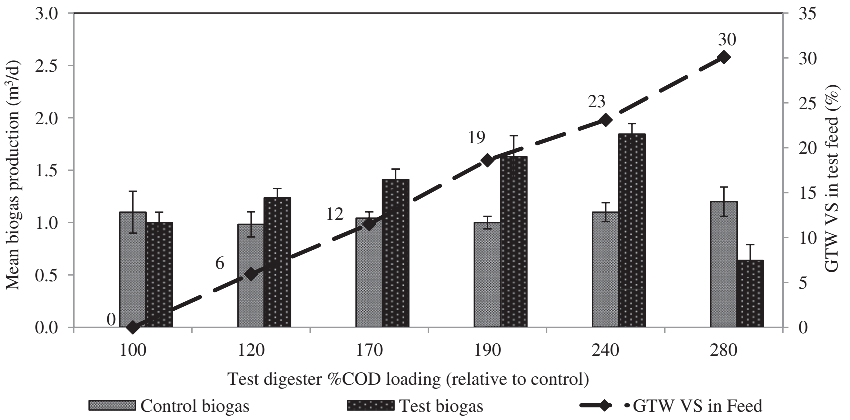

Fig. 2. Mean biogas production and GTW VS percentage at various loading rates (control digester biogas production values for the 100–170% loading period were measured; those for during the 190–280% loading period were estimated).

Table 4
Description of similar previous studies of anaerobic co-digestion of MWS and GTW.

References	Substrate sources (MWS + GTW)	Operational conditions (mesophilic)[a]	Optimum OLR (kg VS/m^3 d)	Initial biogas generation (m^3/m^3 d)	GTW added at optimum loading (%VS)	GTW added at failure loading (%VS)	Biogas increase (at optimum loading) (%)
Present study	25% WAS & 75% PS from WWTP + GTW from restaurant waste	1200 L-pilot scale 20 days SRT	1.58	0.83	23	30	67
Girault et al. (2012)	100% WAS from WWTP + GTW from meat industry	200 L-batch 25 days SRT	1.2	0.74	52	> 60	55
Silvestre et al. (2011)	30% WAS & 70% PS from a WWTP + GTW from DAF[b] unit	5.5 L-lab scale 20 days SRT	1.5	0.35	23	NA	128
Wan et al. (2011)	100%TWAS from WWTP + Un-dewatered FOG	4 L-lab scale 15 days SRT	2.34	0.46	64	74	125
Luostarinen et al. (2009)	Sewage sludge from WWTP + GTW from meat processing facility	4 L-lab scale 16 days SRT	3.46	0.70	46	71	164

[a] All the studies operated at the mesophilic (35–37 °C) condition in the continuous mixed reactor.
[b] Dissolved air floatation.

to 30% of the total 1.60 kg VS/(m^3 d) loading. This indicates that a process upset had occurred at considerably lower proportions or loadings of grease VS than reported by Girault et al. (2012), Wan et al. (2011) or Luostarinen et al. (2009). This may be due in part to the greater process control that is possible at bench scale and to differences in the waste grease origins and mixture characteristics. An examination of the test digester process parameters during this loading period will be discussed in Section 3.4.

3.3. Quasi steady state operation

Volatile solids removal is a major anaerobic digestion performance indicator as it relates to the mass of biosolids that must be disposed ultimately. Typical VS destruction in anaerobically digested thickened waste activated sludge (TWAS) has been reported to be in the range of 30–45% (Wan et al., 2011). During the 190% test digester COD loading period, VS removal reached 44% in the control digester, and 56% in the test digester. This represents VS removal rates of 0.42 and 0.64 kg VS/(m^3•d) in the control and test digesters, respectively. Improved VS removal has been commonly reported by other researchers as a benefit of co-digestion of GTW and MWS (Luostarinen et al., 2009; Silvestre et al., 2011; Wan et al., 2011).

The degree of COD removal is a measure of organic waste stabilization. The percent COD removals are shown in Fig. 3 for the baseline and quasi steady state 190% loading periods. COD removal in the test digester reached 76% during the period of 190% COD loading, while 54% COD removal was observed in the control digester during this same period. These values represent COD removal rates of 2.28 kg COD/(m^3 d) and 0.89 kg COD/(m^3 d) in test and control digesters, respectively. The effluent COD concentrations were approximately the same from each digester during the 190% test digester COD loading period despite the 90% greater COD loading to the test digester (data not shown).

As indicated in Table 3 and shown in Fig. 3, biogas production was similar in each digester during the baseline loading period. During the 190% test digester COD loading period, test digester biogas production of 1.63 (m^3/d)·(1.36 m^3/m^3 d) was estimated to be 63% greater than that of the control. The VS and COD percentage removals in the test digester were 12% and 22% greater in test digester relative to the control, respectively (Fig. 3). Other researchers have also reported enhancements in biogas production and VS and COD removals during the co-digestion of MWS and GTW (Girault et al., 2012; Kabouris et al., 2008; Silvestre et al., 2011). In a similar study using lab-scale reactors, Kabouris et al. (2009) conducted mesophilic co-digestion of MWS and FOG. These researchers reported 79% and 98% increase in the VS and COD removals, respectively when the feed consisted of 44% FOG VS and 59% FOG COD compared to the feeding of only municipal sewage sludge.

3.4. Process stability

Biogas generation in the test digester increased with increasing COD loading until a large reduction in its production was observed at the 280% COD loading (see Fig. 2). At this point volatile solids from GTW represented 30% of the total 1.6 kg VS/(m^3 d) loading to the test digester. The cause of this reduction in biogas generation was investigated by reviewing parameters including pH, partial and total alkalinity, VFA, TAN, TKN and %CO_2. The values of these parameters are shown in Table 5. A comparison between the values of these parameters measured for the test and control digesters shows little difference. During co-digestion, the test digester TAN concentration remained well below the range of 1.7–14 g/L reported to cause upset (Chen et al., 2008). Based on the pH of 7 and a

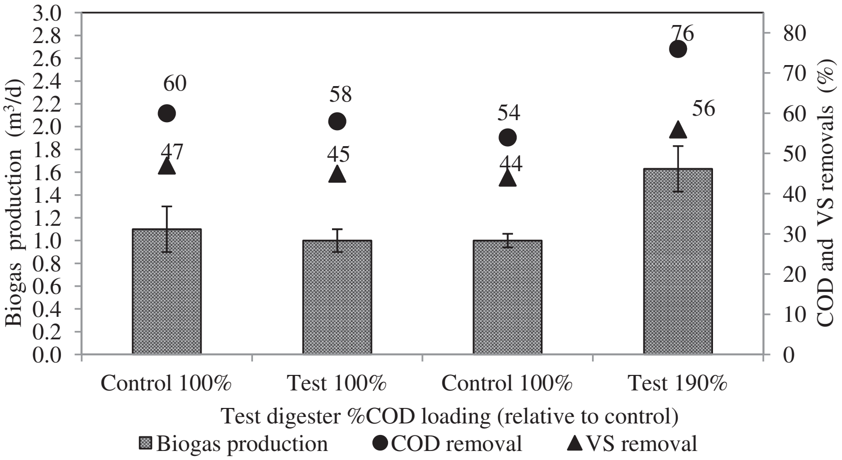

Fig. 3. Biogas production, %VS and %COD removals at baseline and quasi steady state.

temperature of 36 °C, the free ammonia concentration was approximately 10 mg NH_3/L which is well below the inhibitory level of approximately 90 mg/L reported by Gallert et al. (1998).

The test digester partial and total alkalinities were lower than those of the control and the total VFA was greater. A reduction in alkalinity is typically caused by an increase in VFA and CO_2 generation. However, the biogas %CO_2 had remained at an acceptable level and the total VFA remained low (38.2 mg/L as acetic acid). The ratio of partial alkalinity (due primarily to bicarbonate ion) to total VFA was 29:1 (mol/mol), which is well above the minimum safe value of 1.4:1 reported by Appels et al. (2008). Other researchers have used the ratio of intermediate alkalinity (IA) to partial alkalinity (PA) as a measure of process stability (Astals et al., 2012; Ferrer et al., 2010). Astals et al. (2012) reported that the IA/PA ratio should remain below 0.4 for stable operation. Fernandez et al. (2001) indicated that the IA/TA ratio should remain below 0.3. Fig. 4 shows that the IA/PA ratio increased in both the control and test digester beginning from the period of 190% test digester loading. The increase in the control digester IA/PA may be due to changing MWS characteristics. The accelerated increase of IA/PA in the test digester is due to the increasing proportion of GTW in its feed. The IA/PA ratio of the test digester effluent reached 0.6 at the 280% loading, which is well above the reported safe level of 0.4. The IA/TA ratio reached 0.30 and 0.38 in the control and test digesters, respectively (data not shown). This indicates that the test digester's buffering capacity was declining and the system was exhibiting signs of instability. System instability is also indicated by the decline in the test digester pH which had remained relatively constant until the 280% COD loading.

A COD/TKN ratio less than 70 is cited by Àlvarez et al. (2010) to avoid nitrogen limitations. The COD/TKN ratio in the feeds to the test and control digesters is shown in Fig. 5. The COD/TKN ratio in control digester remained between 10 and 20 throughout the study, whereas that of the test digester increased with increasing proportions of GTW in its feed, to reach a value of 50 at the 280% COD loading. Therefore an excess of nitrogen was available in both the control and test digesters throughout the study.

The relatively low VFA concentrations in the test digester and steady %CO_2 in its biogas suggest that methanogens inhibition was not the cause of the observed decline in biogas production. Therefore, inhibition of other microbial populations must be considered.

Table 5
Reactor performance indicators.

Parameters		Nominal test digester COD loading (%)					
		100	120	170	190	240	280
Effluent							
Control	TAN (mg/L)	889 ± 40	897 ± 22	957 ± 94	1085 ± 29	906 ± 27	858 ± 43
	TKN (mg/L)	1766 ± 49	1919 ± 112	1993 ± 41	2157 ± 80	2097 ± 211	1905 ± 70
	PA (mg/L)	2970 ± 224	2857 ± 195	3094 ± 148	3228 ± 143	2982 ± 137	2717 ± 120
	TA (mg/L)	3607 ± 263	3483 ± 178	3829 ± 173	4334 ± 273	4186 ± 191	3869 ± 75
	IA (mg/L)	637 ± 152	626 ± 102	735 ± 124	1106 ± 287	1204 ± 111	1152 ± 111
	VFA (mg/L)	3.9 ± 1.1	5.8 ± 2.8	7.6 ± 4.1	15.9 ± 6.4	16.9 ± 2.3	13.3 ± 2.1
Test	TAN (mg/L)	879 ± 37	836 ± 7	943 ± 53	1096 ± 41	815 ± 36	690 ± 47
	TKN (mg/L)	1700 ± 62	1945 ± 150	1929 ± 49	2289 ± 64	2225 ± 85	1966 ± 110
	PA (mg/L)[a]	2965 ± 182	2729 ± 196	2755 ± 144	3020 ± 253	2492 ± 248	1852 ± 133
	TA (mg/L)[a]	3634 ± 130	3313 ± 197	3465 ± 155	3945 ± 375	3677 ± 334	2967 ± 130
	IA (mg/L)	669 ± 130	584 ± 160	710 ± 106	925 ± 276	1185 ± 136	1115 ± 55
	VFA (mg/L)[b]	3.7 ± 0.9	7.2 ± 2.6	6.5 ± 0.9	23.6 ± 3.0	27.9 ± 2.5	38.2 ± 5.6
Biogas							
Control	Biogas (m^3/d)	1.1 ± 0.2	0.98 ± 0.1	1.04 ± 0.1	1.0 ± 0.1	1.1 ± 0.1	1.2 ± 0.1
	%CO_2	31.4 ± 2.0	35.1 ± 1.7	34.3 ± 2.8	34.8 ± 3.5	33.8 ± 4.0	30.4 ± 3.5
Test	Biogas (m^3/d)	1.0 ± 0.1	1.24 ± 0.1	1.41 ± 0.1	1.63 ± 0.2	1.83 ± 0.1	0.64 ± 0.1
	%CO_2	29.7 ± 3.0	33.5 ± 1.7	32.1 ± 3.5	33.6 ± 3.4	34.4 ± 3.2	34.5 ± 3.9

[a] Partial alkalinity (PA), total alkalinity (TA) and intermediate alkalinity (IA) represented as mg/L $CaCO_3$.

[b] Volatile fatty acids (VFA) represented as mg/L acetic acid.

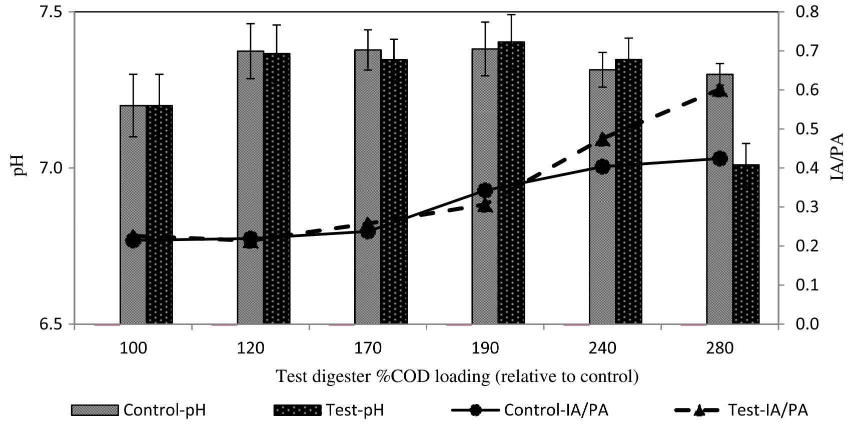

Fig. 4. Effluent pH and IA/PA ratio at various organic loadings.

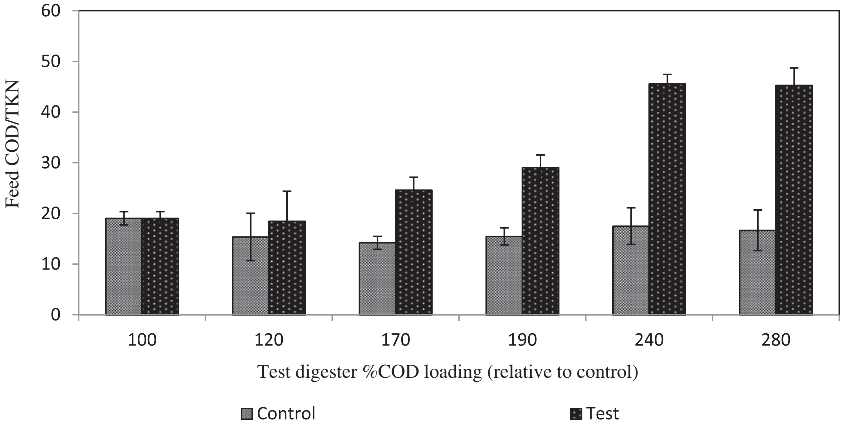

Fig. 5. Feed COD/TKN ratio at various organic loadings.

None of the measures of process stability that have been examined would indicate a process upset that could account for the observed reduction in biogas production. The sole indication of a process upset was the reduced biogas production in the test digester shown in Fig. 2 and S-1 (in the Supplementary Data). Following the conclusion of the test runs, the test digester was drained, cleaned and re-started with blended municipal wastewater treatment plant sludge. Good gas production was obtained, indicating that the equipment was functioning properly. Thus, test digester equipment failure was also ruled out.

Other researchers have reported either a similar rapid reduction in biogas production as the proportion of grease in co-digestate was increased or a lag in biogas production when the initial feed contained a high proportion of lipid. Cirne et al. (2007) reported a lag time in the initiation of biogas generation when the proportion of lipid in an anaerobic digester feed exceeded 31% on a COD basis. This lag period lasted approximately 25 days when the proportion of lipid initially fed was 47%. A rapid increase in VFA concentration was observed during this period. This is somewhat contrary to results reported by Girault et al. (2012) who observed a decline in biogas generation when grease VS was increased to greater than or equal to 74% of the total feed VS. However, during the reduced biogas production, these researchers observed no accumulation of VFAs and the pH values were reported to remain relatively steady within the range of 7.2 to 6.9. Results similar to those reported by Girault et al. (2012) have also been reported by Pereira et al. (2005) and Silvestre et al. (2011). Silvestre et al. (2011) reported long chain fatty acid concentration to increase by more than two-fold during the period of low biogas production, while VFA concentration remained relatively low. These researchers attributed the reduction in methane production to mass transfer limitation caused by an accumulation of long chain fatty acids (LCFA). This inhibition can occur without an increase in VFA, presumably due to inhibition of acidogenesis and acetogenesis (Girault et al., 2012).

The effect of LCFA inhibition has been shown to be reversible (Cirne et al., 2007; Pereira et al., 2004) and so the reactor in the present study may have recovered. Nevertheless, such a process upset would not be acceptable at a full-scale facility. Therefore, a safe upper limit on GTW loading may be identified based on the results of the present study. These results indicate that a GTW loading in excess of 23% VS or 58% COD relative to the total feed VS or COD loading were detrimental to the process stability (see Fig. 2). These values are lower than some reported from bench-scale studies. This may be due to the lower mixing efficiency and greater difficulty in controlling other operational variables at pilot- or full-scale facilities as well as differences in the waste grease characteristics.

4. Conclusions

Mesophilic co-digestion of MWS and GTW was found to be feasible up to a maximum GTW amounting to 23% of the 1.58 kg VS/(m^3 d) loading to a pilot-scale CSTR digester, operating at 35 °C and a 20 day SRT. Biogas production at this maximum feasible loading of GTW was enhanced 67% relative to the control digester. COD and VS removals in the test digester at the 190% relative COD loading were 2.56 and 1.53 fold those of in the control digester, respectively. This resulted in essentially equivalent VS and COD concentrations in the reactors' effluents despite the higher loading to the test digester.

Increasing the GTW addition to 30% of the 1.6 kg VS/(m^3 d) test digester loading resulted in a marked decline in biogas generation. No sign of conditions that would cause methanogens inhibition was observed and the reduction in biogas production was attributed to an accumulation of long chain fatty acids as has been reported in other studies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.03.021.

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