Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste (OFMSW): Full scale vs Laboratory Results

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Abstract: There is limited information available to describe anaerobic digestion of OFMSW that are generated in North America. In this study, the impact of SRT, solids recycle and feeding frequency on VS destruction and biogas generation was investigated at bench, pilot and full scale. VS destruction and biogas production were improved by approximately 20% when the SRT was increased from 10 to 30 days. Recycling of solids to maintain an SRT of 30 days while operating at an HRT of 15 days was able to achieve similar VS destruction to the once-through reactor with an SRT of 30 days. The pilot scale digester that was fed 4 times per day and 7 days per week had superior performance over the bench scale digester that was operated at the same SRT and was fed once per day and 5 times per week, indicating that more consistent feeding could enhance digester performance. The VS destruction at the full scale facility was considerably less than that observed in the smaller scale digester. Implementation of more consistent feeding may significantly improve process performance. Other factors that impact the process performance, such as inadequate mixing might also be responsible for the reduced performance of the full scale facility.

Keywords: anaerobic digestion, municipal solid waste, specific methane production, volatile solids destruction

INTRODUCTION
Anaerobic digestion is a process that can be employed to produce stabilized solids with reduced pathogens and a biogas consisting mainly of methane and carbon dioxide. Typically used to treat sludges in municipal wastewater treatment plants, anaerobic digestion can also be used to treat the organic fraction of municipal solid waste (OFMSW). There are a number of advantages associated with this application of anaerobic digestion, including the potential for energy recovery, the production of an end-product suitable for land application with little or no additional processing, and a decreased dependency on landfills or incineration as waste management options. This practice is more commonly employed in Europe, but relatively new to North America. It might be anticipated that the waste properties in North America would differ from that of Europe due to the differing climate as well as socio-economic conditions. Differing waste properties might impact the extent of solids destruction achieved, the biogas yields as well as process operating parameters such as solids residence time and organic loading. This paper describes bench, pilot and full scale testing that was performed to assess the biodegradability of a Canadian OFMSW and the impact of process operating conditions on digestion of this waste.

The Dufferin Organics Processing Facility (DOPF) in Toronto, Ontario operates a full scale anaerobic digester for treatment of source-separated organic waste gathered from residential and commercial sources. This digester was initially intended to operate as a full scale demonstration unit that could be employed to identify optimal operating conditions. Due to the need for OFMSW processing capacity, the digester is now a mainstay of the City's operations and optimization studies with the full scale digester are not possible. There was, however, a belief that the operating conditions of the plant were sub-optimal. The digester is fed Monday to Friday from early morning (6:00 am) to late evening (10:00 pm), except statutory holidays. On weekends and statutory holidays, the digester is mixed but not fed. DOPF experiences challenges with the existing digestion process, characterized by an accumulation of volatile fatty acids during the week while the reactor is fed.
continuously. On the weekends, when the feed is stopped, the volatile fatty acid concentrations recover to normal ranges. Due to the lack of flexibility in operating the full scale operation, the Wastewater Technology Centre (WTC) in Burlington, Ontario conducted bench and pilot scale tests using the same organic waste feed, to assess the impact of solids retention time, solids recycle and feeding frequency on digester performance. This paper compares the results of these tests to the full scale operation at DOPF.

MATERIALS & METHODS

Waste Preparation

The waste used to feed the anaerobic digesters was gathered from residential and commercial sources within the City of Toronto. The residential component was separated at the household and was composed primarily of kitchen waste with additional paper fibers, sanitary products, houseplants and animal litter. Commercial sources included bars, restaurants, bakeries and other businesses that generate organic waste.

Upon receipt at the DOPF, large items of contaminant material are manually removed from the waste. The waste is then transferred to the patented German BTA wet pretreatment system, a batch process with two objectives: (1) to separate film plastic and contaminating materials from the organic fraction of the waste; and, (2) to transform the waste into an organic pulp. Recycled process water and City water are added to the BTA wet separation system prior to the pulping cycle to dilute the organic pulp material to a total solids content of 6% to 7%. After pulping, film plastic and floatable contaminants are removed from the top of the separation vessel by raking. Heavier contaminants settle to the bottom of the vessel and are removed through a trap.

Following pretreatment, the pulp is transferred to a temporary storage tank, where grit is removed and it is then fed to the anaerobic digester. In the bench and pilot scale portion of this study, pulp was collected weekly and transported to the WTC where it was stored at 4°C prior to use. The pulp was ground for 3 to 4 hours at the WTC using an ABS Piranha Submersible Grinder Pump S10/4 to prevent plugging of the lines in the smaller scale equipment. Although particle size is known to effect methane production (Hartmann, 2006), recent data from Nopharatana (2007) suggests that decreased particle size does not appreciably affect methane production rate at smaller sizes (2 and 50 mm).

Equipment

The study consisted of bench and pilot scale testing and the results were compared to data collected at the full scale plant. A range of operating conditions was examined with the bench scale digester while a more regular feeding frequency was studied with the pilot digester. The periods of operation for the various process conditions are summarized in Table 1.

Bench Scale Digesters. Three 15 L cylindrical bench scale reactors were operated over the course of the study. Each reactor was mechanically mixed and the temperature was maintained at 35°C through the use of heat tracing that was controlled on the basis of a thermocouple immersed in the reactor. The reactors were fed and wasted daily for five days per week using a peristaltic pump.

Pilot Scale Digester. The 540 L pilot scale digester with a liquid volume of 500 L was fed 4 times per day, 7 days per week using an automated wasting and feeding system. During the waste period, approximately 9L of waste was removed from the pilot reactor and replaced with feed. The pilot reactor was mixed through continuous liquid recycling and the temperature was maintained between 34-36°C.

Full Scale Digester (DOPF). The DOPF digester, with a volume of 3600 m³, is a gas-mixed reactor with a solids recycling system and is operated at approximately 37°C. The solids recycling system involves dosing a portion of the digestate with cationic polymer and separating the solid and liquid components through an Alfa Laval drum thickener. A fraction of the solids stream, at approximately 10% solids, is returned to the digester, while the liquid fraction is added to the facility's process water system. The solids recycle system increases the solids residence time in the digester and typically maintains a solids concentration in the digester of 4-5% total solids. The HRT and SRT of the digester were estimated to be 17 and 27 days respectively. The digester
is fed continuously for 16 hours per day, 5 days per week. The final product is dewatered using screw presses that separate the contents of the digester into a solid fraction, i.e. a digested solid material with a solids content of 22 – 25 percent, and a liquid fraction which is temporarily stored in the process water tank before being either added to the hydropulper (i.e. recycled through the process) or discharged to the sanitary sewer.

**Operation**

The bench and pilot scale reactors at the WTC were initially seeded with inoculum from the DOPF digester. On subsequent days, the feed volume was adjusted to obtain the desired volatile solids loading rate. For one of the bench scale reactors (Bench-30R), the hydraulic and solids retention times were decoupled through solids recycling. Half of the daily waste volume was centrifuged for 15 minutes using a Sorvall Legend RT centrifuge at 4150 rpm and 25 deg C. The liquid waste was decanted off the solids and discarded. The solid component was weighed and then returned to the digester along with the daily feed volume. Operating parameters for each of the reactors are summarized in Table 1.

**Table 1. Bench, Pilot and Full Scale Operation**

<table>
<thead>
<tr>
<th></th>
<th>Bench-10</th>
<th>Bench-15</th>
<th>Pilot-15</th>
<th>Bench-30</th>
<th>Bench-30R</th>
<th>Full Scale</th>
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<td>Apr 12,</td>
<td>Mar 29,</td>
<td>Nov 3,</td>
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**Sampling and Analysis**

**Full Scale.** On each sampling day, four 5L grab samples of pulp and liquid effluent and four 2 kg grab samples of digested solids were collected and then composited prior to analysis of TS, VS, VFA, alkalinity and NH3. Grab samples of biogas were collected in 6 L SUMMA canisters for compositional analysis near the beginning, midpoint and endpoint of the daily schedule of pulp delivery to the anaerobic digestion system (approximately 8:00 am, 3:00 pm, 9:00 pm respectively). Biogas volume was measured continuously by an in-line flow meter and recorded by the facility's SCADA system.

**Bench and Pilot Scale.** Grab samples from each stream were collected for analysis twice a week. Total volatile fatty acids were measured using the Hach Method 8196 Esterification for Volatile Acids (Hach, 1997). Specific volatile fatty acids were determined by ion chromatography. Total solids, volatile solids, alkalinity, pH and ammonia were measured as per Standard Methods (APHA, 2005).

Biogas production in the bench scale digester was measured using a wet tip gas meter. An on-line Fluid Components International LLC, ST98 flow meter recorded the biogas flow on the pilot scale equipment. Biogas composition was analyzed with an Agilent 3000 Micro gas chromatograph (GC) for methane, carbon dioxide, oxygen and nitrogen. The methane and carbon dioxide calibration was verified before and after each set of gas analyses. Initially, gas samples were taken with a syringe and injected into the GC for analysis. Over the course of the study, gas sampling bulbs were installed on each reactor to provide a direct line to the GC, thus reducing error associated with sampling.

**RESULTS & DISCUSSION**

The testing conducted in this study was performed over a period of time that spanned several seasons. Waste properties might be expected to change with seasons due to differing materials entering the waste stream and also due to decomposition of the waste prior to processing during warm weather. Figure 1 shows the solids and VFA profile of the feed over the course of the study. Over time, the feed VFA concentration increased and the volatile fraction of the solids decreased. These results suggest that there was some deterioration of the feed during the warmer seasons. Wastes that were treated during this period could be expected to be less degradable than those treated during the cold weather season where the organics were better preserved.
The properties of the waste stream varied somewhat with time during this study and hence there was day-to-day variability in the biogas production and effluent solids concentrations. To facilitate data interpretation, the average specific methane production was determined from the slope of a plot of the cumulative methane production versus the cumulative mass of volatile solids fed during a stable period of operation (Davidsson, 2006). Stable periods were identified as those where the ratio of volatile fatty acid (VFA) to alkalinity concentrations was consistent. The VFA to alkalinity ratios during these periods did not exceed 0.15, and for some runs the maximum was considerably less than this. Figure 2 presents this calculation for the bench scale digester that was operating with solids recycle as an example. The VFA/alkalinity ratio during the stable period was consistently less than 0.05. A similar methodology was employed to determine the volatile solids destruction for each of the reactors. The cumulative mass of volatile solids fed and the cumulative mass of volatile solids wasted were each plotted and the slopes of these lines were used to calculate the average volatile solids destruction. The results obtained from the four bench scale tests, the pilot test and the full scale plant are outlined in Table 2.

Figure 1: Feed solids and VFA profile over the testing period.

Figure 2. Cumulative methane production versus mass of volatile solids fed during the test period for Bench-3OR. The stable period is highlighted.
Impact of SRT on Process Performance

The bench scale portion of this study facilitated a direct comparison of the impact of SRT on process performance. From Table 2 it can be seen that at bench scale the VS destruction obtained at SRTs of 10-15 days were reduced with values in the range of 57-59%. Increasing the SRT in the bench scale reactors to 30 days resulted in a substantial increase in the VS reduction to 68%. The specific biogas and methane production increased when the SRT increased from 10 to 15 days and then decreased somewhat in the once-through digester operating at an SRT of 30 days. The somewhat anomalous results for the 30 day SRT digester were attributed to error associated with measuring the smaller volumes of biogas generated in this unit.

Impact of Solids Recycle

Solids recycle is practiced at the DOPF to reduce HRT while maintaining an extended SRT. The recycling of solids is not performed in a controlled manner and hence its impact on performance at full scale was difficult to assess. In this WTC study, the recycling of solids was implemented under controlled conditions at bench scale. The HRT and SRT were maintained at 15 and 30 days respectively and hence direct comparison of the once-through digesters was facilitated. From Table 2 it can be seen that implementation of solids recycle substantially enhanced the performance of the digester as compared to once-through operation at a 15 day HRT. VS destruction increased from 57% to 68% while the specific biogas and methane productions increased by 26-28%.

The bench scale reactor with solids recycle was also compared against that of the once-through digester with an HRT of 30 days. From Table 2 it can be seen that VS destruction was virtually identical in the two reactors. The specific biogas and methane production appeared to be somewhat higher in the reactor with recycle. The cause of the inconsistency between the solids and gas data was not readily apparent however it should be noted that the reactors were operated at different times and the changes in waste composition that were previously noted may have had some effect on biogas yields.

Comparison of Bench, Pilot and Full Scale Performance

The performance of the bench and pilot scale digesters operating at an HRT of 15 days was compared to assess the impact of feeding frequency on digester performance. The bench scale digester was fed once per day, 5 days per week while the pilot digester was fed 4 times per day, 7 days per week. From Table 2 it can be seen that all of the process indicators suggested improved performance in the pilot scale digester as compared to the bench scale digester. VS destruction increased from 57% to 69% while the specific biogas and methane production increased by approximately 30%. The pilot scale digester appeared to perform similarly to the bench scale digesters that were operated at an SRT of 30 days. The results suggest that continuous operation of these types of digesters can result in substantial improvement in performance.

The performance of the full scale digester was compared to that of the bench and pilot scale systems to assess current performance of the full scale facility to the more carefully controlled systems. The bench scale digester that most closely emulated the full scale system was the reactor with solids recycle (Bench-30R). From Table 2 it can be seen that the bench scale digester performed considerably better than the full scale digester for all of the responses monitored in this study. The VS destruction in the full scale digester was only 41.5% while the bench scale digester achieved a VS destruction of 67.6%. The specific biogas and methane production values were similarly considerably greater in the bench scale system.

The differing performances at the full scale as compared to the bench scale system might be attributed to more than one factor. The VS concentrations employed to estimate the loading to the full scale digester were based upon measurements taken at the WTC. It is believed that there was some deterioration of the samples in transit to the WTC and hence the actual loading to the full scale digester was likely somewhat higher than that which was measured. An initial test of the feed characteristics over transport and storage showed that up to 20% of VS may have been destroyed in the transport and storage of the organic pulp. Therefore, the VS destruction of the full scale system may have been as high as 51.2%. In addition, the feed to the WTC systems was ground whereas the full scale system was not and hence this pre-treatment of the solids may have
enhanced the smaller scale digestion processes somewhat. Finally, the active fraction of the full scale digester volume is unknown. Given the nature of the feed and the difficulties with obtaining proper mixing of these large scale systems it might be that not all of the full scale digester volume is being completely used. Hence, it is possible that the effective volume is somewhat less than the total volume which would result in a reduction of the actual HRT and SRT.

Hartmann et al (2006) reported that the biogas and methane yields generally decreased with increasing organic loading rate (OLR). The overall specific biogas and methane results for all of the systems examined in this study are presented versus the OLR in Figure 3. From this figure it can be seen that, with the exception of the 30-day SRT bench scale reactor (OLR of 1.9 kg/m$^3$/day) this trend was followed in the current study.

![Figure 3: Specific gas production vs OLR.](image)

**Table 2. VS Destruction and Biogas Production Results**

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<tr>
<td><strong>VS destruction (%)</strong></td>
<td>58.5 (± 0.5)</td>
<td>57.2 (± 0.4)</td>
<td>68.8 (± 0.6)</td>
<td>67.6 (± 0.3)</td>
<td>67.6 (± 0.3)</td>
<td>41.5 (± 0.5)</td>
</tr>
<tr>
<td><strong>Specific biogas production (m$^3$/kg VS fed)</strong></td>
<td>0.528 (± 0.010)</td>
<td>0.798 (± 0.006)</td>
<td>1.033 (± 0.008)</td>
<td>0.704 (± 0.010)</td>
<td>0.807 (± 0.007)</td>
<td>0.736 (± 0.003)</td>
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<tr>
<td><strong>Specific methane production (m$^3$/kg CHL fed)</strong></td>
<td>0.360 (± 0.007)</td>
<td>0.508 (± 0.006)</td>
<td>0.668 (± 0.006)</td>
<td>0.425 (± 0.005)</td>
<td>0.672 (± 0.006)</td>
<td>0.377 (± 0.001)</td>
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<tr>
<td><strong>Average OLR (kg/m$^3$/day)</strong></td>
<td>5.8 (± 0.4)</td>
<td>3.3 (± 0.5)</td>
<td>2.6 (± 0.5)</td>
<td>1.9 (± 0.4)</td>
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<td><strong>Period of stability</strong></td>
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<td>May 26 to Jul 28</td>
<td>Aug 23 to Sep 25</td>
<td>Apr 26 to Jun 28</td>
<td>Jun 6 to Aug 4</td>
<td>Nov 25 to Feb 14</td>
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CONCLUSIONS

The main conclusions from the study are:

• VS destruction and hence biogas production could be improved by approximately 20% by increasing the digester SRT from 10 to 30 days

• Recycling of solids to maintain a SRT of 30 days while operating at an HRT of 15 days was able to achieve similar VS destruction to the once-through reactor that had an SRT of 30 days. This can result in considerable reduction in the digester volume required to process OFMSW

• The pilot scale digester that was fed 4 times per day and 7 days per week had superior performance over the bench scale digester that was operated at the same SRT and was fed once per day and 5 times per week. Hence, more consistent feeding would appear to enhance digester performance.

• The VS destruction at the full scale facility was considerably less than that observed in the smaller scale digesters. Implementation of more consistent feeding may significantly improve process performance. Other factors that impact of process performance such as inadequate mixing might also be responsible for the reduced performance of the full scale facility.

ACKNOWLEDGEMENTS

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REFERENCES


