THE EFFECT OF SCALE–UP ON THE DIGESTION OF SWINE MANURE SLURRY IN PSYCHROPHILIC ANAEROBIC SEQUENCING BATCH REACTORS

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ABSTRACT. This study evaluated the effect of scale–up on the performance and stability of anaerobic sequencing batch reactors (ASBRs) treating high–strength swine manure at 20° C. The performance of three semi–industrial–scale ASBRs, with total volumes of 2.5, 8, and 12 m³, respectively, was compared to that of laboratory–scale (42 L) ASBRs. Two bioreactor configurations, cylindrical with either flat or conical bottoms, were also evaluated. There was no significant difference (P < 0.05) in methane yield between the three semi–industrial–scale ASBRs. Over the six–month experimental period, methane production averaged 0.24 ± 0.04 L CH₄ per g total chemical oxygen demand (TCOD) fed to the bioreactors. The total and soluble CODs were reduced by 79.5% ± 5.2% and 86.8% ± 2.5%, respectively. The ASBRs were not affected by elevated ammonia–nitrogen concentrations throughout the experiment and high volatile fatty acid (VFA) levels in the mixed liquor at the end of the feed period. The bioreactors maintained an adequate pH and produced a high–quality biogas, with a methane content ranging from 57% to 78%. Results were similar to those obtained with laboratory–scale ASBRs, with volumes 60 to 285 times smaller than the volumes of the semi–industrial–scale ASBRs. Therefore, further scale–up of the semi–industrial–scale ASBRs, by a factor of 20 to 40, to operate on commercial farms should not affect process efficiency and stability. Results also indicated that the conical–bottom ASBR did not perform differently from the flat–bottom ASBRs at the scale tested in this study.

Keywords. Anaerobic treatment, Animal manure, Psychrophilic anaerobic digestion, Scale up, Sequencing batch reactor.

There is a growing public concern about current manure management practices because of bad odors, fly breeding, weed seed preservation, and air, soil, and water pollution. The integration of biological treatment to existing manure management practices would minimize these potential environmental nuisances and valorize the nutrient content of animal waste. Manure could become a source of energy and an odorless source of fertilizer, instead of simply being a problematic by–product of the farming industry.

Previous studies have shown that psychrophilic anaerobic digestion is a suitable biotechnology for the treatment of animal manure (Kroeker et al., 1979; Lo and Liao, 1986; Safley and Westerman, 1992, 1994; Stevens and Schulte, 1977; Wellinger and Kaufmann, 1982). In laboratory–scale anaerobic sequencing batch reactors (ASBRs) operated at 20° C, the reduction in soluble and total chemical oxygen demands (SCOD and TCOD) of swine manure ranged from 84% to 96% and from 41% to 91%, respectively (Massé et al., 1996, 1997, 2000, 2003). Odor emissions were also considerably attenuated during treatment. The ASBRs were stable under various feeding frequencies, mixing regimes, and temperature fluctuations between 10° C and 20° C. However, these studies were conducted at a relatively small scale, in ASBRs with a total capacity of 42 L. Before the implantation of the technology on commercial farms, research at an intermediate scale is necessary to determine scale–up effect on the performance and stability of the ASBR process. The objective of this study was thus to compare the performance and stability of three semi–industrial–scale ASBRs with that of laboratory–scale ASBRs. The main considerations in the scaling–up of the ASBR technology were:

- Operating strategies: the operating parameters that were successfully used with the laboratory–scale ASBRs (i.e., an organic loading rate of 3 g TCOD per liter of sludge per day of feeding, a treatment cycle duration of 28 days, feed and react periods of 14 days each, and an operating temperature of 20°C) were also applied to the semi–industrial–scale ASBRs in this study.
- Design configuration: two semi–industrial–scale ASBRs were cylindrical and had flat bottoms similar to that of the laboratory–scale ASBRs, while the third semi–industrial–scale ASBR was also cylindrical but had a conical bottom.

MATERIAL AND METHODS

SWINE MANURE

In Canada, swine manure is collected in gutters under partially slatted floors. The gutters are usually cleaned once...
a week to once a month. The manure is then stored for 8 to 10 months in the late fall, winter, and early spring. To reduce the cost of storage, manure is not diluted with water.

During this research project, manure slurry was collected before each ASBR cycle from the gutters under a partially slatted floor in a growing−finishing barn of a typical Canadian commercial swine operation. The pigs were fed a commercial standard diet. They entered the growing−finishing barn at 30 kg and left at 100 kg. The collected manure was stored in a tanker for a maximum of two weeks at temperatures ranging from 5°C to 20°C. The physico−chemical characteristics of the swine manure fed to the semi−industrial−scale ASBRs are presented in table 1.

**BIOREACTOR CONFIGURATION AND OPERATION**

Figure 1 is a schematic of the semi−industrial−scale ASBRs used in this study. The three ASBRs, named ASBR 1, ASBR 2, and ASBR 3, were located in controlled−temperature rooms maintained at 20°C. ASBR 1 had a conical bottom and a volume of 2.5 m³. ASBRs 2 and 3 were cylindrical and had volumes of 8 and 12 m³, respectively.

The ASBRs were inoculated with anaerobic sludge collected from the secondary clarifier at the municipal wastewater treatment plant of Ottawa, Ontario. They were fed swine manure for 21 months before the initiation of this study.

Table 2 summarizes the operating conditions during the study. The organic loading rate (OLR), based on the amount of TCOD fed per volume of sludge present at the start of a cycle per day of feeding, averaged 3.07 g/L/d. It was calculated as follows:

\[ L_f = \frac{V_f C_f}{V_i t_f} \]  

where \( L_f \) is the loading rate (g COD/L/d) based on feeding days, \( V_f \) is the volume of feed (L), \( C_f \) is TCOD concentration in the feed (g/L), \( V_i \) is the volume of sludge in the reactor at the beginning of the cycle (L), and \( t_f \) is the duration of the fill period (d).

In table 2, the OLR was also calculated base on total cycle time, as follows:

\[ L_c = \frac{V_f C_f}{V_i t_c} \]  

where \( L_c \) is the loading rate (g COD/L/d) based on total cycle time, and \( t_c \) is the duration of the cycle. In the text of this article, however, OLR refers to \( L_f \).

Sludge volume at the start of a cycle was 1.21, 3.76, and 5.58 m³ for ASBRs 1, 2, and 3, respectively. The ASBRs were fed once a week for two consecutive weeks. The feeding period was followed by a two−week react period, which actually lasted 13 to 15 days (table 2). Settling of the microorganisms occurred during the last week of the react period, and bioreactor effluent was removed on the last day of the react period. Total treatment cycle duration ranged from 27 to 29 days. The bioreactors were fed as soon as the effluent was removed. During the feeding and react periods, the ASBR content was mixed twice a week by recirculating the bioreactor content for 15, 30, and 45 min for ASBRs 1, 2, and 3, respectively. Mixing allowed the collection of representative mixed−liquor samples.

**SAMPLE ANALYSIS**

Biogas production was continuously monitored and evacuated with controlled−flow pumps (fig. 1). Biogas composition (CO₂ and CH₄) was determined weekly with a Hach Carle 400 AGC gas chromatograph (Hach, Loveland,
Table 2. Organic loading rate, cycle duration, and methane yield during the treatment of swine manure in semi-industrial-scale ASBRs operated at 20°C

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Organic Loading Rate</th>
<th>Methane Yield (L CH4/g TCO2fed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lf (g/Ld of feeding)АО</td>
<td>Lc (g/Ld of total cycle)В</td>
</tr>
<tr>
<td>1</td>
<td>3.18</td>
<td>1.54</td>
</tr>
<tr>
<td>2</td>
<td>2.87</td>
<td>1.49</td>
</tr>
<tr>
<td>3</td>
<td>3.23</td>
<td>1.62</td>
</tr>
<tr>
<td>4</td>
<td>2.72</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>3.18</td>
<td>1.65</td>
</tr>
<tr>
<td>6</td>
<td>3.21</td>
<td>1.61</td>
</tr>
<tr>
<td>Average[^e]</td>
<td>3.07 ± 1.54</td>
<td></td>
</tr>
</tbody>
</table>

[^a] Based on the amount of TCOD fed per volume of sludge present at the start of a cycle per day of feeding.
[^b] Based on the amount of TCOD fed per volume of sludge present at the start of a cycle per day of cycle.
[^c] Includes the react, settling, effluent removal, and idle phases.
[^d] ND = not determined because of a breakdown in the biogas recording device.
[^e] Averages followed by the same letter are not different at P < 0.05.

RESULTS AND DISCUSSION

MIXED-LIQUOR VS CONCENTRATION AND SLUDGE RETENTION TIME (SRT)

Mixed-liquor VS concentration at the end of cycles averaged 56 ± 13, 104 ± 10, and 145 ± 23 g/L in ASBRs 1, 2, and 3 respectively. In ASBRs 1 and 3, mixed-liquor VS concentration tended to increase in time, but variation between the ASBRs and in time partly reflects the difficulty of collecting representative mixed-liquor samples. Mixing of the semi-industrial ASBRs may not have been sufficient to suspend all particles.

Based on measured VS concentrations in the mixed liquor and the effluent, the effluent contained 16.1% ± 5.8% of the mixed-liquor VS. Therefore, if sludge VS concentration remains relatively constant in the ASBRs, sludge VS would be completely renewed every 6.2 cycles, which would be equivalent to an SRT of 172 days, based on an average HRT of 28 days. However, reliable SRT measurements would require precise measurement of sludge VS concentration as well as information on VS composition, especially biomass as opposed to undigested organic feed concentrations in the sludge bed and the effluent.

BIOGAS AND METHANE PRODUCTION

Methane concentration in the biogas was lower during the feeding period due to increased acidification and hydrolysis rates, which accelerated CO2 release, and higher during the react period (fig. 2). Methane concentration ranged from 57% to 71% at the beginning of the feeding phase, and from 67 to 79% at the end of the react phase. These values were similar to those obtained with laboratory-scale ASBRs treating swine manure at 20°C (Massé et al., 1997).

Biogas production increased during the feeding period as the food-to-microorganism ratio increased (fig. 2). It reached a maximum a few days after the last feeding and then rapidly declined until it reached a minimum value at the end of the treatment cycle. Low biogas production at the end of ASBR cycles favors biomass settling before effluent withdrawal.
Methane yield ranged from 0.17 to 0.32 L/g TCOD\textsubscript{fed} and averaged 0.24, 0.22, and 0.27 L/g TCOD\textsubscript{fed} for ASBRs 1, 2, and 3, respectively (table 2). Over the six treatment cycles, there was no significant difference (P < 0.05) in methane yield between the three semi–industrial–scale ASBRs. Expressed in term of TCOD reduction as opposed to TCOD fed, methane yield averaged 0.30, 0.28, and 0.33 L/g TCOD\textsubscript{degraded} for ASBRs 1, 2, and 3, respectively. These values are lower than the theoretical maximum methane yield (0.38 L/g TCOD\textsubscript{degraded} at 20°C), mainly because a fraction of manure TCOD, that is largely composed of heavy organic particles, is reduced through sedimentation at the bottom of the bioreactors during the settling period and is not converted into biogas during the treatment cycle.

ASBR configuration had no apparent impact on methane yield. The conical–bottom ASBR was designed to ease mixing and minimize the formation of dead zones where biomass remains stagnant around the circumference of the reactors. In this study, the presence of dead zones was not measured, but the diameter of the cylindrical bioreactors (2.0 and 2.4 m for ASBRs 2 and 3, respectively) may have been small enough to prevent the formation of dead zones. It is also possible that the presence of dead zones did not have a significant effect on ASBR performance at the OLRs fed in this study.

In the laboratory–scale ASBRs treating swine manure at 20°C, the methane yield averaged 0.27 L/g TCOD\textsubscript{fed} (Massé et al., 2000, 2003). The slightly higher methane production from the laboratory–scale ASBRs was mostly due to the lower OLRs fed to the laboratory–scale (1.3 to 2.3 g/L/d) than the semi–industrial–scale (2.7 to 3.2 g/L/d) bioreactors.

VFA CONCENTRATIONS

Figure 3 presents VFA concentrations during the experimental period in ASBR 2. Similar patterns were obtained for the other two bioreactors. The average acetic acid concentrations reached a maximum of 3189 ± 832 mg/L during the feeding period and decreased to 254 ± 200 mg/L at the end of treatment cycles. Acetic acid is the direct precursor of methane, and rapid disappearance during the react period indicates adequate methanogenesis activity.

Propionic and butyric acid profiles are indicators of process stability. When a process becomes unstable, propionic and butyric acid concentrations usually accumulate in the reactor. In figure 3, the propionic and butyric acid profiles are similar to the acetic acid profile. Therefore, most of the propionic and butyric acids were utilized during the react period. The rapid utilization of propionic and butyric acids indicates that the ASBRs are stable. Valeric and caproic acid concentrations ranged from 36 to 212 mg/L at the end of the feeding period and were mostly below the detection limits at the end of cycles.

Isovaleric acid concentration ranged from 177 to 575 mg/L at the end of the feeding period. Residual isovaleric acid concentration at the end of treatment cycles varied between 143 and 416 mg/L in ASBR 1, between 71 and 318 mg/L in ASBR 2, and between 0 and 145 mg/L in ASBR 3. Isovaleric acid has also been considered as a potential indicator of instability in continuous–flow stirred–tank reactors (CSTRs) treating swine manure at 35°C. Hill and Bolte (1989) suggested that concentrations between 8.5 and 25 mg/L indicated that problems were developing, while failure occurred at levels exceeding 25 mg/L. In the semi–industrial ASBRs, long SRTs and exposure to high isovaleric acid concentrations during the feeding period (fig. 3) may have allowed the growth of isovalerate–degrading bacteria and thus reduced the risk of failure at high concentrations. Additionally, other operating parameters, such as temperature and hydraulic retention time (HRT), may have contributed to reactor stability.
COD AND SOLIDS CONCENTRATION

Mixed-liquor SCOD concentrations sharply increased during reactor feeding and rapidly decreased during the react period (fig. 4). There was no accumulation of residual SCOD in the bioreactors at the end of treatment cycles. In effluent, SCOD ranged from 5895 to 12401 mg/L, with averages of 9391, 8036, and 7524 mg/L for ASBRs 1, 2, and 3, respectively (table 3). Effluent SCOD was significantly higher (P < 0.05) in ASBR 1 than in ASBR 3, which is consistent with the slightly lower methane production from ASBR 1 (table 2).

In laboratory-scale ASBRs operated at 20°C, effluent SCOD concentrations ranged from 2790 to 5597 (Massé et al., 2003). The lower concentrations in laboratory-scale than semi-industrial-scale ASBRs were mostly due to the lower SCOD in the manure fed to the formers. The SCOD averaged 25.65 ± 2.53 g/L and 48.83 ± 11.90 g/L in the manure fed to the laboratory-scale and semi-industrial-scale ASBRs, respectively.

Reduction in TCOD, SCOD, TS, and VS are presented in table 3 for the semi-industrial-scale ASBRs. The SCOD removal was significantly lower (P < 0.05) in ASBR 1 than in ASBR 3, but the actual difference was small, with reductions of 85.1% and 88.1%, respectively, for the two bioreactors. The SCOD reductions are comparable to those obtained in laboratory-scale ASBRs treating swine manure at 20°C, which ranged from 81% to 96% (Massé et al., 1996, 1997, 2000, 2003).

There was no significant difference (P < 0.05) in TCOD, TS, and VS reduction between the three semi-industrial-scale bioreactors. During the six-month experimental period and for all three ASBRs, TCOD, TS, and VS concentrations
Figure 4. Soluble COD concentration in semi-industrial-scale ASBRs during the treatment of swine manure slurry at 20°C.

AMMONIA AND TOTAL NITROGEN

The TKN concentration in the mixed liquor ranged from 4983 to 6742 mg/L, and the ammonia–N concentration ranged from 3921 to 5359 mg/L. Ammonia–N represented 62% ± 4% and 79% ± 3% of the TKN in the raw manure and the mixed liquor, respectively. Additional NH$_3$–N is formed during the degradation of organic nitrogen (protein).

Tolerance of the ASBR system operated at psychrophilic temperature to high NH$_3$–N concentrations was previously reported and discussed in Massé et al. (2003). In ASBR, the long SRTs allow biomass adaptation to high concentrations of ammonia–N. In addition, the psychrophilic system may be more tolerant of high NH$_3$–N concentrations than mesophilic or thermophilic bioreactors because the ratio of free (NH$_3$) to total (NH$_3$ + NH$_4^+$) ammonia decreases with temperature.

Free ammonia or dissolved ammonia gas (NH$_3$), as opposed to ammonium ions (NH$_4^+$), is considered the inhibitive component of the ammonia–nitrogen system. Based on the range of measured NH$_3$–NH$_4^+$ concentrations (3921 to 5359 mg/L) and pH (7.5 to 8.2), the free NH$_3$ concentration in the semi-industrial ASBRs ranged from approximately 50 to 310 mg/L. The high stability and performance of the semi-industrial ASBRs during the project indicates that they did not suffer from high free NH$_3$ concentrations.

CONCLUSION

Semi-industrial–scale ASBRs with total capacities of 2.5, 8, and 12 m$^3$ were efficient and stable during the treatment of high-strength swine manure slurry. The ASBRs were not affected by elevated ammonia–nitrogen concentrations in the mixed liquor and high VFA levels at the end of the feed period. The ASBRs maintained an adequate pH and produced a biogas with a high concentration of methane. Overall methane production rate averaged 0.24 ± 0.04 L/g TCOD fed to the reactors. All these results were similar to those obtained from laboratory–scale ASBRs, which were 60 to 285 times smaller than the semi-industrial–scale ASBRs.

The volume of a bioreactor on a commercial operation should range from 250 to 500 m$^3$, and thus be 20 to 40 times larger...
than the semi–industrial–scale ASBRs used in this study. Further scale–up of the bioreactors to meet commercial farms need could thus be based on the design and operating strategies of the semi–industrial–scale bioreactors. This study also indicated that the bioreactor diameter, volume, and bottom shape (conical and cylindrical) did not affect the bioreactor performance and stability.

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REFERENCES


