Development of a cartridge design anaerobic digestion system for lignocellulosic biomass

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A novel cartridge design anaerobic digestion system was developed for the treatment of lignocellulosic biomass. This new design is composed of a novel anaerobic digestion chamber with three replaceable feedstock cartridges. This design has multiple advantages, e.g. high stability, easy to operate, and no liquid waste, over conventional anaerobic digestion systems. In a seven-month test, maize straw was employed as the feedstock, and the system was operated in three scenarios: no rotation of cartridge; rotation with 14 g dry maize straw in each cartridge; and rotation with 28 g dry maize straw in each cartridge. Results showed that biogas production from this system was comparable to solid-state anaerobic digestion units, and the rotation of cartridges significantly improved the stability of methane yield and reduced hydrogen sulfide in biogas. Digestion effluent was completely reused in the rotation tests.

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1. Introduction

There has been growing interest in using anaerobic digestion to treat lignocellulosic biomass such as crop residues and yard wastes, and in the meantime, generate biogas for energy production (Sawatdeenarunat, Surendra, Takara, Oechsner, & Khanal, 2014). However, current design of either liquid anaerobic digestion (L-AD, works with less than 15% total solids content) or solid-state anaerobic digestion (SS-AD, works with greater than 15% total solids content (Li, Zhu, Wan, & Park, 2011)) have met with considerable challenges and usually requires pretreatment of feedstock (Zheng, Zhao, Xu, & Li, 2014). Floating of lignocellulosic biomass has been a big problem for L-AD systems. Size reduction and mechanical mixing alleviate this problem but can be energy consuming (Surendra & Khanal, 2014). Digestion effluent presents another challenge for L-AD. Since L-AD operates with a relatively low total solids content, a large amount of water is usually added prior to digestion, thus generating a lot of effluent. Land application of L-AD effluent as a liquid fertiliser is one option. However, there are health concerns regarding pathogens and heavy metals presented in effluent (Sheets, Yang, Ge, Wang, & Li, 2015). Food safety has become a hallmark of U.S. regulations, which may influence farmer perception of using effluent fertilisers for crops intended for human consumption. Consequently, many large AD
operations have limited outlets for effluent disposal (USFDA, 2011). Composting of AD effluent is another option. However, odour emission is a concern and prior to composting, effluent needs to be dewatered, which is an energy intensive process. Therefore, strategies for reducing L-AD effluent are urgently needed.

On the other hand, the major criticism of SS-AD is instability (Brown, Shi, & Li, 2012; Sheets et al., 2015). Due to the high total solids content, mixing of feedstock and inoculum may be incomplete, which could lead to accumulation of inhibitors such as volatile fatty acids and free ammonia, and eventually may cause digester failure (Fagbohungbe et al., 2015; Karthikeyan & Visvanathan, 2012; Li, Park, & Zhu, 2011; Wang, Xu, & Li, 2013; Zhu, Yang, & Li, 2014). Instability also refers to the unstable biogas production. Batch systems are commonly adopted for SS-AD, however, feedstock degradation rate varies over the batch digestion process and so does biogas yield (Liew, Shi, & Li, 2012). A previous study showed that SS-AD of giant reed, a typical lignocellulosic biomass, had fluctuating daily biogas yield with peak values achieved on day 12 at a feedstock/effluent mixing ratio of 2.0 (Yang & Li, 2014). Instability of SS-AD gives rise to challenges in system management and biogas utilisation.

This study aimed to develop a novel system to resolve the aforementioned challenges in both L-AD and SS-AD by improving biogas stability and reducing effluent generation in anaerobic digestion of lignocellulosic biomass. A key component of the new design is a cartridge design anaerobic digestion chamber. The objectives of this study were: 1) to examine the bench-scale new anaerobic digestion system and to obtain preliminary data; and 2) to compare system performance with three different operating strategies.

2. Materials and methods

2.1. Feedstock and inoculum

Maize straw collected from the Illinois State University Farm at Lexington, IL, USA, in October 2015 was used as the feedstock in this study. Maize straw was air dried to less than 15% moisture content, and then ground to pass a 5 mm sieve (Mighty Mac, MacKissic Inc., Parker Ford, PA, USA). The physical and chemical properties of maize straw are listed in Table 1. Effluent taken from a mesophilic liquid anaerobic digester (fed with municipal sewage sludge, operated by Bloomington Normal Water Reclamation District, IL, USA) was used as the inoculum. Digestion effluent provides nutrients and already adapted digestion microbes. The inoculum was activated in a 37 °C incubation chamber for one week prior to use.

2.2. Anaerobic digestion system design and operation

A schematic design of the cartridge anaerobic digestion system is shown in Fig. 1. This novel anaerobic digestion chamber has three replaceable cartridges, a clarifier, and an ammonia stripper. The solids removal and ammonia stripping units were not operated in this study. This system has feedstock packed in the replaceable cartridges only, whereas conventional L-AD or SS-AD systems have feedstock evenly distributed inside the digester. The digestion chamber (L × W × H: 23 cm × 15 cm × 15 cm) was made of transparent plastic and had an inner size of 4 L. The three cartridges (L × W × H: 3.8 cm × 15 cm × 14 cm, 0.8 L each) were made of perforated plastic with 0.24 cm diameter holes and 25% open area. Maize straw was loaded into the three cartridges. In addition, 1 L inoculum and ~1.8 L DI (deionised) water was added to the chamber, which left about 0.5 cm head space (150–200 mL, or <5% of the digestion chamber volume). The digestion chamber was put into a 37 °C incubator. A 5 L biogas bag (CEL Scientific, Santa Fe Springs, CA, USA) was attached to the top of the digestion chamber, and biogas was collected and analysed every 2–3 days. When a biogas bag was replaced, the digestion liquid was recirculated for 5 min using a pump with a flow rate of 0.2 L min⁻¹. Digestion liquid was taken out from the top layer close to the right side of the chamber, and was injected into the bottom layer close to the left side of the chamber. This recirculation promoted mass transfer in the digestion chamber and also evened out the distribution of inhibitors.

This system was operated in the following three scenarios:

1) Each cartridge was filled with 14 g dry maize straw and all three cartridges were put into the chamber at the same time. This scenario was referred to as “no rotation”. Volatile solids (VS) concentration in this scenario was 8.4 g L⁻¹.

2) One cartridge was filled with 14 g dry maize straw and put into the chamber to start the anaerobic digestion process. Then 10 days later, a second cartridge filled with 14 g dry maize straw was added, and followed by a third cartridge added into the chamber after another 10 days. On day 30,
the first cartridge was taken out and was replaced by a new cartridge with 14 g dry maize straw. The rotation continued until the test was completed in a total of 130 days. This scenario was referred to as “rotation with 14 g maize straw”. Volatile solids (VS) concentration in this scenario was 8.4 g L⁻¹. Anaerobic digestion is composed of a series of biochemical processes, and each process generates different products. Rotation of cartridges kept the feedstock in the three cartridges digested at different stages, thus avoiding accumulation of digestion intermediates such as ammonia and volatile fatty acids (VFA) which could inhibit microbial activities. Rotation also separates biogas production peaking time in the three cartridges, therefore was expected to provide a relatively more stable biogas yield.

3) The third scenario was similar to the second one with only one difference that 28 g, instead of 14 g, dry maize straw was added into each cartridge. This scenario was referred to as “rotation with 28 g maize straw”. Volatile solids (VS) concentration in this scenario was 16.8 g L⁻¹.

2.3. Analytical methods

The composition of biogas, including CH₄, CO₂, O₂, H₂S and balance gas (mainly N₂), was measured using a biogas analyzer (Landtec Biogas 5000, Dexter, MI, USA). The analyser was calibrated by the manufacturer before the test and was checked with standard biogas every month. The total solids (TS), volatile solids (VS), pH, and alkalinity of the feedstock and inoculum were measured based on a slightly revised Standard Methods Examination of Water and Wastewater (APHA, 2005). Specifically, the samples were oven dried at 105 °C for 24 h to find the mass difference so that TS content could be calculated. The dried samples were then put into a 550 °C oven for 4 h to measure volatile compounds. A 3 g sample was diluted with 30 mL of DI water, and then the pH and alkalinity were measured using a pH titrator. Ammonium and volatile fatty acids were analysed using HACH Method 10031 and 8196, respectively. Organics such as cellulose, hemicellulose, lignin, and starch were analysed at the Rock River Laboratory, Inc (Watertown, WI, USA). These samples were oven dried and then ground to 1 mm with a cyclone grinder before taking measurement.

2.4. Data analysis

Data were analysed using R Studio software and SigmaPlot. Statistical methods such as t test were applied to compare the performance of digesters operated under different scenarios. Averages and standard errors are reported in this paper.

3. Results and discussion

3.1. Results of the “no rotation” scenario

Three cartridges, each filled with 14 g maize straw, were put into the digestion chamber at the same time. This operation performed similarly to a typical SS-AD digester, and showed one peak in the daily methane yield (Fig. 2). The achieved peak yield of 17.22 L[CH₄] kg⁻¹[VS] day⁻¹ on day 6 was quite comparable to peak yields generated from SS-AD systems reported previously (Yang, Xu, Ge, & Li, 2014). The accumulative methane yield achieved in 32 days was 218.05 L[CH₄] kg⁻¹[VS], which was also comparable to typical SS-AD systems (Li, Zhu et al., 2011). Methane percentage was stabilised at 45–55% in 6 days. H₂S concentration increased to over 250 ppm in the initial 12 days, and then gradually declined, with a 32-day average of 152.14 ppm. It is important to note that the added inoculum may contribute to the H₂S emission. The contribution from the inoculum was believed to be marginal as the controls (digesters that filled with the inoculum only) showed minimum biogas yields with less than 1 ppm H₂S. NH₄–N and VFA concentrations and pH values were measured every 9–11 days and were in the range of 852–910 mg L⁻¹, 420–556 mg L⁻¹ and 7.1–7.3, respectively, which were in the normal operation ranges. At the end of the test, no significant solids concentration increase in effluent was observed. The “no rotation” scenario provided a baseline performance of this system, and in general, its performance was close to typical SS-AD systems but with no concern of over accumulating free ammonia in effluent.

3.2. Results of the “rotation with 14 g maize straw” scenario

The three cartridges, each filled with 14 g maize straw, was added to the digestion chamber on day 0, 10, and 20, respectively, and rotation started on day 30 with one cartridge replaced at a time for every 10 days. The daily methane yield
was relatively stable with a 130-day average of 7.76 L \([\text{CH}_4]\) kg\(^{-1}\)\([\text{VS}]\) day\(^{-1}\), which was 10% higher than the “no rotation” scenario (Fig. 3). Methane concentration quickly increased and reached the stable phase in 10 days and then kept at 50–60% until the end of the test. The methane content declined slightly (5–10%) when a cartridge was replaced, mainly because the digestion chamber was opened and a small amount of air was introduced into the chamber head space (150–200 mL). The methane percentage usually returned to normal in 4–5 days (the second biogas measurement after cartridge replacement). Average oxygen content in biogas was 2.04%.

The concentration of H\(_2\)S was quite constant for the 130-day test, with an overall average of 59.92 ppm, which was significantly lower than that in the “no rotation” scenario (average of 152.14 ppm). After day 100, the H\(_2\)S concentration continuously lowered to less than 50 ppm. The decline of H\(_2\)S was probably due to a small amount of air/oxygen being introduced to the digestion chamber, which converted H\(_2\)S to other forms of sulphur. A previous study on micro aeration has showed that air dose of 0.28–6.00 m\(^3\) h\(^{-1}\) into full scale digesters with biogas production of 520–9600 m\(^3\) day\(^{-1}\) reduced H\(_2\)S emission by 73.8–99.1% (Jeníček, Horejší, Pokorná-Krayzelová, Bindzar, & Bartáček, 2017). Micro-oxygen injection, in general, would not negatively affect anaerobic digestion in terms of biogas production.

3.3. Results of the “rotation with 28 g maize straw” scenario

Operation of this scenario was almost the same as the second scenario, except that the amount of maize straw put into each cartridge was doubled to 28 g. The daily methane yield was stable 6 days after the rotation was started and achieved an average of 6.43 L\([\text{CH}_4]\) kg\(^{-1}\)\([\text{VS}]\) day\(^{-1}\), which was 17% lower than the “rotation with 14 g maize straw” scenario (Fig. 4). It is important to mention that maize straw was slightly more packed in cartridges when it was doubled to 28 g. The compaction may have increased mass transfer barriers, e.g. anaerobic digestion microbes may have taken a longer time to get access to the inner space of the cartridges, leading to reduced methane yield per kg VS. The digestion chamber, however, still had space for a fourth cartridge, which could be used to maximise biogas production. Methane concentration...
Table 2 – Comparison of maize straw digestion performance.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Daily methane yield L[CH4] kg−1 [VS] day−1</th>
<th>H2S conc. ppm</th>
<th>NH4−N conc. g L−1</th>
<th>pH value</th>
<th>Alkalinity g[CaCO3] kg−1</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Rotation</td>
<td>7.03 ± 5.36</td>
<td>152 ± 74.0</td>
<td>0.89 ± 0.03</td>
<td>7.21 ± 0.16</td>
<td>7.82 ± 0.42</td>
</tr>
<tr>
<td>Rotation with 14 g</td>
<td>7.76 ± 1.23</td>
<td>59.9 ± 12.4</td>
<td>0.39 ± 0.1</td>
<td>7.13 ± 0.11</td>
<td>7.23 ± 0.27</td>
</tr>
<tr>
<td>Rotation with 28 g</td>
<td>6.43 ± 1.21</td>
<td>83.4 ± 88.6</td>
<td>0.12 ± 0.02</td>
<td>7.50 ± 0.13</td>
<td>8.12 ± 0.56</td>
</tr>
</tbody>
</table>

was stabilised in 5 days and remained relatively stable thereafter. H2S concentration, however, was quite different from the previous two scenarios, with a high concentration of 354 ppm on day 2 and then gradually declined to less than 30 ppm on day 67. The average NH4−N concentration was 120.19 mg L−1, which was still lower than the inhibitory level. The lower NH4−N concentration observed in this scenario than in the second scenario could be because of the compaction that might have slowed the transfer NH4−N from the cartridge to the effluent.

3.4. Comparison of the three scenarios

This new system showed promising results. All three scenarios achieved acceptable average daily methane yield (Table 2). Compared to the “no rotation” test, the two rotation tests showed much more stable biogas production rate, as indicated by the much smaller standard deviations in daily methane yield. Rotation also reduced the concentration of H2S, probably due to the introduction of a small amount of air/oxygen into the digestion chamber. In comparison to typical solid-state anaerobic digestion process, which may suffer from excessive ammonium accumulation (typical concentration of 2–6 mg L−1 (Wang et al., 2013; Yang et al., 2014)), this design significantly reduced the risk of free ammonia inhibition, so that digester stability improved. The pH value and alkalinity were stable and healthy for all three tests.

Contents of cellulose, hemicellulose, and lignin in collected samples are shown in Fig. 5. Compared to the undigested maize straw (raw feedstock), the digested maize straw collected at the end of all three tests showed significantly lower (p value < 0.05) cellulose and hemicellulose but significantly higher lignin contents, indicating the degradation of hemicellulose and cellulose. Hemicellulose is known for quick degradation, and in this study, it declined 40%, 45%, and 39% in the “no rotation”, “rotation with 14 g maize straw”, and “rotation with 28 g maize straw” tests, respectively. Lignin, by contrast, is highly resistant to degradation in an anaerobic digestion process, and showed an increased content (relative percentage) in all digested maize straw samples as other degradable organics were reduced. Compared to other two tests, the digested maize straw collected from “rotation with 14 g maize straw” test showed lower cellulose and hemicellulose but higher lignin content, which was consistent with its higher methane yields. The raw feedstock contained 0.54 ± 0.02% of starch, while the digested maize straw collected from the three tests had 0.20–0.35% starch, with no significant differences.

4. Conclusions

This new cartridge design anaerobic digestion system was able to treat maize straw, a typical lignocellulosic biomass, with successful outcomes. Methane production from this new design was comparable to solid-state anaerobic digesters, while the system stability was improved. Rotation of cartridges improved the average methane yield, balanced daily methane production rate, and reduced hydrogen sulfide concentration in biogas. Effluent was completely reused in the rotation tests, and no solids or free ammonia accumulation was observed in this test. Organic degradation rates were also comparable to other anaerobic digestion processes.

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References


