Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure

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Abstract
Anaerobic digestion of dairy cow manure (CM), the organic fraction of municipal solid waste (OFMSW), and cotton gin waste (CGW) was investigated with a two-phase pilot-scale anaerobic digestion (AD) system. The OFMSW and CM were digested as single wastes and as combined wastes. The single waste digestion of CM resulted in 62 m3 methane/ton of CM on dry weight basis. The single waste digestion of OFMSW produced 37 m3 methane/ton of dry waste. Co-digestion of OFMSW and CM resulted in 172 m3 methane/ton of dry waste. Co-digestion of CGW and CM produced 87 m3 methane/ton of dry waste. Comparing the single waste digestions with co-digestion of combined wastes, it was shown that co-digestion resulted in higher methane gas yields. In addition, co-digestion of OFMSW and CM promotes synergistic effects resulting in higher mass conversion and lower weight and volume of digested residual.

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1. Introduction

Millions of tons of wastes are generated each year from agricultural, municipal, and industrial sources. In 2001, a total of 229.2 million tons of municipal solid waste (MSW) was produced in the United States (US EPA, 2002). Agricultural waste, including animal manure, is another source of solid waste. The quantity of animal manure produced in the United States is 130 times greater than the amount of human waste (US Senate Committee on Agriculture, Nutrition and Forestry, 1997). The 2002 farm bill identified manure waste as a major national environmental problem. The potential pollutants from decomposing livestock manure include biological oxygen demand (BOD), pathogens, nutrients, methane, and ammonia emissions (USDA, 2002; US EPA, 2003).

Another agricultural waste in the United States is the residual generated by the cotton ginning industry. Approximately 2.8 million tons of cotton gin waste (CGW) is produced annually across the cotton belt of the United States (Thomasson et al., 1998). In the decade of 1990–1999, a regulatory change prohibited the incineration of CGW. Over the years, extensive research has been conducted to evaluate the feasibility of using CGW for various applications including manufacture of fire logs (Karpiscak et al., 1982), pellet stove fuel (Holt et al., 2004), use as an energy source (Agblevor et al., 2003; Beck and Clemens, 1982; Lacewell et al., 1982; White et al., 1996), use as livestock feed (Castleberry and Elam, 1998; Castleberry and Emmett, 1999; Holloway et al., 1974; Poore and Rogers, 1995), raw material in asphalt roofing (Truhett, 1994), and direct use as a soil amendment. Despite extensive research efforts, very few uses for CGW have ever reached widespread commercial acceptance and CGW remains a financial liability for most producers (Castleberry and Elam, 1998). A 1997 survey of Texas’ high plains ginners found that the average disposal cost for CGW was $1.44/ton of waste (Castleberry and Elam, 1998).

The uncontrolled decomposition of organic solid waste can result in large-scale contamination of soil, water, and air (Ghosh et al., 1997). Decomposition of one metric ton of organic solid waste can potentially release 50–110 m3 of carbon dioxide and 90–140 m3 of methane (Ghosh et al., 1997) into the atmosphere. If the organic component of the solid waste is converted into energy through anaerobic digestion, it will reduce the adverse impact on the environment and contribute to reduction in consumption of fossil fuel. Anaerobic digestion is a process by which complex organic materials are first hydrolyzed and fermented by acid bacteria into volatile fatty acids (VFA). The VFA are then consumed by methanogenic bacteria and converted into methane gas. However, not all solid wastes can easily be digested.

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Co-digestion of solid waste can utilize the nutrients and bacterial diversities in various wastes to optimize the digestion process. Hartmann and Ahring (2005) conducted laboratory scale experiments on a completely mixed thermophilic reactor for co-digestion of OFMSW and cow manure. Their co-digestion experiments showed higher biogas production and a more stable process. Carucci et al. (2005) performed small-scale laboratory experiments on co-digestion of food waste and aerobic sludge from industrial wastewater treatment. These experiments showed that co-digestion of the two wastes can reduce inhibition of methanogenesis and increase methane yield.

This paper demonstrates the application of a two-phase anaerobic digestion system where co-digestion of various agricultural and municipal organic solid wastes was evaluated. Digestion of single wastes (OFMSW and CM) was investigated in separate experiments to assess the effect of co-digestion.

2. Methods

2.1. System design

Fig. 1 shows a schematic of the two-phase anaerobic digestion system. The solid phase reactor was constructed from a 1.8 m (W) by 1.7 m (L) by 2.1 m (H) prefabricated commercial dumpster. The total container volume was about 6.4 m³. The container had access fittings for transport of liquid influent, leachate effluent, and gas effluent. The liquid influent was distributed over the solid waste by a sprinkler system. A 7.6 cm deep reservoir was provided below a perforated floor at the bottom of the container. This reservoir was used for short-term storage of the leachate. A 1 mm (40-mil) high density polyethylene (HDPE) cover was fitted to the top of the container and sealed with a neoprene gasket, C-clamps, and silicone caulking.

Two up-flow anaerobic filters (UAF) were constructed using PVC pipes. Each pipe was 3.6 m long with a diameter of 0.3 m resulting in total volume of 222 L. Initially, the UAF reactors were filled with an inert commercial plastic packing material with 90% void space (Yu et al., 2002). Influent and effluent sampling ports were installed in the system and a gas effluent port was provided in the column headspace. Each column was filled with tap water and seeded with 10 L of digester supernatant from the anaerobic digester at the Las Cruces, NM municipal wastewater treatment plant.

2.2. General operation

In the solid phase reactor, water was applied to the waste using the sprinkler system. The leachate was collected in the sub-drain at the bottom of the reactor and re-circulated through the solid bed until a pH level between 5.5 and 6.0 was reached. A low pH indicated the accumulation of volatile fatty acids (VFA) in the leachate. Once the pH was reduced, the liquid was transferred to the UAF reactors where the VFA were utilized by methanogens and converted to biogas. The transfer of leachate was based on a plug-flow approach with a residence time ranging from one to three days.

The feeding process was operated in a batch mode. To feed the UAF reactors, the valves located at the bottom of the solid phase reactor and the UAF reactors were opened. At the same time, the valves located on top of the UAF reactors were opened to transfer the overflow from the UAF reactors to the solid phase. Effluent transfer from the UAF to the solid phase resulted in transport of methanogenic bacteria and inoculation of the solid phase reactor. Once the feeding cycle was terminated, the valves that control this cycle were manually closed and the re-circulation in the solid phase reactor was set and repeated (see Fig. 1). The feeding process of the UAF reactors continued using the batch approach until the pH level in the leachate from the solid phase reactor reached and remained above 7.0. This was indicative of a very low concentration of available VFA to feed the UAF columns for methane generation.

The time for VFA production to start, duration of VFA production, and onset of methane production in the solid phase, were strong functions of reactor temperature, composition of the feedstock, the remaining biodegradable material in the feed stock, the volume of the leachate in the solid phase reactor, the depth of the solid phase feed stock and the permeability of the solid phase feedstock.

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**Fig. 1.** Schematic of the two-phase pilot-scale anaerobic digestion system.
2.3. Sampling and analyses

Temperature, pH, chemical oxygen demand (COD), and gas production rate were measured for the duration of each experiment. Leachate samples were collected daily from the solid phase and the UAF reactors to measure temperature and pH. For on-site measurement of temperature and pH, a portable glass thermometer (mercury, −20 to 150 °C) and a hand-held pH meter were used, respectively. Additional liquid samples were taken periodically to analyze for COD and VFA. These samples were stored at 4 °C until the tests were done in the laboratory. The COD was measured by a digestion colorimetric method (HACH Reactor Digestion Method 8000) using a HACH™ DR/2000 spectrophotometer. VFA concentration was measured as acetic acid equivalent using a standard distillation method (APHA et al., 1989). The gas production rate was measured using wet-tip gas meters (Speece gas meter, Nashville, TN). These positive displacement gas meters measured gas production from the solid phase reactor and the two columns, as shown in Fig. 1. The biogas was released to the atmosphere but gas samples were collected twice per week and analyzed for methane content by gas chromatography (Tracor GC). Other gas components were measured only periodically.

2.4. Feedstock composition

2.4.1. Municipal solid waste (MSW, single feedstock)

The municipal solid waste from New Mexico was analyzed by sampling its various components. A 270 kg sample was obtained from a random curbside collection truck and sorted into the different categories. The organic fraction of municipal solid waste (OFMSW), which will digest, represented about 61% of the total MSW. The OFMSW was composed of approximately 62% paper, 23% food waste, and 15% yard clippings. Table 1 compares the composition of New Mexico MSW to the national average (US EPA, 2002).

A total of 140 kg of unsorted bagged MSW (76.5% dry weight) from City of Las Cruces NM residential route packer truck was weighed and added to the solid phase reactor. The solid phase reactor was subsequently sealed and the digestion process started by applying 380 L of water to the MSW. The amount of water applied was determined experimentally such that after the drainage process was completed, about 15–20% (by volume) of leachate was available for recirculation.

2.4.2. Cow manure (CM, single feedstock)

As preliminary assessment, a small-scale experiment was conducted to evaluate the methane production potential of fresh dairy manure. The feedstock consisted of 187 kg of manure on dry weight basis. In two separate experiments, cow manure was utilized as a single feedstock. The waste was collected from a solids separator at a local dairy in southern New Mexico. This is not whole manure, but is screened material from the milk floor washing. The total dry weight of CM was 667 kg. Water equivalent to approximately 15% of the volume of solid waste was added to the system and the experiment started. The initial volatile solids content (VS) of this waste stream was 81–82%.

2.4.3. Co-digestion of OFMSW and CM (OFMSW + CM)

For this experiment the reactor was loaded with 182 kg of OFMSW (82% dry mass). The OFMSW was a simulated waste mixed according to the composition of the segregated waste stream for the City of Albuquerque, NM. The composition was about 70% paper, 20% food waste, and 10% grass clippings. Eighteen kg of fresh dairy cow manure (25% dry mass) was added to the mix as an additional layer. The ratio of manure to OFMSW was determined such that a C/N ratio of 20/1 was obtained. Four hundred-fifty liters of tap water were added to the solid phase. The resulting composition was 83.7% paper, 18.2% food waste, 9.1% grass clippings, and 9% cow manure. The initial volatile solids content was 89% for the OFMSW and 81–82% for cow manure.

2.4.4. Co-digestion of cotton gin waste (CGW) and cow manure (CGW + CM)

The solid phase reactor was filled with a mixture of 618 kg of fresh cow manure and 521 kg of CGW resulting in a dry weight ratio of 1.5. Previous laboratory experiments had shown that a 1:5 manure to cotton gin trash dry mass ratio resulted in the most rapid co-digestion (Funk et al., 2005). Manure and CGW were placed in the solid phase reactor in alternating layers of approximately 140 kg each. Water equivalent to 15% of the total volume of solid waste was added to the reactor. The initial volatile solids content was 87% for the cotton gin trash and 81–82% for cow manure.

3. Results and discussion

3.1. pH

Fig. 2 shows pH values as a function of time in the solid phase reactor for various experiments. Generally, the pH dropped rapidly at the beginning of each experiment as the easily digestible fraction of organic matter was hydrolyzed and converted to fatty acids. After the initial drop, the pH began to rise gradually as the fatty acids were transferred to the methane phase reactors and were consumed by methanogens. The fluctuation of pH during the experiments was due to the periodic accumulation of fatty acids in the solid phase reactor and the subsequent transfer and consumption of VFA by methanogenesis. The pH values for the single wastes (MSW, CM) gradually increased and stayed high, indicating depletion of VFA in the leachate. The digestion process of the single waste experiments (MSW, CM) was mainly limited to the first 50 days of operation. On the other hand, the pH of the co-digested wastes continued to decrease throughout the experiments after a temporary rise in the early stages. For combined waste, the digestion activities continued for an additional two months resulting in further digestion and gas production.

3.2. Chemical oxygen demand (COD)

Fig. 3 shows the COD concentrations of the solid phase effluent for various wastes. The COD values were high in the beginning and gradually decreased as the COD was consumed by fermenting and methanogenic bacteria. Most of the digestion of single wastes (MSW, CM) was limited to the first 50 days of operation after which the gas production rate was drastically reduced. The co-digested wastes (CGW + CM) had the highest initial COD values due to the high organic matter in the mix. Generally, the final COD measured in the effluent from the solid phase after the digestion process was approximately 5000 mg/L. The VFA constituted
only a fraction of COD in the leachate. Fig. 4 compares the COD and VFA concentrations for the first two weeks of each experiment. The VFA/COD ratio varied from 0.28 (OFMSW + CM) to 0.39 (CGW + CM) with an average value of 0.32.

3.3. Gas production

Gas production rate and total production of biogas are a function of the feedstock’s organic content and biodegradability. The solid phase was inoculated by transferring methanogens from the methane reactors to the solid phase reactor during closed loop for leachate transfer or feeding. Biogas was produced and measured independently in the methane reactors (up-flow anaerobic filters, UAF) as well as in the solid phase reactor by wet-tip gas meters (Fig. 1).

Biogas production, cumulative production, and methane content were measured for each experiment. The results are summarized in Fig. 5 and Table 2. The methane content in the biogas produced in all the experiments ranged between 72.3% and 73.1% by volume. Compared to single-phase systems, which produce biogas with methane content fluctuating between 40% and 60% (Yu et al., 2002), this two-phase reactor resulted to be more efficient in terms of biogas quality.

Anaerobic digestion of MSW started slowly and resulted in eventual standard temperature and pressure (STP) methane gas production of 37 m³/ton of dry waste. The single waste digestion of cow manure resulted in 62 m³ methane/ton of dry waste. The combined OFMSW + CM digestion experiment produced 172 m³ methane/ton of combined dry waste. The co-digestion of CGW + CM produced 87 m³ methane/ton of combined dry waste. The biogas yields in terms of volatile solids (VS) were 30.5, 77.4, 194, and 99.6 m³ of methane per ton of VS loaded for single MSW, single CM, OFMSW + CM, and CGW + CM, respectively.
3.4. Solid residual material

At the conclusion of each experiment, the leachate was drained and the digester cover was removed. The final volume and weight of the residuals were measured and compared to the initial values. Table 3 shows results for the different feedstocks. The weight reductions were found to be 78% for OFMSW + CM, 52% for CGW + CM, and 16% for CM. Similarly, the volume reductions were 98%, 58%, and 18% for OFMSW + CM, CGW + CM, and CM, respectively. For the experiment utilizing MSW as a single feedstock, the weight and volume reduction was less than 10%. The digestion of MSW was severely limited by the plastic bags. This was an unsorted unshredded waste stream intended to be representative of a municipal landfill. The microbes clearly had difficulty accessing the substrate.

4. Conclusions

Single waste anaerobic digestion and co-digestion of municipal solid wastes and agricultural wastes were investigated using a two-phase pilot-scale anaerobic digestion system. The biogas produced in the two-phase anaerobic digestion had a higher methane content (72% or more) than conventional single-phase systems, which typically produce a gas that is 60% methane. The co-digestion of OFMSW and CGW with cow manure utilized intrinsic

### Table 2
Experimental results for different types of feedstock

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MSW 1</th>
<th>CM 1</th>
<th>OFMSW+CM 1</th>
<th>CGW+CM 1</th>
<th>MSW 2</th>
<th>CM 2</th>
<th>OFMSW+CM 2</th>
<th>CGW+CM 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of experiment (days)</td>
<td>113</td>
<td>73</td>
<td>45</td>
<td>141</td>
<td>151</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total biogas produced (m³)</td>
<td>4.0</td>
<td>64.8</td>
<td>17.1</td>
<td>96.6</td>
<td>46.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average methane content (%)</td>
<td>73.1</td>
<td>72.3</td>
<td>72.3</td>
<td>72.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane produced (m³ STP)</td>
<td>2.9</td>
<td>41.8</td>
<td>12.3</td>
<td>54.0</td>
<td>26.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane yield (m³ CH₄/ton dry waste)</td>
<td>37</td>
<td>62</td>
<td>66</td>
<td>87</td>
<td>172</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane yield (m³ CH₄/kg VS)</td>
<td>0.03</td>
<td>0.08</td>
<td>0.07</td>
<td>0.10</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 4. Maximum VFA and COD concentrations in effluent from the solid phase reactor.](image1)

![Fig. 5. Cumulative gas production for different types of feedstock.](image2)
Table 3
Characteristics of feedstock before and after anaerobic digestion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MSW</th>
<th>CM</th>
<th>OFMSW + CM</th>
<th>CGW + CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet weight before digestion (kg)</td>
<td>140</td>
<td>2668</td>
<td>909</td>
<td>200</td>
</tr>
<tr>
<td>Dry weight before digestion (kg)</td>
<td>107</td>
<td>667</td>
<td>187</td>
<td>154</td>
</tr>
<tr>
<td>Weight reduction (%)</td>
<td>8.7</td>
<td>46</td>
<td>40.1</td>
<td>78.3</td>
</tr>
<tr>
<td>Volume reduction (%)</td>
<td>&lt;10</td>
<td>18</td>
<td>21</td>
<td>98</td>
</tr>
<tr>
<td>Initial volatile solids (%)*</td>
<td>NA</td>
<td>81</td>
<td>81</td>
<td>87</td>
</tr>
</tbody>
</table>

* MSW was in unbroken plastic bags no VS measurements were taken. For OFMSW + CM and CGW + CM the VS for each constituent is given in order of constituent in column title.

cellulose degrading bacteria and the additional nutrients in the manure to better digest the fiber in CGW and the paper fraction of OFMSW. Co-digestion of OFMSW and CM has an apparent synergistic effect which overcomes the imbalance in nutrients and improves biodegradation. This effect resulted in higher methane yield compared with anaerobic digestion of cow manure as single waste. In the same manner, co-digestion of CGW and OFMSW with cow manure showed a weight reduction of 52 and 78%, respectively as compared to only 9 and 16% for single MSW and CM, respectively. The same tendency was observed for volume reduction.

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