Anaerobic monodigestion of poultry manure: determination of operational parameters for CSTR

R. Chamy, C. León, E. Vivanco, P. Poirrier and C. Ramos

ABSTRACT

In this work the anaerobic monodigestion for the treatment of turkey manure was evaluated, without its codigestion with another substrate. The effect of the organic loading rate (OLR) and the substrate concentration (high total solids (TS) concentration) or product concentration (high volatile fatty acids (VFA) and/or ammonia (NH₃-N) concentrations) was studied. The results show that for a continuous stirred tank reactor (CSTR) operation, a maximum of 40 g/L of TS and 4.0 g/L of ammonium (NH₄⁺) was required. In addition, the maximum organic loading rate (OLR) will not exceed 1.5 kg VS/m³d. Higher TS and NH₄⁺ concentrations and OLR lead to a reduction on the methane productivity and volatile solids (VS) removal. During the CSTR operation, a high alkalinity concentration (above 10 g/L CaCO₃) was found; this situation allowed maintaining a constant and appropriate pH (close to 7.8), despite the VFA accumulation. In this sense, the alkalinity ratio (α) is a more appropriate control and monitoring parameter of the reactor operation compared to pH. Additionally, with this parameter a VS removal of 80% with a methane productivity of 0.50 m³CH₄/m³Rd is achieved.

Key words | biomethanization, continuous stirred tank reactor, solid wastes, turkey manure

INTRODUCTION

Anaerobic digestion is a biological process, involving different types of microorganisms, which is accomplished by four sequential steps (hydrolysis, acidogenesis, acetogenesis and methanogenesis). In this manner, organic matter is transformed into biogas (mainly made up by methane, 60–70% of the biogas). For the anaerobic treatment of solid wastes, the hydrolytic phase is the limiting step, due to the low solubility and complexity of the residue. Anaerobic digestion of solid wastes is the process that, in most of the cases and due to environmental, energy, economic and legal considerations, is the best way to convert organic matter into value-added products, like methane and stabilized sludge with soil conditioning characteristics, avoiding the disposal of solid waste in a dump or landfill, incineration and composting (Angelidaki et al. 2003; Edelmann 2003).

The continuous stirred tank reactor (CSTR) is the main industrial-scale reactor used due to the simplicity of the process, the reactor operation and the low investment cost. An important parameter in methane production by means of anaerobic digestion (biomethanization) of solid wastes can be the solid content inside the reactor, which will affect the mixing, process dynamics and the reactor feeding method. The appropriate solid concentration inside the reactor will vary between 10 and 50 g/L of TS (Chamy et al. 1998; Angelidaki et al. 2006), which can be accomplished by dilution of the feed, operating the reactor with low OLR or codigesting with other wastes. Operating the digester above these ranges will induce a process destabilization, generating a decrease in both organic matter removal and methane production. This factor will depend on the waste composition and biodegradability, which is linked to the VFA and/or ammonia production, acclimatization and biomass type and the reactor operation conditions (digester type and configuration, temperature and/or pH).

During the anaerobic digestion of animal manure (cattle, pigs and poultry), release of ammonia may occur. High release of NH₃-N induces the inhibition of methanogenic bacteria (Pechan et al. 1987; Angelidaki & Ahring 1993, 1994; Krylova et al. 1997). Therefore, for the anaerobic treatment of manure the common way to avoid inhibition problems by NH₃-N is its codigestion with others wastes, mainly agro-industrial wastes or the organic fraction of the urban solid wastes (Hartmann et al. 2003; Hartmann & Ahring 2005; Karakashev et al. 2005; Gelegenis et al. 2007;
The application of waste codigestion allows the balance of nutritional composition and the carbon/nitrogen (C/N) ratio of the feed (Hartmann et al. 2003; Hartmann & Ahring 2006; Lehtomäki et al. 2007). The appropriate C/N ratio is between 25 and 30, based on biodegradable carbon and total nitrogen (Angelidaki et al. 2003; Hartmann & Ahring 2006), which allows a stable and efficient anaerobic digestion behavior. Lower C/N ratios indicate excess of required nitrogen for the biomass, causing inhibition by NH$_3$-N. Otherwise, when the C/N ratio is above the appropriate value, it becomes nitrogen-deficient, so the anaerobic digestion and biomass synthesis is affected (Angelidaki et al. 2003; Hartmann & Ahring 2006). However, the availability, transport costs and variation of the waste composition to codigest with the manure are the negative factors affecting codigestion, and therefore they prevent the biomethanization of manure. When it has a large amount of breeding birds and there is not enough substrate for codigestion, it is necessary to create the conditions for manure monodigestion.

In this work, the operational conditions for the anaerobic digestion of turkey manure, without its codigestion, were evaluated; considering the behavior evaluation of a pilot-scale CSTR (1.6 m$^3$) at different organic loading rates (OLR), hydraulic retention times (HRT) and substrate concentrations.

**MATERIALS AND METHODS**

**Inoculum**

Anaerobic sludge from an industrial-scale CSTR, used for the sludge treatment of a wastewater treatment plant (activated sludge system) was used as inoculum.

**Waste characteristics**

The waste used was turkey manure (with sawdust), provided by the turkey-breeding farm. The manure was collected, approximately once at month; and it was stored in a cooling chamber (4 °C) to avoid changes in its initial composition. Table 1 shows the waste composition, which was made up by high solid concentration (51.2% [w/w]), from which 71.5% was organic matter, expressed as volatile solids. In addition, it had high ammonium concentration. The chemical oxygen demand (COD) was 1.1 g O$_2$/g TS. The turkey manure also had chips, which is part of the bed on which the turkeys are confined.

**Experimental procedure**

The study was carried out in a 2.0 m$^3$ total volume (1.6 m$^3$ active volume) pilot-scale CSTR. The reactor was made of fiberglass (6.0 mm thickness), a round steel lid (8.0 mm thickness) and carbon steel support. Figure 1 shows the pilot-scale reactor. Heating was automatically fixed at 37 °C. Mixing was maintained at 85 rpm through a gear motor (1 HP power) and the system consisted of a stainless steel central axle with four inclined blades (45°) and 4 fiberglass baffles. The digester is located in Quillota (V Region, Chile), at the Agronomy School of the Pontificia Universidad Católica de Valparaíso. The reactor was inoculated with anaerobic sludge, filling the digester up to the reaction volume (1.6 m$^3$). Then, the reactor was closed and the mixing started. Later, nitrogen gas was injected to remove the oxygen inside the reactor. Once the reactor was loaded with sludge, heating was activated (programmed at 37 °C). The reactor feeding was semi-continuous, i.e., fresh waste was added on a daily basis to the reactor. Five organic loading rates were analyzed (see Table 2). An increase in the OLR produced a decrease of the HRT.

**Analytical methodology**

During the reactor operation, total solids (TS) and volatile solids (VS) were determined periodically according to Standard Methods (APHA/AWWA/WEF 2005). Ammonium (NH$_4^+$) concentration was measured using a selective electrode (Cole-Parner, model: 27502-03). Also the alkalinity ratio ($\alpha$) (ratio of organic acids vs. total alkalinity) was quantified through titration with sulphuric acid (H$_2$SO$_4$) 0.1 N according to Jenkins et al. (1985). The methane and carbon dioxide content were analyzed with gas chromatography (PerkinElmer Clarus 500). The methane and biogas  

<table>
<thead>
<tr>
<th>Density [kg/m$^3$]</th>
<th>TS [% w/w] (wet basis)</th>
<th>VS [% w/w] (dry basis)</th>
<th>Moisture [%]</th>
<th>COD [g O$_2$/g TS]</th>
<th>pH</th>
<th>NH$_4^+$ [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>424.0 ± 4.3</td>
<td>51.2 ± 9.8</td>
<td>71.5 ± 20.3</td>
<td>48.8 ± 8.8</td>
<td>1.1 ± 0.2</td>
<td>5.2 ± 0.6</td>
<td>2.2 ± 0.3</td>
</tr>
</tbody>
</table>
volume was expressed at standard pressure and standard temperature conditions (1 atm and 0 °C).

RESULTS AND DISCUSSION

The anaerobic pilot-scale CSTR was operated continuously for 337 days, feeding only turkey manure. During the entire reactor operation, the pH value was between 7.0 and 8.0, without the requirement of acid or alkali. In Tables 3 and 4, a detailed description of operational conditions and parameters is presented.

Table 2 | Operational parameters

<table>
<thead>
<tr>
<th>Operational parameters</th>
<th>HRT [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLR [kg VS/m³d]</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>192</td>
</tr>
<tr>
<td>1.0</td>
<td>160</td>
</tr>
<tr>
<td>1.5</td>
<td>77</td>
</tr>
<tr>
<td>2.0</td>
<td>55</td>
</tr>
<tr>
<td>2.5</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 3 | Average of the operational parameters (TS and NH₄⁺ concentrations, VS removal, α and methane production) during each OLR studied and their corresponding values achieved for the biomethanization of turkey manure in a pilot-scale CSTR

<table>
<thead>
<tr>
<th>Operational period [d]</th>
<th>OLR [kg VS/m³d]</th>
<th>TS [g/L]</th>
<th>NH₄⁺ [g/L]</th>
<th>VS removal [%]</th>
<th>α</th>
<th>Productivity [m³/m³.d] Biogas</th>
<th>CH₄</th>
<th>Yield [m³/kg VSadded] Biogas</th>
<th>CH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–121</td>
<td>0.5</td>
<td>23.8</td>
<td>1.1</td>
<td>91.5</td>
<td>0.36</td>
<td>0.30</td>
<td>0.21</td>
<td>0.60</td>
<td>0.42</td>
</tr>
<tr>
<td>122–191</td>
<td>1.0</td>
<td>33.5</td>
<td>4.0</td>
<td>87.6</td>
<td>0.31</td>
<td>0.74</td>
<td>0.52</td>
<td>0.74</td>
<td>0.52</td>
</tr>
<tr>
<td>192–280</td>
<td>1.5</td>
<td>57.0</td>
<td>5.3</td>
<td>78.1</td>
<td>0.35</td>
<td>0.83</td>
<td>0.50</td>
<td>0.54</td>
<td>0.32</td>
</tr>
<tr>
<td>281–315</td>
<td>2.0</td>
<td>76.0</td>
<td>6.8</td>
<td>67.7</td>
<td>0.42</td>
<td>0.88</td>
<td>0.19</td>
<td>0.44</td>
<td>0.10</td>
</tr>
<tr>
<td>316–337</td>
<td>2.5</td>
<td>81.2</td>
<td>7.0</td>
<td>66.1</td>
<td>0.47</td>
<td>0.94</td>
<td>0.24</td>
<td>0.38</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Figure 1 | Pilot-scale reactor (2.0 m³) used in the biomethanization of turkey manure.

Organic loading rate

The OLR increase (see Figure 2) produced an increment in biogas productivity, but a decrease in methane productivity, methane production yield and volatile solids removal. This could have been possible because substrate is not fully consumed for methane generation, resulting from the high OLR and/or low HRT to properly degrade the recalcitrant matter in the waste (feathers and sawdust). This finding is consistent with the decrease in organic matter removal. The minimum VS removal was 66% (at 2.5 kg VS/m³d), which was the maximum OLR studied and higher than the value reported for pilot and industrial-scale CSTR (50–58% of VS removal) (Safley et al. 1987; Espinosa-Solares et al. 2006; Kaparaju et al. 2008). The OLR performance of 1.0 kg VS/m³d achieved the maximum methane and biogas production yield (0.52 and 0.74 m³/kg VSadded, respectively), a VS removal of 88% and a methane and biogas productivity of 0.52 and 0.74 m³/m³ R, respectively. The manure biomethanization in mesophilic CSTR is reported with a methane productivity and methane production yield of 0.3–1.0 m³ CH₄/m³ R 0.2–0.5 m³ CH₄/kg VSadded, respectively, for an OLR of 1.1–3.3 kg VS/m³d (Pechan et al. 2005; Safley et al. 1987; Demirer & Chen 2005; Karim et al. 2005a, b; Gelegenis et al. 2007; Lehtomäki et al. 2007), see Table 5. According to what has been already published and for the results obtained, with a low OLR (1.5 kg VS/m³d), an appropriate methane productivity (0.50 m³ CH₄/m³ R) was obtained. This finding could be due to the high VS removal obtained (67.7%), compared to the values reported, allowing the conversion of organic waste into methane.

Total solids concentration

To evaluate the effect of solids concentration inside the reactor, the HRT was reduced and the OLR was increased, which can be seen in Figure 3. An increase in TS...
concentration produced an increase in biogas productivity. At low total solids concentrations (up to 35 g/L of TS) a strong increase in biogas productivity took place. Nevertheless, at high TS concentration (nearly 60 g/L of TS), productivity did not increase intensively. However, the methane productivity decreased with an increase in the total solids concentration inside the reactor. Regarding the methane and biogas production yield and volatile solids

Table 4 | Average of the operational parameters (biogas content, pH, total alkalinity and VFA concentrations) during each OLR studied and their corresponding values achieved for the biomethanization of turkey manure in a pilot-scale CSTR

<table>
<thead>
<tr>
<th>Operational period [d]</th>
<th>Biogas content [%]</th>
<th>Volatile fatty acids [g/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH₄</td>
<td>CO₂</td>
</tr>
<tr>
<td>1–121</td>
<td>70.0</td>
<td>30.0</td>
</tr>
<tr>
<td>122–191</td>
<td>70.0</td>
<td>30.0</td>
</tr>
<tr>
<td>192–280</td>
<td>60.0</td>
<td>40.0</td>
</tr>
<tr>
<td>281–315</td>
<td>22.0</td>
<td>78.0</td>
</tr>
<tr>
<td>316–337</td>
<td>25.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Where: N.D.: not detected.

Figure 2 | OLR effect in the pilot-scale CSTR operation on methane and biogas productivity and yield and VS removal. ◇: biogas, △: methane, □: VS removal.

Table 5 | Manure biomethanization in mesophilic CSTR

<table>
<thead>
<tr>
<th>Manure type</th>
<th>OLR [kg VS/m³d]</th>
<th>HRT [d]</th>
<th>Methane productivity [m³CH₄/m³Rd]</th>
<th>Methane yield [m³CH₄/kg VS added]</th>
<th>COD removal [%]</th>
<th>VS removal [%]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bovine</td>
<td>2.0</td>
<td>20</td>
<td>0.32</td>
<td>0.16</td>
<td>25</td>
<td></td>
<td>Lehtomäki et al. (2007)</td>
</tr>
<tr>
<td>Bovine</td>
<td>3.2</td>
<td>16</td>
<td>0.75</td>
<td>0.23</td>
<td>33</td>
<td>41</td>
<td>Karim et al. (2005b)</td>
</tr>
<tr>
<td>Bovine</td>
<td>4.6</td>
<td>16</td>
<td>0.79</td>
<td>0.17</td>
<td></td>
<td></td>
<td>Karim et al. (2005a)</td>
</tr>
<tr>
<td>Bovine</td>
<td>6.3</td>
<td>20</td>
<td>0.86</td>
<td>0.13</td>
<td>63</td>
<td>43</td>
<td>Demirer &amp; Chen (2005)</td>
</tr>
<tr>
<td>Poultry</td>
<td>2.7</td>
<td>20</td>
<td>0.32</td>
<td>0.12</td>
<td></td>
<td></td>
<td>Gelegenis et al. (2007)</td>
</tr>
<tr>
<td>Poultry</td>
<td>1.1</td>
<td>51</td>
<td>0.29</td>
<td>0.26</td>
<td></td>
<td>73</td>
<td>Pechan et al. (1987)</td>
</tr>
<tr>
<td>Poultry</td>
<td>1.6</td>
<td>23</td>
<td>0.38</td>
<td>0.23</td>
<td></td>
<td>55</td>
<td>Safley et al. (1987)</td>
</tr>
<tr>
<td>Poultry</td>
<td>3.2</td>
<td>20</td>
<td>0.97</td>
<td>0.30</td>
<td></td>
<td>70</td>
<td>Gelegenis et al. (2007)</td>
</tr>
<tr>
<td>Turkey</td>
<td>1.5</td>
<td>77</td>
<td>0.50</td>
<td>0.32</td>
<td></td>
<td>78.1</td>
<td>This study</td>
</tr>
</tbody>
</table>
removal, they decreased at high TS concentrations inside the reactor. Therefore, this situation would indicate a substrate inhibition or problems due to low water activity, with maximum TS concentrations of 40 g/L inside the reactor.

**Ammonium concentration**

During the anaerobic digestion of turkey manure, the ammonium production was high and its concentration inside the reactor was higher than the affluent. The NH$_4^+$ concentration increased at each organic loading rate studied and its effect on methane and biogas production and VS removal can be seen in Figure 4. The increase in ammonium concentration inside the reactor, as a consequence of the increase in the total solids concentration and organic loading rate, shows trends similar to the ones presented by the methane and biogas productivity and yield and VS removal related to the increase in total solids concentration and organic loading rate. When the NH$_4^+$ concentration was higher than 5.3 g/L, there was a lower increase in biogas productivity and an acute decrease of VS removal, methane productivity and of the methane and biogas production yield. This finding indicates that above this concentration, there is an ammonium inhibition and the maximum ammonium concentration inside the reactor is 4.0 g/L.

According to the results, the anaerobic monodigestion of turkey manure is possible up to an organic loading rate of not more than 1.5 kg VS/m$^3$d, without exceeding a TS concentration of 40 g/L inside the reactor, in order to achieve an adequate methane and biogas productivity.

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**Figure 3** | TS concentration effect in the pilot-scale CSTR operation on methane and biogas productivity and yield and VS removal. ◊: biogas, Δ: methane, □: VS removal.

**Figure 4** | NH$_4^+$ concentration effect in the pilot-scale CSTR operation on methane and biogas productivity and yield and VS removal. ◊: biogas, Δ: methane, □: VS removal.
(0.50 and 0.83 m³/m³ d, respectively) an adequate production yield (0.32 and 0.54 m³/kg VS added, respectively) and a high removal (88% of volatile solids). Operating the reactor above this OLR generates high fluctuations (data not shown) and a decrease in the organic matter removal and in methane productivity and production yield. Likewise, a significant increase in biogas productivity was not obtained and volatile fatty acid accumulation occurred, mainly of acetic and propionic acid. When the organic loading rate was between 0.5 and 1.5 kg VS/m³ d, the alkalinity ratio was under 0.4 (see Table 3), which indicates that there was an appropriate VFA consumption. However, when the OLR was 2.0 and 2.5 kg VS/m³ d, the α was 0.42 and 0.47, indicating a volatile fatty acid accumulation. In this way, high organic loading rates produce an extra inhibition through VFA. Furthermore, an important decrease of methane content in the biogas was generated, which varies from 60 to 25%, between the OLR of 1.5 and 2.5 kg VS/m³ d, indicating the failure of the anaerobic digestion process at high organic loading rates.

The factors that can be taken into account in the destabilization of the anaerobic digestion process are total solids and ammonium concentration, whose maximum tolerable concentrations to carry out the biomethanization are 40 and 4.0 g/L of TS and NH₄⁺, respectively. Higher concentrations are harmful for the anaerobic digestion of turkey manure. Therefore, maintaining these ammonium and total solids levels inside the reactor, would be the key factor to have a successful operation in the reactor.

The biomethanization of turkey manure presented a high alkalinity concentration (above 10 g/L) (see Table 4), therefore, this high buffering capacity allowed stabilizing the process in a pH value of 7.8, which is adequate for anaerobic digestion (pH between 7.0 and 8.0). The monitoring of the reactor behavior, with respect to the VFA accumulation, is adequate through the alkalinity ratio, which has a limit of 0.4, to maintain a stable operation and balanced anaerobic digestion process. When organic acid accumulation occurs, an additional inhibition variable is added in the solids biomethanization, due to the acetoclastic methanogenic bacteria (VFA consumers) which are inhibited by their high concentration.

**CONCLUSIONS**

The biomethanization process of turkey manure, based in the performance of a mesophilic pilot-scale continuous stirred tank reactor, can be conditioned by the solids concentration and ammonium release during the anaerobic digestion process. So, if the conditions are maintained to prevent exceeding a concentration of 40 g/L of total solids and 4.0 g/L of ammonium inside the reactor and an organic loading rate of 1.5 kg VS/m³ d, it is possible to achieve the anaerobic monodigestion of turkey manure without its codigestion.

**REFERENCES**


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