Anaerobic digestion of animal waste: 
Waste strength versus impact of mixing 

Khursheed Karim a, Rebecca Hoffmann a, Thomas Klasson b, M.H. Al-Dahhan a,*

a Chemical Reaction Engineering Laboratory (CREL), Department of Chemical Engineering, Washington University, St. Louis, MO 63130, USA
b Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Received 31 March 2003; received in revised form 10 January 2005; accepted 16 January 2005
Available online 2 April 2005

Abstract

We studied the effect of mode of mixing (biogas recirculation, impeller mixing, and slurry recirculation) and waste strength on the performance of laboratory scale digesters. The digesters were fed with 5% and 10% manure slurry, at a constant energy supply per unit volume (8 W/m3). The experiments were conducted in eight laboratory scale digesters, each having a working volume of 3.73 L, at a controlled temperature of 35 ± 2 °C. Hydraulic retention time (HRT) was kept constant at 16.2 days, resulting in a total solids (TS) loading rate of 3.08 g/Ld and 6.2 g/Ld for 5% and 10% manure slurry feeds, respectively. Results showed that the unmixed and mixed digesters performed quite similarly when fed with 5% manure slurry and produced biogas at a rate of 0.84–0.94 L/Ld with a methane yield of 0.26–0.31 L CH4/g volatile solids (VS) loaded. This was possibly because of the low solids concentration in the case of 5% manure slurry, where mixing created by the naturally produced gas might be sufficient to provide adequate mixing. However, the effect of mixing and the mode of mixing became prominent in the case of the digesters fed with thicker manure slurry (10%). Digesters fed with 10% manure slurry and mixed by slurry recirculation, impeller, and biogas recirculation produced approximately 29%, 22% and 15% more biogas than unmixed digester, respectively. Deposition of solids inside the digesters was not observed in the case of 5% manure slurry, but it became significant in the case of 10% manure slurry. Therefore, mixing issue becomes more critical with thicker manure slurry.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Anaerobic; Biogas; Digestion; Draft tube; Manure; Mixing

1. Introduction

Growth in livestock industries has resulted in large amounts of animal waste (cow manure) generation. In the United States over 100 million tons of dry matter is produced every year (Fontenot and Ross, 1980). This has brought in the requirement of safe waste management. Different types of waste management options may include technologies based on physical, chemical, or biological conversions. Examples are combustion/incineration (gasification), chemical conversion (methanol) and biological conversion (anaerobic digestion). Combustion/incineration efficiently recovers the greatest amount of energy from manure, but the practicality of using the ash as a recycled material has yet to be proven. Moreover, self-sustaining incineration requires a waste of about 30% solids. Wetter manure with lower solids content requires supplemental fuel to sustain incineration (OSU, 2000). The possibility of producing methanol production from animal wastes is promising, but there is no specific technology or research is available yet. Anaerobic Digestion is biological means of decomposition of manure in an oxygen-free environment, and has the advantage of producing a fuel gas (methane) and odor free residues rich in nutrients, which can be used as fertilizers.
The performance of anaerobic digesters is affected primarily by the retention time of substrate in the reactor and the degree of contact between incoming substrate and a viable bacterial population. These parameters are primarily a function of the hydraulic regime (mixing) in the reactors. The importance of mixing in achieving efficient substrate conversion has been noted by many researchers, although the optimum mixing pattern is a subject of much debate. Mixing of the substrate in the digester helps to distribute organisms uniformly throughout the mixture and to transfer heat. Furthermore, agitation aids in particle size reduction as digestion progresses and in removal of gas from the mixture. Mixing can be accomplished through various methods, including mechanical mixers, recirculation of digester contents, or by recirculating the produced biogas using pumps.

The two very important aspects of digester mixing are the intensity and duration of mixing. Most of the literature on anaerobic digestion emphasizes the importance of adequate mixing to improve the distribution of substrates, enzymes and microorganisms throughout the digester (Chapman, 1989; Parkin and Owen, 1986; Lema et al., 1991). However, the information available in the literature about the effect of the intensity and duration of mixing on the performance of anaerobic digesters is contradictory. Several studies indicated that a lack of sufficient mixing in low solids digesters dealing with municipal waste resulted in a floating layer of solids (Diaz and Trezek, 1977; James et al., 1980; Stenstrom et al., 1983). Chen et al. (1990) observed higher methane yield in the case of a 4.5 m³ digester under unmixed conditions than continuously mixed conditions. In another study, Ben-Hasson et al. (1985) observed 75% lower methane production rate from dairy cattle manure under continuously mixed conditions than unmixed conditions. On the contrary, Ho and Tan (1985) reported greater gas production for a continuously mixed digester than for an unmixed digester fed with palm oil mill effluents, and Hashimoto (1983) found higher biogas production from beef cattle wastes under continuously mixed conditions than under intermittent mixing conditions. At the same time, Dague et al. (1970), Mills (1979) and Smith et al. (1979) recommended intermittent mixing of anaerobic digesters over continuous mixing. It has been observed that very rapid mixing disrupts the structure of flocs inside a biological reactor which disturbs the syntrophic relationships between organisms, thereby adversely affecting the reactor performance (Whitmore et al., 1987; Dolfing, 1992; Stroot et al., 2001). However, there is no clear information available in the literature about the threshold limits of digester mixing, other than a power input of 0.20–0.30 HP/1000 cu ft (5.26–7.91 W/m³) is recommended by the US EPA for proper digester mixing (US EPA, 1979).

The contradictory findings reported in the literature about the effect of mixing on the performance of anaerobic digesters bring the need of extensive research in this direction. Therefore, the present study was designed to focus on the performance of digesters having three different modes of mixing—biogas recirculation, impeller mixing, and slurry recirculation—keeping same amount of energy applied per unit volume of the waste digested.

2. Methods

The reported study was performed in the three sets of experiments. The first set of experiments was performed with four laboratory scale digesters, Digesters 1–4, each having a working volume of 3.73 L, were operated at a controlled temperature of 35 ± 2 °C. Schematics of the digesters are shown in Fig. 1. Digester 1 consisted of a hopper bottom with a 60° slope angle, because Choi et al. (1996) reported that a 60° double sloped bottom helped in reducing the sedimentation of solids. Digester 2 consisted of a hopper bottom with a 25° slope angle, as this lesser slope angle is easy to construct in the field and requires less earth work. Biogas generated in the digesters was collected in tedlar bags and was recirculated from the top of the digesters by an air pump and draft tube arrangement. The draft tubes were located at mid-height of the hopper bottoms (Table 1). The biogas recirculation rate was kept as 1 L/min, as no significant change in the digester performance was observed with increased biogas recirculation rate up to 3 L/min rate (Karim et al., 2003). Digester 3 had a hopper bottom with a 25° slope angles and was mixed by 62 mm diameter axial flow impeller (Lightnin A-310, Rochester, New York, USA), and the impeller motor was Model 5vb, EMI Inc. (Clinton, Connecticut, USA). Digester 4 had a hopper bottom with a 25° slope angles and was mixed by slurry recirculation. The pump used for slurry recirculation was, a Masterflex pump from Cole Parmer Instrument Co. (Chicago, Illinois, USA).

All four digesters were mixed while keeping a constant energy supply per unit volume of slurry treated (8 W/m³). In the case of digesters mixed by biogas recirculation, power per unit volume was calculated per Eq. (1) (Casey, 1986).

\[
P = \frac{\lambda G_s P_2}{(\lambda - 1)} \left[ \left( \frac{P_1}{P_2} \right)^{\left(\frac{\lambda - 1}{\lambda}\right)} - 1 \right]
\]

where \(P\) is power, \(V\) is the volume of the slurry mixed, \(G_s\) is specific biogas recirculation rate (m³/d m³), \(P_2\) is the head space pressure (equal to 101416.83 N/m² (atmospheric) = 101,325 Pa), \(P_1\) is the pressure at the injection point (i.e., \(P_2 + \) Static head of slurry), and \(\lambda\) is the polytropic exponent. Under isothermal conditions the value of \(\lambda\) approaches unity, while under adiabatic conditions
its value for biogas is approximately 1.3. Since the
digesters in this study were operated at a controlled tem-
perature of 35 ± 2 °C. The value of $\lambda$ was taken as 1.01,
as suggested by Casey (1986).

---

**Table 1**
Operational conditions for the digesters

<table>
<thead>
<tr>
<th>Expt. set</th>
<th>Digester</th>
<th>Mode of mixing</th>
<th>Hopper bottom angle (deg)</th>
<th>Draft tube position from bottom (mm)</th>
<th>Feed manure slurry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Biogas recirculation (1 L/min)</td>
<td>60</td>
<td>48</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Biogas recirculation (1 L/min)</td>
<td>25</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Impeller (275 rpm)</td>
<td>25</td>
<td>NA</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Slurry recirculation (0.82 L/min)</td>
<td>25</td>
<td>NA</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Unmixed</td>
<td>25</td>
<td>NA</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Impeller (275 rpm)</td>
<td>25</td>
<td>NA</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Unmixed</td>
<td>25</td>
<td>NA</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Biogas recirculation (1 L/min)</td>
<td>25</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Impeller (275 rpm)</td>
<td>25</td>
<td>NA</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Slurry recirculation (0.82 L/min)</td>
<td>25</td>
<td>NA</td>
<td>10</td>
</tr>
</tbody>
</table>

* NA: Not applicable.
Keeping the same power input per unit volume of the slurry treated (8 W/m³), the impeller speed for Digester 3 was calculated as 275 rpm, using Eq. (2). The torque applied was determined by a rotating torque meter (Bex-O-Meter, Model 38, The Bex Company, San Francisco, California, USA).

\[ P = \text{Torque (N m)} \times \text{Angular velocity (rpm)} \]  

Similarly, the slurry recirculation rate (0.82 L/min) was decided based on Eq. (3).

\[ P = \rho gHQ \]

where, \( Q \) = discharge (m³/s), \( H \) = head of the slurry (m), \( \rho \) = density of the slurry pumped (kg/m³).

The digesters were inoculated with 373 mL (10% of the total working volume) anaerobic seed sludge collected from an active laboratory-scale digester containing cow manure. The seed sludge had total suspended solids (TSS) and volatile suspended solids (VSS) of 66.13 g/L and 35.63 g/L, respectively. The remaining 90% of the working volume was filled with fresh prepared 5% manure slurry (i.e., having 50 g dry solid per liter of slurry). Manure slurry, having 50 g dry solid per liter, was considered for this study knowing the fact that dairy manure “as excreted” has approximately 12% total solids (TS) and 10.5% volatile solids (VS), while most of the treatment systems operate at a lower solids concentration than the “as excreted” values (Burke, 2001). The raw cow manure was collected fresh (less than 2 days old) from University of Tennessee Institute of Agriculture, Tennessee and stored in a freezer. It was verified that the cows were not receiving any antibiotic treatment, as some of the antibiotic treatments limit the viability of methane generating microorganisms in their manure (Masse et al., 2002). The waste slurry was prepared from the collected raw manure after blending, screening, settling and dilution. The blending of the manure was done at 10,500 rpm for 2 min in a household blender to break big pieces of wood, straw and hay, and to create the slurry. Later on, an equal volume of water was added to the blended slurry to dilute it and then it was screened through a 2 mm sieve, followed by settling for one hour to remove sands. After total solids for the prepared slurry were determined, it was then diluted with tap water to achieve the required solid concentration (50 g TS/L). The characteristics of the prepared feed slurry are given in Table 2.

Digester 1 and 2 were started simultaneously, whereas Digesters 3 and 4 were started after 48 days due to late procurement of fittings. Hydraulic retention time (HRT) was kept constant at 16.2 days, resulting in a total solids loading rate of 3.08 g/Ld (2 g volatile solids/Ld) for all four digesters. Effluent (460 mL) was taken out from the bottom of the digesters on alternate days and fed with same amount of freshly prepared cow manure slurry.

Since, there were no replications, digesters were operated under steady-state conditions for a long period (approximately three to four weeks) for statistical comparison. However, a second set of experiments, as explained in the following paragraph, was conducted to check the reproducibility of the digester performance. Steady-state conditions were considered achieved when the variation in biogas production and total COD (chemical oxygen demand) concentration in the effluent was within 15% of the average value (Haghighi-Podeh et al., 1995).

The second set of performance experiments was conducted to compare the performance of mixed and an unmixed digesters, as well as to check the reproducibility of the performance data obtained in the first set of experiments. Two 3.73 L working volume digesters, Digesters 5 and 6, with 25° hopper bottom (Table 1), were operated for approximately two months. One of the digesters was unmixed and the other was mixed by impeller at 275 rpm. All other conditions were kept the same, as described in the first set of experiments.

Later, a third set of experiments was conducted to evaluate whether mixing becomes more important with an increase in the TS concentration in the animal waste slurry. To evaluate this, four digesters, Digestor 7 (unmixed), Digestor 8 (biogas mixed), Digestor 9 (impeller mixed) and Digestor 10 (slurry recirculation), of 3.73 L working volume and with 25° hopper bottom, as mentioned in Table 1, were operated for approximately 120 days. The digesters were fed with 10% (i.e., 100 g TS/L) manure slurry, resulting in TS and VS loadings of 6.2 g/Ld and 3.2 g/Ld, respectively, until the 71st day. Thereafter a more dilute manure slurry (3.5%) was fed for four feeding days to destabilize the digesters, followed by continuation of 10% manure slurry feed till the end of the study. The digesters were destabilized to study the recovery process and to check the reproducibility of their performance. The feed slurry was

### Table 2

Characteristics of the prepared feed, 5% and 10% manure slurry

<table>
<thead>
<tr>
<th>Feed manure slurry (%)</th>
<th>TS a (g/L)</th>
<th>VS a (g/L)</th>
<th>TSS a (g/L)</th>
<th>VSS a (g/L)</th>
<th>TCOD a (g/L)</th>
<th>DCOD a (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>51 ± 1</td>
<td>34 ± 2</td>
<td>37 ± 5</td>
<td>25 ± 3</td>
<td>58.7 ± 4</td>
<td>19.6 ± 1</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>52.6 ± 3</td>
<td>40 ± 8</td>
<td>36 ± 7</td>
<td>61 ± 10</td>
<td>15 ± 2</td>
</tr>
</tbody>
</table>

* TS = total solids, VS = volatile solids, TSS = total suspended solids, VSS = volatile suspended solids, TCOD = total chemical oxygen demand, DCOD = dissolved chemical oxygen demand, NA = not available, ± shows the standard error.
prepared per the procedure described for the first set of experiments. Input power density for the mixed digesters was kept the same as used in the first set of experiments (8 W/m$^3$).

Feed and effluent samples were analyzed for total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), volatile fatty acids (VFA), total chemical oxygen demand (TCOD), dissolved chemical oxygen demand (DCOD), and total nitrogen (TN). Total volume of the biogas generated was measured, and the composition of the biogas was analyzed three times a week. All analyses were performed per standard procedures (APHA, 1998), unless otherwise mentioned.

Volatile fatty acids (formic, acetic, propionic, butyric, and valeric acids) were determined by centrifuging a small sample at greater than 10,000 rpm for 5 min, filtering the liquid through a 0.2-μm-pore-size filter, and injecting a 10 μL sample into a high pressure liquid chromatograph (HPLC). In the HPLC, the mobile phase (filtered 5 mM H$_2$SO$_4$) was pumped at 0.6 mL/min through a 300 mm × 7.8 mm (8 μm particle size) RHM Monosaccharide column (Phenomenex, Torrance, CA), held at a temperature of 65 °C, to a refractive index detector (Model 2410, Waters Corporation, Milford, MA) held at a temperature of 40 °C.

Biogas volume was measured using wet gas test meters (GSA/Precision Scientific, Chicago, Ill), and the samples (1 mL) for biogas composition were collected using a gas-tight syringe. The samples were injected in duplicate into a Gow-Mac (Model 69-350 Series, Lehigh Valley, PA) gas chromatograph (GC) equipped with a 6 ft × 1/8 in., 80 × 100 Hayeseyp Q, S.S. packed column (Supelco, USA). The oven, injector and thermal conductivity detector (TCD) temperatures were kept as 45, 90 and 110 °C, respectively. The carrier gas (helium) flow rate through the column was maintained as 30 mL/min. Initially, the GC was calibrated with 99.9% pure methane (CH$_4$) and nitrogen standards.

Average steady-state data and the standard error presented in the paper have been calculated as a mean value over 20–30 days of observations. Statistical significance ($P = 0.05$) of the experimental data was tested using one way ANOVA statistical program (Microsoft Excel 2002).

### 3. Results and discussion

#### 3.1. First set of experiments (Digesters were fed with 5% manure slurry)

Four laboratory scale digesters, fed with cow manure slurry, were continuously operated over a period of approximately 108 days. Initially there was variation in the performance of the four digesters, however it decreased with time. All four digesters behaved quite similarly as shown in Table 3. Total solids and volatile solids reduction was approximately 37–40% and 50–63%, respectively, in all four digesters. Total COD in the feed was approximately 58.7 g/L, approximately 33% of which was present in the form of dissolved COD. The reduction of TCOD was observed as 56%, 58%, 57%, and 56% for Digesters 1–4, respectively. The effluent DCOD concentration from the digesters was observed at 3.7–4.2 g/L, showing approximately 79–81% reduction in the DCOD in the digesters under steady state conditions. Better reduction of DCOD is quite obvious as the dissolved substrate would be more readily available for bacterial attack. The nitrogen component of the influent slurry under anaerobic conditions remained unchanged. Volatile fatty acids concentrations in the effluents from the digesters were observed as less than 250 mg/L with pH in between 7 and 7.8.

The average biogas production rates for Digesters 1–4 were 0.84 ± 0.1, 0.94 ± 0.07, 0.88 ± 0.09, and 0.85 ± 0.09 L/L.d with methane content as 62 ± 3, 56 ± 3, 61 ± 3, and 67 ± 2%, respectively. The biogas production rate was calculated as volume of biogas produced per liter of digester volume per day and averaged over a period of more than 30 days (86th day onward). The biogas production rate data shows that Digester 2 produced slightly more biogas than the other digesters, but the corresponding methane content was found to be lower in comparison, probably due to infiltration of air, which was observed to be up to 18% in the case of Digester 2. It is worthwhile mentioning that biogas circulation in laboratory digesters increases the chances for infiltration of air into the system (due to slight air permeability of tubing, leakage on the vacuum side of the air pump, etc.). Average steady-state performance

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Average steady-state feed and effluents characteristics data, averaged over last 30 days, for 5% feed slurry study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS (g/L)</td>
</tr>
<tr>
<td>Feed</td>
<td>51 ± 1</td>
</tr>
<tr>
<td>Digester 1</td>
<td>31 ± 3</td>
</tr>
<tr>
<td>Digester 2</td>
<td>30 ± 4</td>
</tr>
<tr>
<td>Digester 3</td>
<td>32 ± 2.5</td>
</tr>
<tr>
<td>Digester 4</td>
<td>31 ± 3.8</td>
</tr>
</tbody>
</table>

$^a$ TN = Total nitrogen, ± shows the standard error.
data of the four digesters were found to be quite similar. However, to elucidate further, the data were subjected to analysis of variance (ANOVA). There was no significant difference for TCOD reduction at the 5% level ($P = 0.68, F = 0.5, F_{crit} = 2.75, df = 3, 60$) for the four digesters. The ANOVA test was also performed for biogas production rate for the four digesters, and it was observed that the value does not differ significantly at the 5% level ($P = 0.05, F = 2.6, F_{crit} = 2.77, df = 3, 56$). Similar results were observed for other parameters.

Volume of biogas produced per unit weight of VS removed was calculated as 0.68–0.84 L. This value compares well with the reported value of 0.7 L/g VS removed, reported by Persson et al. (1979). Methane yield was calculated based on the mass of the VS added every day; it was observed to be 0.21–0.27 L/g VS added. It is important to note that the VS loading in the present study was 2 g/Ld. The observed methane yield is in accordance with a reported methane yield of 0.376 L/g VS added, observed at a loading of 2.86 g VS/Ld (Linke, 1997).

3.2. Second set of experiments (Digesters were fed with 5% manure slurry)

Results of the second set of performance studies, including stagnant and impeller-mixed digesters, showed no significant difference in their start-ups and performance. Unmixed and impeller-mixed digesters produced biogas at a rate of 0.84 ± 0.07 and 0.93 ± 0.09 L/Ld. Their methane contents were 64 ± 3% and 66 ± 2%, respectively. The impeller-mixed digester produced slightly more biogas (approximately 10%) than the unmixed digester. To elucidate further, steady-state biogas production rates of the two digesters were subjected to analysis of variance (ANOVA). At the 5% level, the two sets of data varied significantly ($P = 0.036, F = 5.04, F_{crit} = 4.35, df = 1, 20$). However, the probability of the difference occurring due to random error in the measurement was 3.6%. Thus the difference recorded in the biogas production rate of the two digesters was more probably due to random error than the effect of mixing. The methane yield, calculated based on the weight of the VS added every day, was 0.27 and 0.31 L/g VS added for the unmixed and impeller-mixed digester, respectively.

To show the reproducibility of the laboratory scale digester performance, the daily biogas production data of Digester 6 (impeller-mixed) was plotted with the one operated during first set of experiments (Digester 3) in Fig. 2. The figure shows that the second set of experimental data matches very well with the first set of experiments. ANOVA of the daily biogas production data for whole operational period at the 5% level showed no significant difference in the two cases ($P = 0.95, F = 0.003, F_{crit} = 4.04, df = 1, 48$). The average steady-state biogas production rates for the impeller-

mixed digester in the first and second sets of experiments were 0.88 L/Ld and 0.93 L/Ld, which is within 6% error. In sum, the performance of the impeller-mixed digester was successfully reproduced, and thus the data observed during the ongoing study is reproducible.

3.3. Third set of experiments (Digesters were fed with 10% manure slurry)

The third set of experiments was conducted with four digesters, Digester 7 (unmixed), Digester 8 (biogas mixed), Digester 9 (impeller-mixed) and Digester 10 (slurry recirculation). The goal was to study whether the role of mixing becomes more important with increase in the total solids concentration in the animal waste slurry. The average steady-state data calculated over a period of 30 days (from Day 41 to Day 71) of TS, VS, TSS, VSS, TCOD, and DCOD in the feed and effluents are given in Table 4. The data show that during steady state period, Digesters 7–10 had a VS removal efficiency of 35%, 39%, 41% and 35%, respectively, while TS removal was in between 41% and 49%. However, the data presented in Table 4 do not clearly show the superiority of any of the digesters.

Daily biogas production from Digesters 7 to 10 along with the TS and VS concentrations in the used feed slurry have been shown in Fig. 3. Digester 10, equipped with slurry recirculation, seems to have produced more gas than any of the other digesters, while the unmixed digester (Digester 7) produced the least. Average steady-state data were calculated over a period of 30 days (from Day 41 to Day 71). ANOVA of the daily biogas production data for the steady-state period at the 5% level showed significant difference among the digesters ($P = 4.41 \times 10^{-7}, F = 14.4, F_{crit} = 2.76, df = 3, 56$). The steady-state biogas production rates for Digesters 7–10 were calculated as 0.93 ± 0.1, 1.07 ± 0.08, 1.14 ± 0.13 and 1.2 ± 0.14 L/Ld. The methane contents were 66 ± 3,
65 ± 4, 65 ± 3 and 66 ± 4, respectively. The above data show that the slurry recirculation digester (Digester 10) had the highest biogas production rate, and the unmixed digester produced biogas at a rate almost 22% less than Digester 10 (Fig. 3). Digester 8 (mixed by biogas recirculation) produced biogas approximately 10% less than Digester 10 (slurry recirculation). However, ANOVA shows that there was no significant difference ($P = 0.26$, $F = 1.31$, $F_{crit} = 4.22$, df = 1, 26) between the biogas production rates of Digester 9 (impeller-mixed) and Digester 10 (slurry recirculation). Methane yield was observed to be 0.19, 0.21, 0.23 and 0.24 L/gVS added for Digesters 7–10, respectively (Table 5).

After steady-state data had been collected for 30 days, the digesters were fed with a more dilute manure slurry (3.5%) in between the 71st and 79th days to perturb the digesters. Thereafter, the digesters were fed with normal 10% manure slurry feed till the end of the study. With the change in feed slurry concentration, all four digesters became unstable and produced less biogas. However, the effect of perturbation was greater in the case of unmixed digester in comparison to mixed digesters, as the biogas production for the unmixed digester dropped severely as shown in Fig. 3. Upon continuation of normal 10% feed slurry, the mixed digesters started recovering, although it took almost 10 days longer for unmixed digester to return to the earlier performance level. These results show that the mixed digesters were better able to handle a sudden change in the influent slurry than the unmixed digester. However, after recovery, all four digesters reached their earlier methane yield level of 0.18–0.25 L CH$_4$/gVS loaded (averaged over the 103rd–120th day), showing the consistency of the reported performance data.

### Table 5

Biogas production rate, methane yield and methane productivity for the digesters under steady-state conditions

<table>
<thead>
<tr>
<th>Set of exp.</th>
<th>Digester</th>
<th>Mode of mixing</th>
<th>VS loading (g/L)</th>
<th>Biogas production rate (L/Ld)</th>
<th>Methane yield (L CH$_4$/gVS loaded)</th>
<th>Methane productivity (L CH$_4$/gVS consumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Biogas recirculation, 60° hopper bottom</td>
<td>2</td>
<td>0.84 ± 0.1</td>
<td>0.26 ± 0.03</td>
<td>0.53 ± 0.06</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Biogas recirculation, 25° hopper bottom</td>
<td>2</td>
<td>0.94 ± 0.07</td>
<td>0.26 ± 0.02</td>
<td>0.43 ± 0.03</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Impeller</td>
<td>2</td>
<td>0.88 ± 0.09</td>
<td>0.27 ± 0.03</td>
<td>0.44 ± 0.04</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Slurry recirculation</td>
<td>2</td>
<td>0.85 ± 0.09</td>
<td>0.26 ± 0.03</td>
<td>0.44 ± 0.05</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Unmixed</td>
<td>2</td>
<td>0.84 ± 0.07</td>
<td>0.27 ± 0.02</td>
<td>0.73 ± 0.06</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Impeller-mixed</td>
<td>2</td>
<td>0.93 ± 0.09</td>
<td>0.31 ± 0.03</td>
<td>0.77 ± 0.07</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Unmixed</td>
<td>3.24</td>
<td>0.92 ± 0.1</td>
<td>0.19 ± 0.02</td>
<td>0.53 ± 0.06</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>Biogas recirculation</td>
<td>3.24</td>
<td>1.07 ± 0.08</td>
<td>0.21 ± 0.02</td>
<td>0.55 ± 0.04</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>Impeller</td>
<td>3.24</td>
<td>1.14 ± 0.13</td>
<td>0.23 ± 0.03</td>
<td>0.55 ± 0.06</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>Slurry recirculation</td>
<td>3.24</td>
<td>1.20 ± 0.14</td>
<td>0.24 ± 0.03</td>
<td>0.69 ± 0.08</td>
</tr>
</tbody>
</table>

± shows the standard error.
3.4. Discussion

In this investigation of different modes of mixing with 5% feed slurry (loading = 2 g VS/L.d), the two different bottoms and three different modes of mixing did not significantly affect the digesters performance. Mechanical mixers are reported to be most efficient in terms of power consumed per gallon mixed (Brade and Noone, 1981). Obviously the digester mixed by an impeller would have had better mixing than the others, although they all behaved the same. In the case of 10% feed slurry the impeller-mixed digester produced approximately 10% more biogas than the unmixed digester. However, this difference was more probably due to random error than the effect of mixing, as ANOVA showed a probable random error difference in the measurement of 3.6%. Moreover, the 10% difference in biogas production was not very significant, especially when the steady-state is considered as 15% variation from the mean daily biogas production. Therefore, mixing had almost negligible effect on the digester performance in the case of digesters fed with 5% manure slurry. A similar finding was observed in a previous study conducted with 5% manure slurry in unmixed and biogas mixed digesters (Karim et al., 2003).

The above findings raise questions of whether the 16.2 days HRT was long enough for the microorganisms to assimilate whatever organics were readily available or if the mixing intensity was not high enough to play a role. To answer the first question, one should conduct a similar study at different HRTs. Linke (1997) conducted studies with cattle and pig waste slurries in a 2.5 L mechanically stirred digester (working volume 2.3 L) at different HRTs, and observed that the methane production rate (L/Ld) increased with reduced HRT, but methane yield (L/g VS added) decreased almost linearly. Since energy production and disintegration of organic matter have priority, Linke (1997) suggested an HRT range of 10–15 days. The answer to the second question is no. Stafford (1981) conducted an extensive study on a laboratory scale digester (3 L volume) to see the effect of eight different stirring rates (140–1000 rpm) on biogas production in an anaerobic digester fed with primary sewage sludge. The digester was fed with primary sewage sludge, keeping the HRT at 10 days. He concluded that as the stirring rate was increased from 140–1000 rpm, the average gas production decreased by approximately 12%. Further, Ghaly and Ben-Hassan (1989) observed higher biogas production rates in a 25 L unmixed digester fed with dairy manure than in a completely mixed digester. However, only further study can reveal if the role of mixing becomes favorable with the increase in TS concentration in the feed slurry.

Another reason for conducting the second set of experiments was to check the reproducibility of the laboratory scale digester performance. The daily biogas production data of impeller-mixed digesters from the first and second set of experiments (Digesters 4 and 6) show that statistically (at the 5% level) there was no significant difference for the whole operational period ($P = 0.95$, $F = 0.003$, $F_{crit} = 4.04$, df = 1, 4.8). Similarly, the biogas production rate and methane yield observed for the unmixed digester (Digester 5) in this study (0.8 L/Ld and 0.27 L/g VS loaded, respectively) are comparable to the earlier observed biogas production rate and methane yield (0.7 L/Ld and 0.29 L/g VS loaded, respectively) for an unmixed digester fed with manure 5% manure slurry at 16.2 days HRT (Karim et al., 2003). Therefore, the performance of the digesters reported in this paper is consistent and reproducible.

The results obtained from the first and second set of experiments did not show a significant effect of mixing or mode of mixing under the studied experimental conditions with 5% manure slurry. However, the role of mixing becomes more significant with an increase in TS concentration in the feed slurry, as observed from the third set of experiments. Statistical analysis (ANOVA) of the biogas production rate for the steady-state period (from day 41 to day 71) showed significant difference among the digesters at the 5% level ($P = 1.26 \times 10^{-7}$, $F = 15.8$, $F_{crit} = 2.76$, df = 3, 58), with 0.08 as the least significant difference value. Thus the unmixed digester’s biogas production rate was significantly different from all other digesters. The above data further show that the slurry recirculation digester (Digester 10) had the highest biogas production rate. The slurry recirculation digester (Digester 10) produced approximately 29% more biogas than the unmixed digester (Digester 7). The impeller-mixed digester (Digester 9) produced approximately 22% more biogas than the unmixed digester (Digester 7), but there was no significant difference in the biogas production for the impeller-mixed digester and the slurry recirculation digester (at the 5% level, $P = 0.26$, $F = 1.31$, $F_{crit} = 4.22$, df = 1, 26). The biogas mixed digester (Digester 8) produced approximately 15% more biogas than the unmixed digester (Digester 7). Therefore, the results show that when thicker manure slurry (10%) was fed, mixing improved the biogas production. We conclude that the role of mixing becomes more important with an increase in TS concentration in the feed slurry.

So far as the mode of mixing is concerned, at the 5% level significant difference was observed ($P = 0.03$, $F = 3.77$, $F_{crit} = 3.22$, df = 2, 41). Statistically, there was no significant difference in the biogas production for the slurry recirculation digester and the impeller-mixed digester, as mentioned earlier. However, the biogas production for the slurry recirculation was significantly higher than that of the biogas mixed digester. The above mentioned statistical comparison of the biogas production for the digesters mixed by slurry
recirculation, impeller and biogas shows that the probability of the difference occurring due to random error in the measurement is 3.6%. Thus the difference recorded in the biogas production rate of the three cases was more probably due to random error than the effect of mixing. The high biogas production in the case of the slurry recirculation digester can also be attributed to the fact that the particles, chunks and flocs were exposed to higher shear and were crushed while passing through the hub of the recycling pump used. However, to provide quantitative information about the differences in degree of mixing, level of stagnancy, shear level inside the digesters, etc., one needs to conduct hydrodynamic studies as explained elsewhere (Karim et al., 2004).

The biogas production rates, methane yields and methane productivities observed during the studies reported in this paper are summarized in Table 5. Methane yield is defined as the volume of methane produced per unit weight of VS loaded, while methane productivity is defined as the volume of methane produced per unit weight of the VS consumed. Biogas production rate increased with an increase in the TS concentration in the feed slurry, while the methane yield decreased (Table 5). These results are as expected as with the increase in solid concentration, the slurry loading increased, and thus the microorganisms had less time to degrade per unit waste. Similar observations were also reported by Linke (1997). It is further evident from the data given in Table 5 that the methane productivity for the digesters varied between 0.43 and 0.77 (i.e., 0.37–0.66 at standard temperature and pressure) without a clear trend. It is reported that dairy cattle manure should theoretically give a methane productivity of 0.469 L/g VS destruction (Moller et al., 2004). In another study, Harikishan and Sung (2003) observed 36–41% VS reduction in cattle waste in a temperature phased anaerobic digester, with a methane productivity of 0.52–0.62 L methane/g of VS destroyed, at a loading rate of 1.87–5.82 g VS/Ld. It is important to note that methane productivity will differ with the type of animal and type of fodder used, and thus will vary with the manure collected from different farms. For the present study the manure was collected from the same farm but at different times; however, all different digesters used for a particular set of experiments received the same manure slurry, though in some cases their values differ significantly from others. For example, the methane productivity of Digester 1 is different from Digesters 2 to 4, and the methane productivity for Digester 10 is different from that of Digesters 7–9 (Table 5). This difference seems to be because of different degrees of mixing (or level of settling/stagnancy) inside the digesters. Since the effluents were taken from the bottom of the digesters, settled volatile solids came out with the effluent giving a higher VS value than were actually present inside the digester, and giving lower VS removal efficiency and higher methane productivity values than the actual ones. As in the first set of experiments, the 60° hopper bottom (Digester 1) provided better settling of solids than did the 25° hopper bottom (Digesters 2–4). Therefore, Digester 1 gave significantly low VS reduction (47%) than Digesters 3–4 (59–61%), though the biogas production rate does not vary much (Table 5). Similarly, Digester 10 in the third set of experiments showed less VS reduction (32%) than Digester 7 (35%), though the biogas production rate of Digester 10 was approximately 22% more than Digester 7 (Table 5). However, a flow imaging technique needs to be used to characterize the flow patterns inside these digesters, as explained elsewhere (Karim et al., 2004). Therefore, methane productivity is not a very reliable parameter for comparing the performance of digesters other than CSTR.

One of the roles of mixing inside digesters is to avoid stratification and accumulation of inert solids, especially if the feed manure has a high concentration of inert solids, such as sand (from bedding). Solids accumulation inside any digester can be judged from the mass balance of TS and VS. From Tables 3 and 4 it can be seen that the amount of TS removed is very much close to the amount of VS removed, and thus there was insignificant accumulation of solids inside the digesters. However, in the third set of experiments (with 10% feed slurry), the amount of TS reduced is almost twice the amount of VS reduced (Table 4). Clearly inert solids accumulated inside the digesters. For confirmation, the digesters were opened after completion of the study, and the bulk liquid was gently poured out, and the deposits were analyzed for TS and VS. It was observed that the Digesters 7–10 was having approximately 337, 205, 260 and 190 g deposits (dry weight), which had approximately 23%, 9%, 5% and 6% VS, respectively. However, the bulk liquid had a TS concentration of 71, 59, 64 and 57 g/L TS with 52%, 57%, 53% and 59% VS for Digesters 7–10, respectively. These results show that the unmixed digester had more deposits and with a high percentage of VS than the mixed digesters. The deposits in the mixed digesters were mostly inert sand. This suggests that stratification and deposition were not problems when more dilute feed slurry (5%) was used, but mixing does become important to avoid stratification/deposition with an increase in the TS concentration in the feed slurry. Stratification will become more critical with an increase in scale of the digester, as it will ultimately reduce the effective volume of the digester and lead to digester’s failure. This brings to the attention the need of inert solids removal prior to the slurry being fed to the digester. Alternatively, there should be a proper arrangement such as scraper and a properly designed effluent port for settled solids removal at the bottom of the digesters. Of the three modes of mixing used, impeller-mixed and slurry recirculation gave better biogas production rate and methane
yield. However, biogas recirculation seems to be a promising option, considering the fact that pumping of thick slurry is not an easy task and the energy requirement for impeller mixing increases in orders of magnitude with the size of the digester.

4. Conclusions

Mixing did not improve the performance of the digesters fed with more dilute (5%) manure, as both unmixed and mixed digesters (energy input of 8 W per m$^3$ volume) performed the same under the studied conditions. Thus, there was no difference in the performance of digesters fed with 5% manure slurry and mixed by different modes of mixing, including biogas recirculation, impeller mixing, and slurry recirculation. However, the effect of mixing and the mode of mixing (at constant energy input of 8 W per m$^3$ volume) became prominent when digesters were fed with thicker manure slurry (10%). With this feed the unmixed digester produced the least biogas. The digesters fed with 10% manure slurry and mixed by slurry recirculation, impeller mixing and biogas recirculation produced approximately 29%, 22% and 15% more biogas than the unmixed digester. Solids deposition and stratification were not observed to be problems with more dilute manure slurry (5%), but became significant when thicker manure slurry (10%) was fed to both unmixed and mixed digesters. However, mixing seems help segregate volatile solids from inert solids, which would help to keep light weight biodegradable deposits at the top of the heavier inert deposits, furthering biodegradation. Based on the findings of this study, it can be concluded that mixing becomes more critical with thicker manure slurries.

Acknowledgement

The authors thank the United States Department of Energy for sponsoring the research project (Identification Number: DE-FC36-01GO11054).

References


