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0273-2289/1559–0291 (Online)/07/136–140/765–776/$30.00

Thermophilic Anaerobic Digester Performance Under Different Feed-Loading Frequency

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Abstract

The effect of feed-loading frequency on digester performance was studied on a thermophilic anaerobic digester with a working volume of 27.43 m^3. The digester was fed 0.93 m^3 of chicken-litter slurry/d, containing 50.9 g/L chemical oxygen demand. The treatments were loading frequencies of 1, 2, 6, and 12 times/d. The hourly pH, biogas production, and methane percent of the biogas were less stable at lower feed frequencies. There was no statistical difference among treatments in methanogenic activity. The feed-loading frequency of six times per day treatment provided the greatest biogas production.

Index Entries: Biogas; chicken litter; digester stability; methane; methanogenic activity; thermophilic.

Introduction

Feed input may be the most important factor in optimizing process control of an anaerobic digester. Feed-input volume, and concentration must be monitored and controlled carefully to ensure stable and efficient operating conditions. Although daily total carbon and total volume inputs into a digester have the greatest effect on digester efficiency, the frequency of feed input events within 1 d also affect performance. Kim et al. *(1)* studied process stability at different temperatures, mixing regimes, and feed frequencies. Biogas production from a single phase, mixed thermophilic laboratory digester continuously fed dog food slurry, yielded 16% more gas compared with the same type of digester fed only once per day.

Feeding events change several physical and biochemical parameters in the digester. Oxygen, carbon, volatile fatty acids, and other materials that affect

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anaerobic microbes are introduced. Buhr and Andrews *(2)* reviewing the work of Golueke *(3)* reported the cyclic nature of a digester fed once per day. At 50°C, biogas release peaked sharply at the time of feed entry, then sharply decreased followed by a gradual increase over the following 24 h CO_2 release, partially caused by temperature reduction, and pH drop, because violative fatty acids (VFA) in the feed, were observed. An increase in biogas production throughout the day corresponded with a decrease in digester volatile acids concentration and an increase in digester pH compared with the time of feed input.

If the feed is not heated to or above digester-media temperature before input, a temperature reduction will occur. In a system using an external heat exchanger with a pump, the microbial consortia can be affected. For example, it has been documented that enzyme deactivation depends on mixing conditions *(4)*. Excess shear force resulting from digestate being passed through a pump for long periods of time or by overmixing can disrupt the microbial communities dependant on each other for fermentation. Shigematsu et al. *(5)* worked with mesophilic acetate-degrading methanogenic consortia under continuous cultivation. They reported fluorescence *in situ* hybridization revealed dilution rate that modifies the consortia structure. Additionally, Sheng et al. *(6)*, studying the role of extracellular polymeric substances (EPS) on the stability of sludge flocs under shear conditions, have shown that external layers are easily dispersible by shear forces, whereas the inner component is more stable.

For digester process control, feed input is the most important and simplest parameter to manage. More frequent feed events could allow more flexibility to change input to maintain steady-state conditions. Investigations at the West Virginia State University (WVSU, WV), Bioplex pilot-plant reactor have shown repeatable pH, biogas production, and biogas composition responses to changes in feed concentration and input volume *(7)*. The goal of the current research is development of supervisory software that uses online real time feedback from a pH meter, biogas flowmeter, and gas chromatograph to adjust and control feed input based on feedback parameters. Considering that studies regarding feed-frequency influence on anaerobic digestion performance in available literature are limited, the purpose of this article is to test the effect of different feed frequencies on performance and stability in a thermophilic digester fed poultry-litter. The results will be used by our research team to define the feed frequency for the supervisory software trials.

Materials and Methods

Experiments were carried out at the facilities of the Bioplex Project at WVSU. Diluted chicken-litter slurry was fed automatically into a 40-m^3 tank. The digester was operated in a semicontinuous process, being fed with fresh slurry every 24, 12, 4, or 2 h. The hydraulic retention time (HRT) was 29.5 ± 1.7 d. During the experiments, the slurry volume inside the tank was kept at 27.43 ± 0.06 m^3. The fermentation media in the digester was mixed through pumping the medium, for temperature control, and bubbling biogas. The digester liquid was pumped through an external heat exchanger and recirculated back into the digester when internal digester temperature fell 0.1°C less than target. A gas blower extracted biogas from the top of the digester and recirculated the gas through a bubbling ring located at the bottom of the digester. According to the previous work, pumping could recycle close to six times the volume of the tank in 24 h as the bubbling rate was 0.01 gas volume/liquid volume/min, operating for 5 min every 60 min. In such conditions, pumping and bubbling, respectively, played the main roles in mixing and gas release from the liquid phase *(7)*. The digester operated under thermophilic conditions (56.7°C). The fermentation media was automatically heated when digester internal temperature fell below target. A pump recycled the work fluid (water and ethylene glycol mixture) for the heat exchanger. The digester effluent was discharged into a 5700-L sedimentation tank. The biogas flowed out by pressure differential through a Coriolis flowmeter, and then flared. Liquid effluent overflowed onto a 100-mesh separator screen and then into a holding tank.

Litter was obtained from a commercial poultry farm located in Moorefield, WV. The litter was taken from a broiler house using wood chips for bedding. Litter was maintained in the rearing house for six consecutive approx 42-d cycles (flocks) of production. Thus, litter resided in the house about 1 yr before disposal. Litter was received at 30–40% moisture, and then diluted with fresh water in a mix tank to 5–7% solids slurry. In the case of volatile acids (VA) and chemical oxygen demand (COD), methods 8196 and 8000 reported in the *Hach Water Analysis Handbook* were used *(8)*. Feed slurry samples were obtained from the feed inlet pipe, once per day, during feeding events. Effluent samples were taken at the time of discharge from the digester tank, before sedimentation or separation. A pipe extending into the top 1/3 of the working digester volume removed effluent by pressure-differential; therefore, the effluent was discharged from the tank during bubble mixing and feeding events when biogas pressure increased more than 2 kPa, because of rapid release of biogas during bubble mixing or input of liquid volume during feeding. Samples were taken once per day during bubble mixing, which occurred each hour, to ensure a representative sample of the substrate, as liquid and solid layers stratify between bubble mixing events. For days when feed input was one time in 24 h, samples were taken 1 h before feed input. For days when feed input was two times in 24 h, the samples were taken 1 h before the midday feed input. For days when feed input was 6 or 12 times/d, samples were taken at the hour before midday feed input. Biogas composition was measured with an online HP Gas Chromatograph (Hewlett-Packard Agilent Model: 5890 Series II GC, Santa Clara, CA) once per hour. Online pH, temperature, and biogas flow were recorded into a computer database every 5 min.

Feed frequencies tested included 1 feeding/d (T1), 2 feedings/d at 12 h intervals (T2), 6 feedings/d at 4 h intervals (T6), and 12 feedings/d at 2 h intervals (T12). Daily feed volume and concentration were, respectively, 0.93 ± 0.06 m^3 and 50.9 ± 5.8 g/L COD. Each treatment was run for at least seven

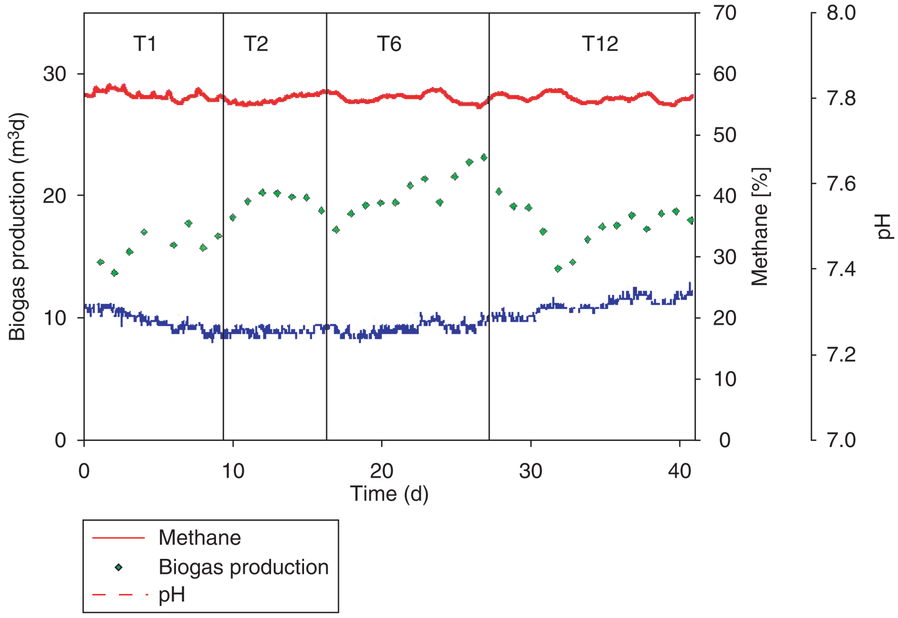

Fig. 1. Biodigester performance during the experiments.

consecutive days with data collection for three consecutive days once the digester had stabilized at the new feed frequency. The digester biochemical parameters along with biogas and methane percent measurements were used to determine steady state. Having similar hydraulic and carbon-loading rates, over a 4-d period, when the biogas production fluctuated less than 10% and methane percent fluctuated less than 2%, along with pH fluctuations within the digester of less than 0.2 and VA fluctuations inside the digester smaller than 10%, the digester was judged to be at steady state. Figure 1 shows the changes in biogas production, methane percentage, and pH during the experiments. Certainly, the steady state used in this article could be considered as a pseudo-steady-state, as it may be necessary to maintain a stable reactor for a period of three times the working HRT to assume steady state. Therefore, the steady state in this article was defined as stated in previous work *(7,9)*. This consideration has resulted in repeatable data from the WVSU pilot plant over a 4-yr period of operation and data collection.

For statistical analysis, an experimental unit was considered to be one 24-h period of continuous operation. Each treatment was sampled three times. Analysis of variance was performed using version 9.1 of the Statistica Analysis System (SAS) (SAS Institute Inc., Cary, NC). When the analysis of variance showed differences among treatments a Tukey test ($\alpha = 0.05$) was performed to compare means.

Results and Discussion

Figures 2–5 show the performance of the reactor under different feed frequencies. For all cases the pH remained almost constant along the

Table 1
Digester Average Temperature Characteristics

Treatment	Temperature[a] (°C)	Maximum deviation from target temperature (°C)	Time to reach target temperature after feeding (h)	Average daily recycled liquid ($m_{pumped}^3\ m_{media}^{-3}$/d)
T1	56.50[b]	2.0	6	4.174[c]
T2	56.60[d]	1.0	3	3.843[c]
T6	56.62[c,d]	0.7	2	3.858[c]
T12	56.64[c]	0.5	1	3.737[c]

[a]Data expressed as means from three replicates.
[b–d]Means with different letters in the same column showed statistical differences ($\alpha = 0.05$).

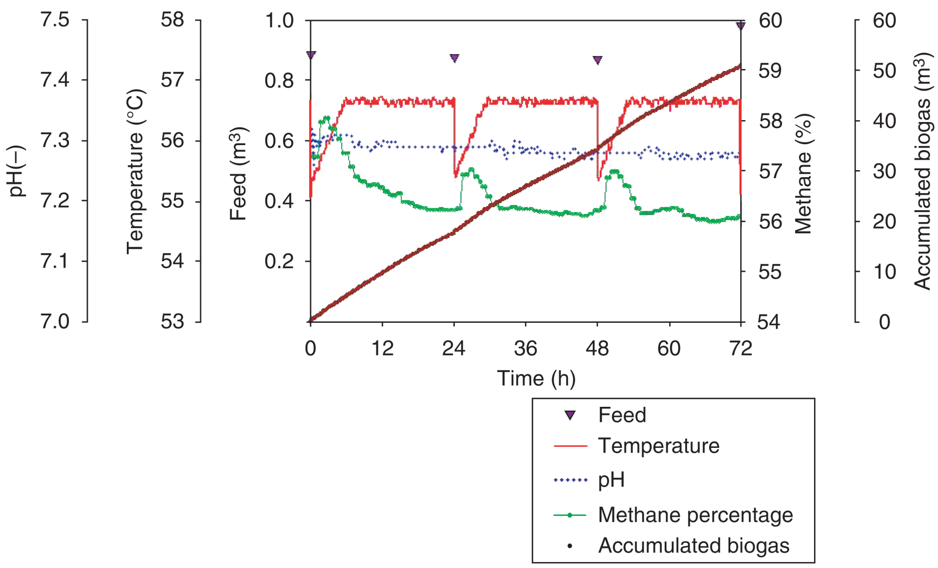

Fig. 2. Biodigester performance during feed intervals of 24 h.

experiments. Temperature of the media had a temporary reduction, dropping the temperature as the feed frequency increased. This was a result of feedslurry entering the thermophilic digester at ambient temperature, thus reducing digester temperature immediately after input. When average daily temperature of the digester was analyzed, significant differences between treatments were observed (Table 1). The temperature reduction and the corresponding recovery time of the process temperature for the treatments, incrementing in frequency (T1, T2, T6, and T12), were as follows: 2°C and 6 h, 1°C and 3 h, 0.7°C and 2 h, and 0.5°C and 1 h. These changes in temperature activated the heating system; as a result, the amount of recycled

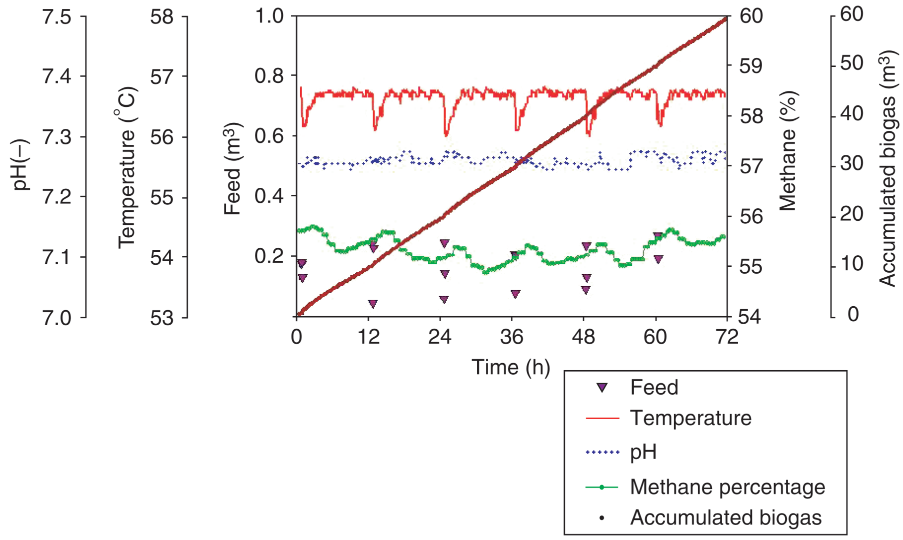

Fig. 3. Biodigester performance during feed intervals of 12 h.

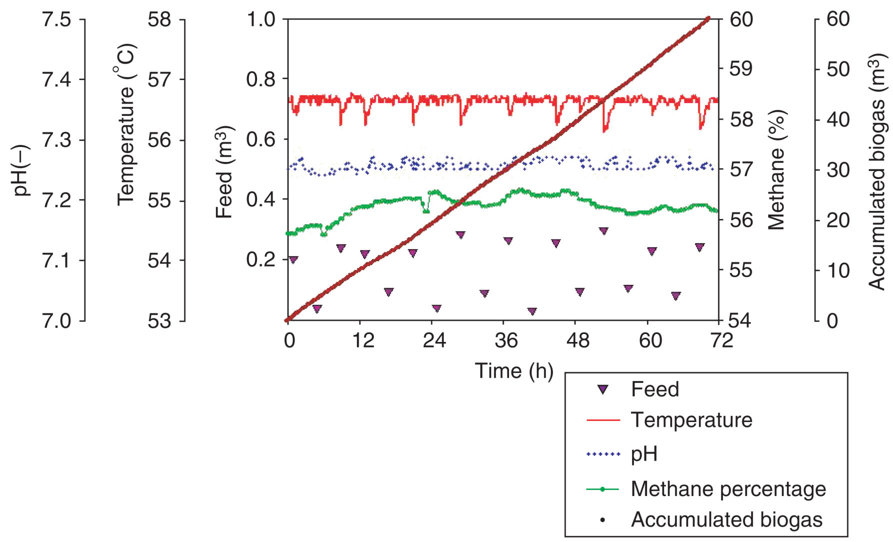

Fig. 4. Biodigester performance during feed intervals of 4 h.

liquid during the treatments was different, ranging from 3.7 to 4.2 m_{pumped}^{3} m_{media}^{-3} d^{-1} (Table 1).

Pumping of the media contributed to release of the methane gas from the digestate. This phenomenon was registered mainly in the treatments T1 and T2 as an increment of methane in the gas phase followed by the pattern imposed by the temperature variations. For T6 and T12, considering the methane percentage variation in the gas phase, no trend was

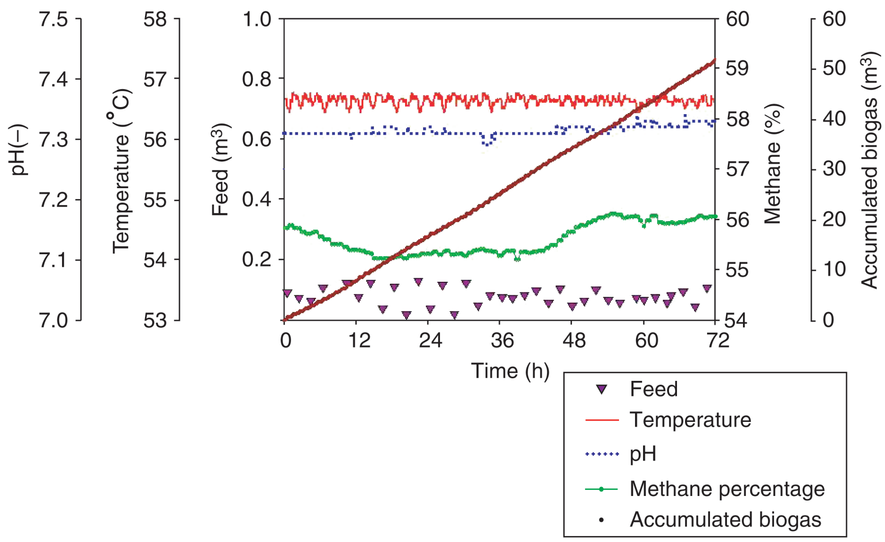

Fig. 5. Biodigester performance during feed intervals of 2 h.

observed. The biogas production was considered in steady-state conditions. In fact, the biogas produced per day along each one of the treatments was practically constant, this is easily observed in Figs. 2–5, wherein the slopes of the corresponding accumulated biogas are almost constant. Thus, the values of the slopes for the four incrementing frequency treatments (T1, T2, T6, and T12) were 0.729, 0.821, 0.834, and 0.708 m^3/h. As a result, the daily biogas production was statistically different, with treatments T6 and T2 in the group with the highest biogas production and T12 and T1 in the group with the lowest biogas production. The difference between the lowest gas production and the highest was close to 20% (Table 2). Regarding the COD loading, there was no statistical difference among treatments. However, a lower amount of carbon was supplied to T12; it had 88% of the amount supplied to T6. Nevertheless, a similar trend to total biogas production was observed when methanogenic activity was analyzed. Even though no statistical difference was observed in the methanogenic activity among treatments, the highest methanogenic activity was achieved by T6 and T2, with the maximum difference between the highest and lowest performing treatment, respectively T6 and T12, close to 7% (Table 2). It is important to note that besides the influence of feed frequency, temperature and mixing could have affected the digester performance.

Temperature reduction in the digester may have impacted the performance during feed-frequency one (T1). When temperature dropped from 56.7°C to 54.4°C, in a thermophilic anaerobic system fed poultry litter, a 35.8% reduction in biogas production occurred *(9)*. After the feed loading event at frequency one (T1), temperature dropped to 55.4°C, and did not reach the normal operating temperature of 56.7°C for 6 h. In fact, T1 was

Table 2
Feed Input and Biogas Average Daily Values

Treatment	Feed (m^3/d)	COD loaded (kg/d)	Biogas production (m^3/d)	Methanogenic activity (m^3/kg_{COD}·d)
T1	0.879[a]	50.4[a]	17.1[b]	0.203[a]
T2	0.905[a]	52.0[a]	19.6[a]	0.209[a]
T6	1.017[a]	53.8[a]	20.5[a]	0.215[a]
T12	0.932[a]	47.5[a]	17.2[b]	0.201[a]

Data expressed as means from three replicates.
[a,b]Means with different letters in the same column showed statistical differences ($\alpha = 0.05$).

the only treatment that was statically different from the other treatments when comparing average daily temperature (Table 1). This extended drop in temperature could have resulted in depressed biogas production during feed frequency one.

Recirculation of the digestate through the heat exchanger may have also impacted performance, because bubble mixing was kept constant throughout the experiment. When comparing the influence on methanogenic activity by the recycled liquid in each treatment, treatments T1 and T12 differed from T2 and T6 (Tables 1 and 2). The maximum performance was around 3.8 $m_{pumped}^3\ m_{media}^{-3}\ d^{-1}$, which is in the same order of magnitude as the one (4.55 $m_{pumped}^3\ m_{media}^{-3}\ d^{-1}$) reported by Lomas et al. *(10)* for the best performance in the treatment of piggery-slurry in a pilot plant. In addition, the pump run time after feed input varied between treatments (Table 1). In this system, recirculation for temperature control contributes to mixing; however, excessive mixing can damage the microbial consortia *(7)*.

Hydrolyzing bacteria appear to be more sensitive to mechanical stress than acetogenic and methanogenic bacteria. This may be owing to their position on the outer layer of the granule. Microbes in a digester form flocs or granules, held together by biofilms, with methanogens forming clusters in the middle of the biofilms *(11)*. Studying cellulose hydrolysis and methanogenesis, Song et al. *(11)* characterized the hydrolyzing bacteria on the biofilm on the outer surface of particles. The bacteria were found to be attached to the surface by EPS. Sheng et al. *(6)* found that the EPS on the outer layer of anaerobic flocs was completely dispersible at infinite shear intensity, whereas inner EPS layers were tightly bound and only dispersible under extremely unfavorable conditions, such as pH 11.0. In this experiment, it stands to reason that the increased pumping at feed frequency one damaged the hydrolyzing bacteria, disrupting the fermentation process resulting in depressed conversion of COD to biogas, whereas acetogenic and methanogenic bacteria remained relatively undisrupted, resulting in practically stable pH, VFA concentrations, and methane percent (Tables 2 and 3).

Table 3
Digester Parameter Average Daily Values

Treatment	Digester pH (–)	Digester VFA (mg/L)	Biogas methane (%)
T1	7.29[b]	1.714[a]	56.5[a]
T2	7.26[c]	1.770[a]	55.3[c]
T6	7.26[c]	1.876[a]	56.3[a,b]
T12	7.31[a]	2.053[a]	55.6[b,c]

Data expressed as means from three replicates.
[a–c]Means with different letters in the same column showed statistical differences ($\alpha = 0.05$).

Conversely, the feed frequency of T12 may have yielded less total biogas per kilogram of COD fed owing to decreased pump run time, resulting in less total mixing than the other treatments. Interestingly, pH and VFA concentration in the digester, and methane percentage in the biogas were stable for all treatments and there was little variation between treatments. However, the total biogas yield was different between treatments; with T1 and T12 significantly different from T2 and T6 (Table 2). This indicates parameters such as pH, VFA concentration, and biogas methane percentage may not be the best indicators of performance for optimizing and controlling the digestion process. Mechichi and Sayadi *(12)*, evaluating these and other parameters for process control of up-flow anaerobic filters for olive waste, concluded pH changes are too slow for early detection of process imbalance. VFA concentration and composition did show rapid response to perturbations, such as increased organic loading rate, change in HRT, and temperature fluctuations. The authors suggest accumulation of longer chain fatty acids than acetate and propionate are good indicators of process imbalance. In this experiment, VFA profiles were not measured.

From an operator's standpoint, more frequent feed input events present both benefits and challenges. For ease of operation and mechanical reliability, less frequent feedings are advantageous. Slurries containing bedding material, such as wood chips in poultry litter, can present materials handling problems, especially at 6–10% total solids. Pump, line, and valve clogging can occur, even when particle size is reduced. A single feeding would allow close monitoring and repair of the equipment used to move slurry into the digester at the time of operation. Continuous or intermittent feeding throughout the day and night would provide more opportunities for the feed system to clog or pump to malfunction, resulting in variable feed input and increased maintenance. For closer process monitoring and control, more frequent feedings would be desirable, especially with inconsistent or uncharacterized feedstocks. Digester pH, biogas production, and biogas composition change in response to changes in feed quality and quantity *(13)*. The more frequent the feed input, the more opportunity the operator has to modify the volume or concentration of the feed to maintain steady-state conditions. This may be more important for plants using mixed feedstock, or regional plants receiving materials from different sources. The presence of inhibitors or toxic compounds may not be discovered until the material is fed and digester performance is impaired. Frequent feed events could limit or discontinue the loading of slurry containing inhibitory levels of compounds such as ammonia or antibiotics until the digester recovers. In contrast, 1 feeding/d would load large quantities of the slurry into the reactor, especially in systems operated at short retention times, reducing performance or causing cessation of methanogenesis.

Conclusions

There were no statistical differences in the daily feed volume and concentration among treatments. Biogas production was greatest at feed frequencies two and six. Regarding methanogenic activity, a similar trend to biogas production was observed with T6 and T2 having the highest performance; however, there was no statistical difference among treatments. Biochemical and online parameters other than biogas volume showed little difference. The average daily temperature of the digester decreased as feed input frequencies decreased. This may have impacted the performance of once per day, and twice per day feedings. Preheating of feed slurry to temperatures at, or above digester operating temperature, before loading, would lessen the impact of the feed frequency on temperature, and as a result could lead to better overall performance. Digester pH, methane percent, and hourly biogas output were most stable at higher feeding frequencies. VFA concentrations of the digester changed very little between treatments, and remained stable throughout the experiment. This suggests parameters such as VFA concentration, pH, and biogas methane percentage may not be the best indicators of digester performance. Further work is needed in order to clarify the roles of temperature, and mixing on digester performance, which is left for future communications.

Acknowledgments

The authors gratefully acknowledge the financial support from West Virginia State University, Division of Agricultural, Consumer, Environmental, and Outreach Programs and Autonomous University of Chapingo, Agroindustrial Engineering Department. The study was funded by USDA Administrative Grant 2004-06200. We would also like to acknowledge the following individuals for their contributions; Dr. David Stafford, Mike Easter, Scot Shapero, and Ami Smith.

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