0273-2289/06/129–132/959–968/$30.00

Macroscopic Mass and Energy Balance of a Pilot Plant Anaerobic Bioreactor Operated Under Thermophilic Conditions

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Abstract

Intensive poultry production generates over 100,000 t of litter annually in West Virginia and 9×10^6 t nationwide. Current available technological alternatives based on thermophilic anaerobic digestion for residuals treatment are diverse. A modification of the typical continuous stirred tank reactor is a promising process being relatively stable and owing to its capability to manage considerable amounts of residuals at low operational cost. A 40-m^3 pilot plant digester was used for performance evaluation considering energy input and methane production. Results suggest some changes to the pilot plant configuration are necessary to reduce power consumption although maximizing biodigester performance.

Index Entries: Biogas; livestock residual; methane; thermophilic anaerobic digestion.

Introduction

Livestock residuals have been becoming an environmental concern as the production of animals has increased throughout the world *(1)*. In the United States alone, more than 350×10^6 t of livestock residuals must be disposed of annually *(2)*. These residuals are often disposed of by application directly on land or are occasionally composted *(3)*. In West Virginia, intensive poultry production generates more than 100,000 t of broiler litter annually.

Alternative processes for reducing the environmental impact are highly demanded. Since the 1960s and 1970s, several research groups have been

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proposing anaerobic digestion as an alternative for pollution control *(4)*. Currently the available technological alternatives based on this process are very diverse. A modification of the typical continuous stirred tank reactor is a promising process owing to its capability to manage considerable amounts of residuals at low operational cost and being a relatively stable process.

There are several factors that influence the anaerobic process. Some of the principal criteria that should be considered to design the processes are as follows: temperature, chemical and biochemical composition, hydraulic retention time (HRT), and mixing. As it has been explained in the literature, the thermophilic process has a better performance than mesophilic and psychrophilic processes *(5)*. As an example, Kim et al. *(6)* reported a higher yield in the thermophilic process (716 mL/g_{VS}/d) compared with the mesophilic one (556 mL/g_{VS}/d). However, that study did not include an evaluation of the energetic cost of the yield increment. It has been reported that the type of manure determines biogas production. Güngör-Demirci and Demirer *(7)* evaluated anaerobic batch fermentation of manure. These authors, working with mixtures of broiler and cattle residuals, reported that the biogas yields decrease as the fraction of broiler manure increased. This behavior was attributed to ammonia inhibition. Regarding power consumption, de Pinho et al. *(8)* worked with anaerobic sequencing batch reactors containing granular or flocculent biomass for the treatment of piggery wastewater. They reported a volumetric power input (VPI) range of 0.18–0.31 kW/m^3 for a 4.5-L reactor operated at 30°C, the device was mechanically stirred by three typical Rushton turbines.

For full-scale treatment plants, these considerations take a key role in the economic feasibility of the technological alternatives. In that context and considering that energy evaluation of the anaerobic digestion process is limited in the published literature, the aim of this article was to evaluate the performance of an anaerobic process, using a mass and energy balance and chemical characterization as tools to analyze a pilot plant scale biodigester.

Materials and Methods

Experiments were carried out at the facilities of the Bioplex Project at West Virginia State University (WV). The anaerobic process is presented in Fig. 1. The dilution system included an axial mixer (M-101), a recirculation loop and settling tank, which was used for removing grit and wood. Diluted chicken litter slurry was fed automatically into a 40 m^3 tank. The biodigester was operated in a semicontinuous process, being fed with fresh slurry every 2 h using a pump (L-102). The feed slurry flow rate was defined to achieve a HRT of 10 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 bubbled. A gas blower (JB-207) extracted biogas from the top of the digester and recirculated the gas through a bubbling ring located at the bottom of the digester. The bubbling rate was fixed at 0.01 ± 0.0005 vvm (gas volume/liquid volume/min), operating for 5 min every

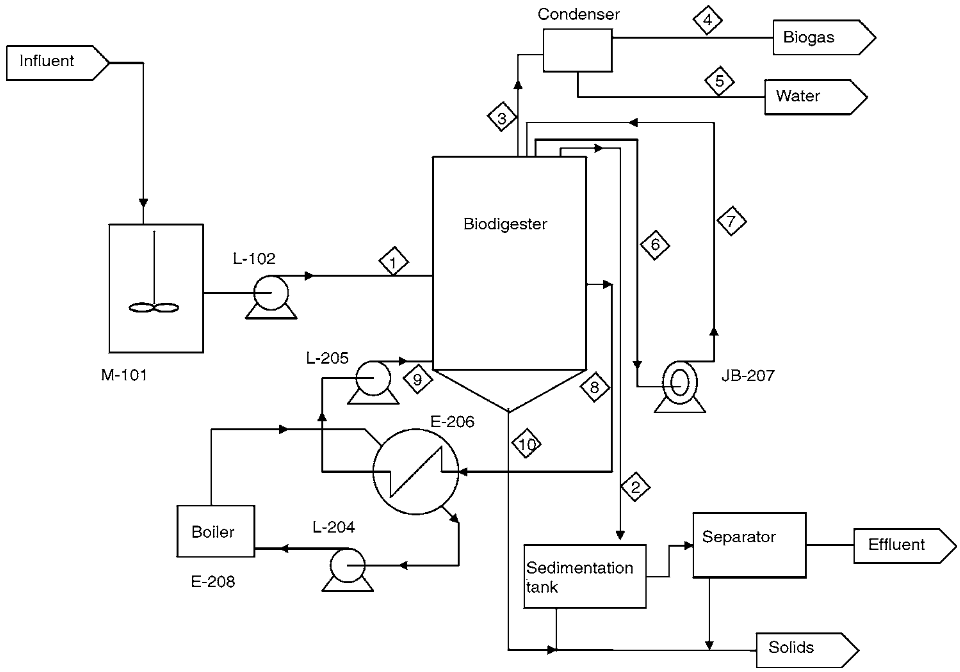

Fig. 1. Process diagram of the thermophilic anaerobic pilot plant.

30 min. The bioreactor operated under thermophilic conditions (56.6°C). The fermentation media was automatically heated when the temperature fell 0.1°C below target. A pump (L-204) recycled the work fluid (water and glycol mixture) for the heat exchanger (E-208). The digester liquid was pumped through an external heat exchanger and recirculated back into the digester using a pump (L-205). The digester effluent was discharged into a 5700-L sedimentation tank. The biogas flowed out by pressure differential through a flow meter and then to the flare for burning. Liquid overflowed onto a separator screen with 1000 mesh and then into a holding tank.

Mass and energy balance *(9)* was evaluated considering a steady state. For that purpose, 24 h of continuous operation was considered as an experimental unit, evaluated in three replicates. Motor power consumption of each device was evaluated at a sampling rate of 0.5 s, using Watt transducers (Omega, OM10 series, Stamford, CT). Signals were acquired and processed using a data acquisition system (National Instruments, NI-DAQ7, NI 4351,and NI 4350, Austin, TX) and a data logger (National Instruments, NI VI Logger, Austin, TX). Energy used by the devices was evaluated from a plot of the power as a function of time. The area under the curve, that corresponded to energy, was integrated using the SigmaPlot 2002 © software (Version 8.02a, Point Richmond, CA).

Liquid flow rate was evaluated using an ultrasonic device (Doppler, 301) although for biogas flow rate a coriolis meter (Emerson, no. CMF0-25M319NABAEZZZ, Boulder, CO) was used. Composition of the biogas was determined using a Drager Multiwarn II methane detector. Natural gas consumption by the hot water boiler used for the heat exchanger loop was recorded every 24-h period. The amount of energy used by this device was calculated based on the material used and the measured composition of the regional natural gas, i.e., 100% methane, and the corresponding heat of combustion *(10)*.

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 reused for six flocks of grow out, which is approx 1 yr. Before digestion, litter was removed from the house and stored in a litter shed for 3 mo. Dry matter, hemicellulose, cellulose, lignin, crude fat, and crude protein were determined using the corresponding procedures of the Official Methods of Analysis *(11)*. Starch was evaluated as described by Hall et al. *(12)*. BOD (biochemical oxygen demand), ALK (alkalinity), TS (total solids), and VS (volatile solids) were determined using the Standard methods for the examination of water and wastewater *(13)*. In the case of VA (volatile acids), COD (chemical oxygen demand), and AMM (ammonia), the methods 8196, 8000, and 10,031 reported in the Hach Water Analysis Handbook were used *(14)*. Chemical composition of the feed and effluent were evaluated by three replicates for each experimental unit. Feed slurry samples were obtained from the feed inlet pipe during feeding events. Effluent samples were taken at the time of discharge from the digester tank, before sedimentation or separation. Dry litter samples (before dilution) were used for hemicellulose, cellulose, lignin, crude fat, and crude protein analysis of the feed. The digester biochemical parameters along with biogas and methane percent measurements were used to determine steady state. At similar hydraulic and carbon loading rates, when the biogas production fluctuated less than 10% and methane percent fluctuated less than 2% in a 24-h period, along with pH fluctuations within the digester of less than 0.1 and VA fluctuations inside the digester smaller than 10% over a 4-d period, the digester was judged to be at steady state.

The biodigester has been operating continuously for 4 yr, having activity reduction just during the winter months (mid-December until March 1). For the experiments presented here, the anaerobic reactor had an adaptation period of 120 d since last winter, which consisted of gradually increasing the feeding rate up to the normal operation conditions. The process was in a steady state for 4 d previous to data acquisition.

Results and Discussion

The poultry litter coming from the farm had a dry matter of 70.93%. The dry matter basis manure proximal analysis indicated the following composition: hemicellulose 12.96%, cellulose 23.75%, lignin 5.07%, starch 1.16%, crude fat 2.36%, and crude protein 21.06%. Chemical characteristics of the slurry used for feeding are presented in Table 1.

Table 1
Characteristics of (Diluted) Manure Used in Experiments

Parameter[a]	Minimum	Maximum	Mean[b] ± SD
TS (%)	5.01	5.73	5.46 ± 0.25
VS of TS (%)	73.3	76.6	74.7 ± 1.24
COD (mg/L)	44,366	64,433	49,626 ± 6054
BOD (mg/L)	8700	14,700	12,478 ± 2291
VA (mg/L)	2196	5546	3681 ± 1079
AMM (mg/L)	1223	1290	1237 ± 21.4
ALK ($CaCO_3$ mg/L)	4900	7490	6210 ± 719
pH	6.72	6.88	6.78 ± 0.06

[a]TS, total solids; VS, volatile solids; COD, carbon oxygen demand; BOD, biochemical oxygen demand; VA, volatile acids; AMM, ammonia; ALK, alkalinity; pH, hydrogen potential.
[b]Mean of three replicates.

The mass balance of the anaerobic process is reported in Table 2. Results indicated that the HRT achieved during the experiments was 9.91 ± 0.15 d. The steady state of the process was confirmed based on the low coefficient of variation registered for the feeding and effluent currents and also on the stabilization of chemical composition of the currents. It is important to note that the volume of digester slurry recycled by pumping was 5.95 ± 0.56 times larger than the slurry inside the tank; although the volume used for mixing by bubbling was 6.41 ± 0.26 times higher than the volume of the slurry inside the tank. The mixing strategy followed in this work indicated that the gas feeding was under the typical order of magnitude used for devices that only use gas to promote mixing. The 0.01 vvm used here is considerably lower than the 1.5 vvm used by bubble columns *(15)* and external-loop airlift reactors *(16)*, and even lower than the 2.5 vvm reported for airlift reactors *(17)*. Similar high gas feeding values (1 vvm) are reported for aerated stirred tanks *(18)*. The low gas feeding value is more evident if it is considered that the bubbling is intermittent. Thus the process presented here suggests that pumping has a key role in mixing.

Table 3 presents the energy used by the process devices during a 24-h period of continuous operation. The main energy consumer is the heat exchanger (94% of the total). The VPI, considering heating, was 0.401 kW/m^3. This value is similar in order of magnitude to the one reported by de Pinho et al. *(8)*. However, these authors only included the mechanical power input in the evaluation. For this particular case, a detailed analysis of the heating system should be considered in order to determine the alternatives to diminish the power consumption. On scale up, fermentative mass and heat transfer area of the vessel do not increase linearly. In fact, when the volume of the tank scales up, the area exposed to heat transfer, and thus the energy exchanged to ambient, increases in lower magnitude than

Table 2
Mass Balance of the Process During a 24-h Period

	Line									
	1	2	3	4	5	6	7	8	9	10
	Mass (kg)									
Trial 1	2891.7	2797.8	39.4	37	2.4	242.3	242.3	188,838.6	188,838.6	54.5
Trial 2	2779.7	2688	39.4	37	2.4	218.7	218.7	155,971	155,971	52.4
Trial 3	2799	2705.7	40.6	38.1	2.5	226	226	154,430.9	154,430.9	52.7
Average	2823.5	2730.5	39.8	37.4	2.4	229	229	166,413.5	166,413.5	53.2
Standard deviation	48.9	48.1	0.584	0.548	0.036	9.88	9.88	15,869	15,869	0.92
Coefficient of variation (%)	1.7	1.8	1.5	1.5	1.5	4.3	4.3	9.5	9.5	1.7

Line numbers correspond to the currents presented in Fig. 1.

Table 3
Energy Balance in a 24 h of Continuous Operation

Device or source	Minimum (kJ)	Maximum (kJ)	Mean[b] ± SD (kJ)
M-101	2780	3316	2993 ± 233
L-102	1196	1374	1316 ± 85
L-204	3214	3982	3492 ± 348
L-205	29,652	35,745	31,684 ± 2872
JB-207	16,344	17,868	16,950 ± 660
E-208[a]	866,010	942,143	894,560 ± 33,870
Biogas produced[a]	661,224	694,213	678,086 ± 13,478

[a]The energy was calculated based on a heat of combustion of 33 943 kJ/m^3.
[b]Mean of three replicates.

does volume. Therefore, in regional digester applications 100 to 1000 times larger than the pilot plant, the heat supply required diminishes considerably.

Exclusively evaluating the mechanical power input, the pump L-205 and the blower JB-207 consume, respectively, 56% and 30%. Both devices have the main purpose of promoting homogeneity inside the vessel in terms of temperature and composition. However, the higher power consumption of the pump L-205 over the blower JB-207 and the reduced gas feeding (0.01 vvm) used in the process confirm that the principal device used for mixing is the pump L-205.

Taking the mechanical energy used for the different devices reported in Table 3 and considering operation and nonoperation times, the total average power of the process was 0.653 ± 0.0015 kW. This value could be transformed taking into account the volume involved in the process, thus the VPI of the process was 0.024 ± 0.0015 kW/m^3, which is in the same order of magnitude of an anaerobic sewage sludge digestion process reported by Pierkiel and Lanting *(19)*. These authors found a VPI ranging from 0.02 to 0.04 kW/m^3. It is important to stress that the VPI registered in the present work is similar to the 0.022–0.038 kW/m^3 range reported for an aerated stirred hybrid reactor *(20)*. On the other hand, the mechanical energy used in the process reported here, represents between 7.7% and 13.2% of the energy used with an anaerobic batch biofilm reactor with mechanical stirring *(8)*. In that report VPI ranged from 0.18 to 0.31 kW/m^3, depending on rotational speed. This showed that the claimed low power consumption using bubbling when is compared with stirred vessels, depends strongly in the kind of impeller. In this particular case, bubbling has similar power consumption like an hybrid geometry *(20)*, but it requires a smaller power input than the Rushton turbines reported by de Pinho et al. *(8)*. Consequently, new strategies for mixing should be explored in order to reduce power consumption.

When the operation time is evaluated, as presented in Table 4, it is easy to observe that in a 24-h period, both the L-204 and L-205 pumps worked for almost 11 h, followed by the blower JB-207 with around 3.5 h. Considering that, for the same period of time, the material inside the tank is recycled almost six times and the L-205 operated for 11 h, the average time that slurry was passing through the pump, and consequently exposed to mechanical stress, was close to 110 min. This long period of time could lead to a detriment in the performance of the process owing to the fact that consortia aggregates could be exposed to intermittent mechanical stress. Thus, the hydrodynamics imposed in the process could have an important influence on biodigester performance. As an example, Jin and Lant *(21)* working with bubble column, airlift, and aerated stirred reactors found that flow regime and hydrodynamics influence the floc size distribution. Further work is necessary in order to elucidate the effect of mechanical stress on microbial communities and thus optimize the biodigester performance.

Table 4
Operation Time in a 24 h Period

Device	Minimum (min)	Maximum (min)	Mean[a] ± SD (min)
M-101	70.4	75.4	73 ± 2.1
L-102	9.7	10.9	10.2 ± 0.5
L-204	606.6	741.8	653.7 ± 62.3
L-205	606.2	750.9	657.6 ± 66.1
JB-207	208.1	230.6	217.9 ± 9.4

[a]Mean of three replicates.

Table 5
Characteristics of the Effluent

Parameter[a]	Minimum	Maximum	Mean[a] ± SD
TS (%)	3.14	3.75	3.35 ± 0.2
VS of TS (%)	62.9	64.9	63.4 ± 0.7
COD (mg/L)	33,433	42,233	36,918 ± 2646
BOD (mg/L)	6200	9900	7322 ± 1212
VA (mg/L)	3546	6735	4875 ± 1142
AMM (mg/L)	1923	2027	2004 ± 32
ALK (as $CaCO_3$ mg/L)	9520	11,900	10,859 ± 719
pH	7.68	7.81	7.74 ± 0.05

[a]Mean of three replicates.

The effluent composition reported in Table 5 was obtained under steady state conditions. The pH in the effluent ranged from 7.68 to 7.81, although in feed ranged from 6.72 to 6.88. The increase in pH from the feed to the effluent is a result of metabolic reactions that occur with anaerobic digestion of poultry litter. Over the 4 yr, the digester has been fed solely poultry litter, pH in the digester has fluctuated between 7.2 and 7.9 and ammonia levels varied from 1500 to 2200 ppm depending on loading rate. Ammonia levels were steady at around 2000 ppm in the effluent; well below inhibitory levels *(22)*. As reported by Stafford et al. *(4)*, digesters fed poultry manure have shown levels of up to 3150 ppm ammonia without inhibitory effects on digestion, even at a 10-d HRT.

As presented in Table 6, methane percent of biogas ranged from 54.5 to 56.0%, although volatile solids destruction from feed to effluent varied from 46.9 to 49.1%. These values are similar to reported data from poultry waste (layer) fed lab scale digesters at 10-d HRTs *(4)*. The biogas generated referred to VS fed was 282.1 mL/g. This is well below reported values in a thermophilic reactor with 10-d HRT of 551 mL/g *(4)*. The lower production of biogas may be attributed to the difference in the quality of the poultry litter (six flocks grow out and stored for 3 mo before feeding) and possibly to the disruption of microbial communities by the sheer force of the recirculation

Table 6
Chemical Changes During Anaerobic Digestion and Bioreactor Performance

Parameter	Minimum	Maximum	Mean[a] ± SD
Methane content (%)	54.5	56	55.3 ± 0.6
VS reduction (kg)	53.4	57.4	55.2 ± 1.7
VS reduction (%)	46.9	49.1	49.7 ± 0.9
Biogas/VS added (mL/g)	273.6	295.2	281.1 ± 10
COD reduction (mg/L)	9100	17,800	12,708 ± 3 04
COD reduction (%)	19.5	33.3	25.3 ± 5.8
BOD reduction (mg/L)	4400	6500	5156 ± 953
BOD reduction (%)	36.9	46.9	41.03 ± 4.2
Biogas/COD added (mL/g)	215.5	242.7	232 ± 11.8
Biogas/BOD added (mL/g)	800.2	1055.2	929.4 ± 104

[a]Mean of three replicates.

pump. Additionally, it is possible to see in Table 6 that COD and BOD had, respectively, 25.3% and 41% reduction during the process. The COD reduction value is considerably below to the 75% reported by Stafford et al. *(4)* for similar 10-d HRT. However, the performance observed in this work is similar to that reported by Güngor-Demirci and Demirer *(7)* for 100% broiler manure, having an initial COD of 53,500 mg/L, in batch process under mesophilic conditions (35°C). These authors reported a reduction of 37.9% in a period of 91 d. Considering the time used in the process, the thermophilic process reported here offers some advantages.

Conclusions

Results indicated that heating is the principal component of energy demand, representing 94% of the VPI. The energetic performance could be enhanced as the heating and insulation systems could be improved. Insulation, fouling, heat transfer area, combustion efficiency, operation conditions, and temperature control strategy are some of the aspects that may be considered. The vessel structure should be also reviewed; alternatives such as a jacketed tank or an internal heat exchanger may be included in the analysis. Additionally, an economical study may be used to define the best options to improve biodigester performance. The mechanical power used in this process is similar to the one used by stirred reactors. Pumping uses 56% of the total mechanical energy and plays the principal role in mixing. The slurry moved by pumping in 24 h represented around six times the fermentation mass. On the other hand, even when the power used for bubbling represents 30% of the total mechanical input, it seems to be useless on this pilot-scale reactor. The pumping process necessary to maintain temperature could possibly affect the consortia performance reflected in the reduced COD and BOD conversions and also in the low biogas yield. New strategies oriented to power consumption and mechanical stress reductions are needed.

In this particular case, the removal of the blower or replacement with a larger unit and the reduction of pumping could contribute to manage that issue. Future modifications to the operational conditions and process arrangement may enhance biodigester performance and therefore increase biogas yield. These issues will be discussed in additional communications.

Acknowledgments

The authors gratefully acknowledge the financial support from BIOPLEX Project, EPSCoR, and Autonomous University of Chapingo. The study was funded by USDA Administrative Grant 2004-06200. We are grateful to Charles "Chip" Vincent, Chris Postalwait, Scot Shapero, and Ysabel Bombardiere for their contributions to the experiments.

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