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EVALUATION OF THE PERFORMANCE OF A 550 COW PLUG-FLOW ANAEROBIC DIGESTER UNDER STEADY-STATE CONDITIONS

J. H. Martin, Jr., P. E. Wright, S. F. Inglis, and K. F. Roos

ABSTRACT

The objective of this study was to characterize the performance of a full-scale, mesophilic plug-flow anaerobic digester for 550 dairy cattle manure based on the degree of waste stabilization, fecal coliform and Mycobacterium avium paratuberculosis density reductions, and biogas production and utilization. M. avium paratuberculosis is a pathogen responsible for paratuberculosis (Johne's disease) in dairy cattle and other ruminants.

Under steady-state conditions, average reductions in total solids, total volatile solids, and chemical oxygen demand were 25.1, 29.7, and 41.9 percent, respectively, with no loss of nitrogen or phosphorus. Reductions in fecal coliform and M. avium paratuberculosis densities were approximately 99.9 and 99 percent respectively. Biogas composition averaged 59.1 percent methane at an average production rate of 1,214 m3 (42,868 ft3) per day. This translates to 2.27 m3 (80 ft3) per cow-day and 0.34 m3 per kg (5.46 ft3 per lb) of chemical oxygen demand destroyed. The annual income derived from the use of the biogas produced to generate electricity is estimated to be $39,474 per year. Based on this income estimate, the simple payback period for the capital invested is approximately 5.6 years.

KEYWORDS: Anaerobic digestion, dairy manure, waste stabilization, pathogen reduction, biogas production and utilization.

INTRODUCTION

Anaerobic digestion is a controlled biological process that can substantially reduce the impact of liquid livestock and poultry manures and manure slurries on air and water quality. Unlike comparable aerobic waste stabilization processes, energy requirements are minimal. In addition, a relatively small fraction of the energy in the biogas produced and captured is adequate to satisfy process needs with the remaining biogas energy available for use as a boiler fuel or to generate electricity. Thus, anaerobic digestion with biogas utilization produces a source of revenue that will partially offset process costs and may increase farm net income.

In the past, interest in anaerobic digestion of livestock and poultry manures was driven primarily by the need for conventional fuel substitutes. For example, interest intensified in France and Germany during and immediately after World War II in response to disruptions in conventional fuel supplies (Tietjen, 1975). This was followed by a renewal of interest in anaerobic digestion of livestock and poultry manures in the mid 1970s stimulated primarily by the OPEC oil embargo of 1973 and the subsequent price increases for crude oil and other fuels. In both instances, this interest dissipated rapidly, however, as supplies of conventional fuels increased and prices declined.

A majority of the anaerobic digesters constructed for biogas production from livestock and poultry manures in the 1970s failed for a variety of reasons. However, the experience gained during this period allowed for the refinement of both system design and operating parameters and the demonstration of technical viability.

In the early to mid 1990s, a renewal of interest in anaerobic digestion by livestock and poultry producers occurred. Three primary factors contributed to this renewal of interest: 1) the need for a cost effective strategy for reducing manure related odors from storage facilities including anaerobic lagoons and land application sites, 2) the re-emerging concern about the impacts of livestock and poultry manures on water quality, and 3) the level of concern about global climate change was intensifying and the significance of methane emissions to the atmosphere was receiving increased attention. Recognition of the magnitude of methane emissions resulting from the uncontrolled anaerobic decomposition of livestock and poultry manures led to the creation of the U.S. Environmental Protection Agency's AgSTAR Program. The primary mission of this program is to encourage the use of anaerobic digestion with biogas collection and utilization in the management of livestock and poultry manures.

Although aerobic digestion had also been demonstrated in the 1960s and 70s to be an effective strategy for controlling odors and water quality impacts of livestock and poultry manures, the cost was prohibitively high due primarily to the electrical energy required. In addition, the reduction in methane emissions realized was at least partially negated by the production of greenhouse gases associated with the generation of the electricity required for aeration.

OBJECTIVE

The objective of this study was to characterize the performance of full-scale, mesophilic plug-flow anaerobic digester for dairy cattle manure based on the degree of waste stabilization, fecal coliform and *Mycobacterium avium paratuberculosis* density reduction, and biogas production and utilization. *M. avium paratuberculosis* is a pathogen responsible for paratuberculosis (Johne's disease) in dairy cattle and other ruminants (Merck, Inc., 1998).

METHODS AND MATERIALS

Study Site—This study was conducted at a 2,200-acre dairy farm, AA Dairy, located in the southern tier of upstate New York. The AA Dairy milking herd consists, on average, of 550 Holstein-Friesian cows housed in free-stall barns. Manure is removed from the free-stall barn alleys by scraping into a holding and mixing tank. From this tank, manure is transferred daily to a plug flow anaerobic digester using a piston pump. After anaerobic digestion, the coarse solids in the digester effluent are separated mechanically using a screw press separator. The liquid fraction is discharged to a 9,084 m^3 (2.4 million gallon) lined storage pond prior to land application.

The plug-flow anaerobic digester was designed and constructed, with the expectation of a future herd expansion to 1,054 cows, by RCM Digesters, Inc., Berkley, California. The digester dimensions are 34.1 m (112 ft) long by 8.5 m (28 ft) wide by 4.3 m (14 ft) deep and has an operating volume of 1,121 m^3 (39,568 ft^3). The design hydraulic retention time (HRT) for the digester, based on herd of 1,054 cows, is 24 days with a predicted rate of biogas production of 1,833 m^3 (64,720 ft^3) per day. The digester channel is covered with an impermeable flexible geo-textile membrane, which is inflated to a nominal positive pressure by the biogas collected to maintain a semi-rigid surface. The digester has been in operation since 1998.

Captured biogas is used to fuel a 130 kW engine-generator set. The engine, a Caterpillar 3306 designed to run on natural gas, was modified to use biogas. The generator is an induction type unit with the following specifications: three phase, 208 volts, and 430 amps at 1,835 rpm. The electricity generated is used to satisfy on-farm demand with any excess energy sold at wholesale rates to the local electric utility, the New York State Electric and Gas (NYSEG) Corporation. Waste heat from the engine cooling system is recovered through a commercially fabricated heat exchanger and used to maintain digester temperature at approximately 95 °F.

Data Collection—The basis for characterizing the performance of this dairy cattle waste management system was materials balances developed from measured concentrations of selected parameters in combination with mass-flow estimates. The following four waste streams were sampled semi-monthly from late May 2001 through early June 2002: anaerobic digester influent, effluent, and liquid and solid phase effluents from the liquid-solids separation unit. Each sample collected for analysis was a composite of several sub-samples collected over a 15 to 20 minute period of flow to insure that the samples analyzed were representative.

As noted above, a piston pump was used to initially transfer manure from a collection sump to the anaerobic digester. This enabled estimation of the volume of manure produced daily, based on the manufacturers specification for volume displaced per stroke, by determining the average number of piston strokes per day using a mechanical counter. The liquid and solid fraction volumes after separation were estimated based on the partitioning of total solids between the two fractions assuming conservation of mass through the separation process.

Additional data collection at AA Dairy included volume of biogas utilized and kJ (kWh) of electricity generated between days of collection of manure samples. The biogas-generated electrical energy used on-site and sold to NYSEG were determined from farm records.

Sample Analyses—All manure samples collected were analyzed for the following parameters: total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), soluble chemical oxygen demand (SCOD), total volatile acids (TVA), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), total phosphorus (TP), orthophosphate phosphorus (OP), and pH. U.S. Environmental Protection Agency (1983) methods were used for TS, TVS, TKN, TP, OP, and pH determinations. American Public Health Association (1995) methods were used to determine COD, SCOD, NH_4-N, and TVA concentrations. All analyses were performed by an analytical laboratory certified by the New York State Department of Environmental Conservation.

Each manure sample was also analyzed to determine densities of the fecal coliform group of indicator organisms (fecal coliforms) and the pathogen, *M. avium paratuberculosis*. Densities of fecal coliforms were estimated using the multiple tube fermentation technique (American Public Health Association, 1995), by the same laboratory that performed determinations of physical and chemical characteristics. Determinations of densities of *M. avium paratuberculosis* were performed by the New York Animal Health Diagnostic Laboratory, Cornell University College of Veterinary Medicine using the "Cornell Method," which has been described by Stabel (1997). Although Stabel reported the Cornell Method to be less sensitive than other methods, it satisfies the requirements of the USDA National Veterinary Services Laboratory proficiency-testing program.

A sample of AA Dairy biogas was analyzed by gas chromatography using ASTM Method D1946 (ASTM International, 1990), to determine methane and carbon dioxide content. The same sample was analyzed using EPA Method 16 to determine hydrogen sulfide content, and using Sensidyne ammonia detector tubes to determine ammonia content.

Data Analysis—Each data set generated was analyzed statistically for the possible presence of extreme observations or outliers using Dixon's criteria for testing extreme observations in a single sample (Snedecor and Cochran, 1980). If the probability of the occurrence of a suspect observation, based on order statistics, was less than five percent ($P<0.05$), the suspect observation was considered an outlier and not included in subsequent statistical analyses. The Student's t test was used in two-way comparisons to determine the statistical significance of the difference between means, and one-way analysis of variance was used for multiple comparisons. If the null hypothesis for multiple comparisons that the means did not differ significantly ($P<0.01$) was rejected, Tukey's Honest Significance Test for pairwise comparisons of means was used (Steel and Torrie, 1980). To equalize variances, densities of fecal coliform bacteria and *M. avium paratuberculosis* were transformed logarithmically, $\log_{10}(Y+1)$, prior to statistical analysis.

RESULTS AND DISCUSSION

Manure Production and Characteristics—

As shown in Table 1, the volume of manure produced per cow-day at the AA Dairy was somewhat higher than the standard reference values proposed by the American Society of Agricultural Engineers (2001) and the U.S. Department of Agriculture (1992). However, both the American Society of Agricultural Engineers (ASAE) and the U.S. Department of Agriculture (USDA) estimates are "as excreted" values. Thus, they do not include any water used for cleaning or spillage from drinkers, which are included in the AA Dairy value.

Generally, the AA Dairy manure characteristics, on a kg per cow-day basis, were within the ranges of the ASAE and USDA values with COD being the one notable exception. The reason for the substantially higher AA Dairy COD values is unclear but may reflect differences in feeding practices or differences in analytical precision and accuracy.

Digester Operation—

Based on manure production of 2.1 ft^3 per cow-day and a herd size of 550 cows, the HRT of the AA Dairy anaerobic digester as operated during this study was 34 days. This is 10 days longer than the design HRT of 24 days, which was based on the assumed future herd size of 1,054 cows. If future herd expansion to 1,054 cows does occur, the digester HRT will be reduced to approximately 18 days, which 75 percent of the design HRT.

Because it was not possible to vary digester HRT in this study, the impacts of a reduction in HRT from 34 to 18 days are unclear. However, it seems reasonable to assume that some increase in the effluent concentrations of TS, TVS, COD, SCOD, and TVA would occur. Thus, the degree of waste stabilization would be reduced. In addition, there is a reasonable expectation that reductions in the densities of fecal coliforms and *M. avium paratuberculosis* would decrease, as would biogas production per cow-day. However, with the projected herd size of 1,054 cows, total biogas production would increase.

Table 1. Comparison of AA Dairy manure production and characteristics with standard reference values assuming a live weight of 1,400 lb per cow.

Parameter	AA Dairy	ASAE (2001)	USDA (1992)
Volume, m^3/cow-day	0.059	0.055	0.052
Total solids, kg/cow-day	6.7	7.6	6.4
Total volatile solids, kg/cow-day	5.7	6.4	5.4
Fixed solids, kg/cow-day	1.0	1.2	1.0
Chemical oxygen demand, kg/cow-day	9.1	7.0	5.7
Total Kjeldahl nitrogen, kg/cow-day	0.28	0.29	0.29
Total phosphorus, kg/cow-day	0.048	0.060	0.044
Orthophosphate phosphorus, kg/cow-day	0.027	0.039	—
pH	7.4	7.0	—

Waste Stabilization—

An assessment of the AA Dairy plug flow anaerobic digester performance, based on comparisons of mean influent and effluent concentrations, is presented in Table 2. As shown, there were substantial and highly significant ($P<0.01$) reductions in TS, TVS, COD, SCOD, and TVA. Conversely, concentrations of NH_4-N and OP increased while there were no statistically significant differences between influent and effluent concentrations of FS, TKN, organic nitrogen (ON), and TP. The lack of significant differences between influent and effluent concentrations of fixed solids (FS) and TP indicate that this digester is operating in an ideal plug flow mode with no accumulation of total solids or related parameters. The one anomaly in these data is the absence of a statistically significant reduction in ON concentration comparable to the increase in the concentration of NH_4-N. The reason for this anomaly is not clear, but the lack of a statistically significant difference between influent and effluent TKN concentrations indicates that nitrogen loss through desorption of NH_4-N in the digester is at most minimal. The differences between influent and effluent concentrations of TVS and COD (Table 2) translate into mass reductions of 934.4 and 2,105 kg (2,060 and 4,641 lb) per day, respectively.

Indicator Organism and Pathogen Reduction—

As shown in Table 3, the $\log_{10}$ densities of both the fecal coliform group of bacteria and *M. avium paratuberculosis* were reduced substantially in the AA Dairy anaerobic digester. On a colony-forming unit (CFU) per g of manure basis, the reduction in the density of total coliforms was almost 99.9 percent while the reduction in *M. avium paratuberculosis* density was slightly greater than 99 percent

Table 2. AA Dairy anaerobic digester performance summary, mg/L[*].

Parameter	Influent	Effluent	Reduction, %
Total solids	113,186[a]±10,097	84,739[b]±5,993	25.1
Total volatile solids	96,080[a]±9,477	67,518[b]±4,446	29.7
Fixed solids	17,106[a]±1,495	17,221[b]±2,461	—
Chemical oxygen demand	153,496[a]±77,178	89,144[b]±23,185	41.9

Soluble chemical oxygen demand	24,239[a]±6,568	16,961[b]±7,073	30.0
Total volatile acids	3,687[a]±806	513[b]±227	86.1
Total Kjeldahl nitrogen	4,631[a]±513	5,111[a]±894	—
Organic nitrogen	2,500[a]±491	2,268[a]±891	—
Ammonia nitrogen	2,159[a]±387	2,881[b]±322	+33.4[†]
Total phosphorus	813[a]±124	838[a]±124	—
Orthophosphate phosphorus	457[a]±104	562[b]±90	+23.0[†]
pH	7.4[a]±0.3	7.9[b]±0.1	—

[*]Means in a row with a common superscript are not significantly different (P<0.01).

[†]Increase in concentration.

Biogas Production—

As described earlier, AA Dairy has the ability only to utilize biogas in an engine-generator set. If the engine-generator set is out of service, biogas is flared to prevent possible failure of the digester's flexible cover. However, only the biogas utilized to fuel the engine-generator set is metered. During this study, this meter failed in late November 2001 and it was not replaced until early January 2002. This failure resulted in the loss of a little over two months of biogas production data. It was followed by an engine-generator set controller problem resulting in that unit being shut down from January through March 2002. However, resolution of this problem by installing a new controller with a cumulative kilowatt-hour meter also resolved a problem of accurately determining cumulative engine-generator set electrical output. Previously, electricity generated was estimated based on engine operating hours and current and voltage measurements (Peranginangin and Scott, 2002).

Table 3. Comparison of AA Dairy anaerobic digester log_{10} influent and effluent densities of fecal coliform bacteria and *M. avium paratuberculosis*[*].

	Influent	Effluent	Reduction
Fecal coliforms, CFU/g[†]	6.08^{a}±0.59	3.30^{b}±0.73	2.78
M. avium paratuberculosis, CFU/g	3.94^{a}±0.72	1.86^{b}±0.72	2.08

[*]Means in a row with a common superscript are not significantly different (P<0.01).

[†]Log_{10} colony-forming units per g of manure.

Because of the gas meter failure followed by the failure of the engine-generator set failure, determination of biogas production from late November 2001 through early April 2002 was not possible. Thus, there were two separate periods for which biogas production was determined. For the period of the study prior to the gas meter and engine-generator set controller problems (21 May through 26 November 2001), biogas production was 1,102 ± 379 m^3 (38,907 ± 13,386 ft^3) per day. For the period of the study after the resolution of the gas meter and engine-generator set controller problems (2 April through 17 June 2002), biogas production was 1,214 ± 89 m^3 (42,868 ± 3,144 ft^3) per day. Although the difference between these two periods in average daily biogas production is relatively small, the accuracy of the biogas production estimate for the 21 May through 26 November time is suspect because of a high degree of daily variability. The coefficient of variation for this period was approximately 34 percent probably reflecting the gradual failure of the gas meter that eventually was replaced. In contrast, variability in daily biogas production for the period after gas meter replacement was only approximately seven percent. Therefore, it seems reasonable to conclude that the estimate of average daily biogas production of 1,214 m^3 (42,868 ft^3) based on data collected from 2 April through 17 June 2002 is the more accurate estimate of biogas production at AA Dairy. This translates into a rate of biogas production of 2.27 m^3 (80 ft^3) per cow-day, which is 31 percent higher that the originally anticipated rate of biogas production of 1.73 m^3 (61 ft^3) per cow-day based on a herd size of 1,054 cows. This is a reflection of the difference between the design HRT of 24 days and the actual HRT of 34 days.

Previously, the methane content of the biogas produced by the AA Dairy anaerobic digester was reported to vary between 50 to 55 percent with a variation in hydrogen sulfide content from 0.1 to 0.36 percent (Peranginangin and Scott, 2002). Results (Table 4) of the analysis of a random sample of the AA Dairy biogas indicated a slightly higher methane content of 59.1 percent. The biogas ammonia content, based on five replicate determinations, was found to be 15±5 parts per million indicating that ammonia desorption in the plug flow digester is nominal and recovery from the biogas produced probably could not be justified economically. This also suggests that ammonia does not contribute significantly to the formation of oxides of nitrogen (NO_x) during dairy manure biogas combustion.

Based on a methane content of 59.1 percent (Table 4) and the previously discussed rate of biogas production of 1,214 m^3 (42,868 ft^3) per day, the rate of methane production by the AA Dairy anaerobic digester is 717 m^3 (25,335 ft^3) per day. Theoretically, the destruction of one kg of ultimate biochemical oxygen demand (BOD_U) under anaerobic conditions should result in the generation of 0.35 m^3 of methane (5.62 ft^3 per lb) (Metcalf and Eddy, 1991). Although not all COD is biodegradable, it can be assumed that COD reduction is equal to the reduction in ultimate biochemical oxygen demand. Thus, the 41.9 percent reduction in COD in the AA Dairy anaerobic digester (Table 2) is equivalent to a 2,105 kg (4,641 lb) per day reduction in BOD_U.

Table 4. AA Dairy Biogas Composition.

Parameter	% by volume
Methane	59.1
Carbon dioxide	39.2
Hydrogen sulfide	0.193
Other gases	1.507

As shown in Table 5, this translates into a rate of methane production of 0.34 m^3 (5.46 ft^3 per lb) of COD destroyed, which is slightly more than 97 percent of the theoretical value. Based on the ratio COD to TVS destroyed of 2.25 (Table 3), 0.36 m^3 (12.64 ft^3) of methane should have been produced per lb of TVS destroyed. The observed value of 0.35 m^3 (12.30 ft^3) of methane produced per lb of TVS destroyed also compares favorably with the theoretical value.

Table 5. Methane and total biogas production as functions of chemical oxygen demand and total volatile solids destruction.

Parameter	Biogas	Methane
$ft^3/lb\ COD_D$	9.24	5.46
$ft^3/lb\ TVS_D$	20.81	12.30

Biogas Utilization—

For the period 2 April through 17 June 2002, 5,158,000 ± 478,800 kJ (1,433±133 kWhr) of electricity was generated daily. The on-line efficiency of the engine-generator set during this period was 96.8 percent. The validity of this estimate of electricity was confirmed by the subsequent determination that the rate of electricity generation for the 180-day period from 2 April though 30 September 2002 was 5,144,400 kJ (1,429 kWhr) per day with an on-line efficiency of 98.8 percent.

On average, 4,231,780 ± 143,644 kJ were generated per 1,000 m^3 (33.29 ± 1.13 kWh per 1,000 ft^3) of biogas utilized. This low conversion efficiency, approximately 20 percent, is probably is the result of the utilization of somewhat less than 50 percent of the engine-generator set's rated capacity of 130 kW. At full load, conversion of biogas energy to electrical energy should approach 30 percent with the added potential of recovering up to 60 percent of biogas energy as heat energy (Koelsch and Walker, 1981).

Solids Separation—

As mentioned earlier, AA Dairy uses a screw press separator to recover solids from the digester effluent for use after composting as a bedding material and for sale as a mulch or soil amendment. On a volume basis, 5.55 m^3 (196 ft^3) of separated solids are generated daily, which reduces the digester effluent flow to the storage lagoon by approximately 17 percent and the mean total solids concentration of the flow to the storage lagoon from 84,739 to 51,088 mg per L. The average total solids content of the separated solids is about 25 percent.

The separated solids at the AA Dairy are composted for further stabilization prior to sale as a mulch material or soil amendment. Assuming that the organic carbon content of the separated solids can be estimated with a reasonable degree of accuracy as approximately 55.5 percent of TVS (Haug, 1980 and Rynk *et al*., 1992), the carbon to nitrogen (C:N) ratio of the AA Dairy separated solids is approximately 23:1. At this C:N ratio, nitrogen availability will not limit the rate of stabilization but some nitrogen loss through NH_3-N volatilization will occur. To minimize nitrogen losses but not limit the rate of stabilization, a C:N ratio of 30 to 35:1 generally is considered as optimal.

COST ANALYSIS

Previously, Moser and Mattocks (2000) reported the total capital cost of the AA Dairy plug flow digester including the engine-generator set and the intertie equipment to be $295,700. However, this sum included two items, a manure collection/mix tank ($12,500) and solids separation equipment ($38,000), that should not have been included. The collection/mix tank would be required without the digester and solids separation does not require anaerobic digestion as a prerequisite. Therefore, the actual cost of this biogas generation/utilization facility was only $245,200.

AA Dairy currently pays an average of $0.029 per kJ ($0.105 per kWh) for electricity purchased from the local public utility and receives an average of $0.015 per kJ ($0.0525 per kWh) sold Assuming a 95 percent on-line engine-generator set efficiency, AA Dairy has the potential of generating 1.78×10^9 kJ (494,812 kWh) of electricity per year, which is slightly more than the estimated annual farm demand of 1.49×10^9 (413, 869 kWh) per year (Peranginangin and Scott, 2002). Assuming that the annual farm demand can be satisfied with biogas generated electricity, the potential value of the electricity used on farm and surplus sold to the local public utility is $45,045 per year. Thus, the simple payback period for the digester-engine generator set is approximately 5.6 years. With a herd expansion to the design value of 1,054 cows, this payback period would be reduced.

CONCLUSION

The results of this study demonstrate that mesophilic anaerobic digestion with biogas utilization can be a cost effective method reducing the potential impacts of dairy cattle manure on air and water quality. It can also directly reduce emissions of methane, a greenhouse gas with a heat trapping capacity approximately 21 times that of carbon dioxide to the atmosphere. In addition, greenhouse gas emissions resulting from the use of fossil fuels to generate electricity are reduced.

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