

Feasibility of Compact, High-Rate Anaerobic Digesters for Biogas Generation at Small Dairy Farms

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ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
Vincent A. DeIorio, Esq., Chairman
Francis J. Murray, Jr., President and Chief Executive Officer

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FOR BIOGAS GENERATION AT SMALL DAIRY FARMS**

Final Report

Prepared for the
**NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY**



Albany, NY
www.nysesda.org

Robert M. Carver, P.E.
Senior Project Manager

Prepared by:
ENVIRONMENTAL MANAGEMENT GROUP INTERNATIONAL, INC.

Yassar H. Farhan, Ph.D., P.E.
Project Manager

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SECTION 1

INTRODUCTION

One of the most promising technologies for on-farm energy generation is anaerobic digestion of manure. This technology has been successfully applied at dairy farms in NYS and across the U.S. to: 1) produce methane gas for heat and electricity generation; 2) reduce or eliminate on-farm electricity costs; 3) reduce or eliminate odors resulting from manure; and 4) control discharge of nitrogen and phosphorus from the residual manure in the environment (USEPA, 2002a).

Currently, the primary system designs available for manure digestion are plug-flow and completely-mixed digesters. These systems typically have hydraulic retention times (HRTs) of 20 to 40 days. Larger farms that use these systems to manage manure and generate biogas have attained between 70% to 90% reduction in energy costs (Wright and Perschke, 1998) and up to 97% odor reduction (Wilkie, 2000).

Plug-flow and completely-mixed digester systems require a relatively large land area, may be adversely affected by manure loading rate variability, and may experience reduced capacity over time due to accumulation of sand or bedding material. These factors, along with the high initial capital investment required, make current digester technologies feasible primarily for larger farms (e.g., for farms with more than 400 cows [Wright and Perschke, 1998; USEPA, 1999]). Typically, smaller farms, which generally have a smaller footprint and variable rates of manure generation, cannot feasibly use current digester technologies for manure digestion.

Given that approximately 95% of the total number of dairy farm operations in NYS have fewer than 350 cows (USEPA, 2001a), it has been difficult for the majority of dairy farms in NYS to benefit from anaerobic digestion for energy generation and manure management. Developing an economically feasible anaerobic digester technology for small dairy farms will greatly enhance the economic viability, power efficiency, and environmental stewardship of this sector.

The goal of this project was to develop and evaluate a compact, high-rate anaerobic digester system that is economically feasible for energy generation and manure management at small farms in NYS. Specifically, this project evaluated anaerobic fluidized bed digester (AFBD) systems, which are an established technology for waste conversion and energy generation in the food and beverage industry (e.g., brewery wastes, cheese-manufacturing wastes, and airport run-off). This project also evaluated several potential AFBD pre-treatment and pre-conditioning processes.

SECTION 2

DESCRIPTION OF ANAEROBIC PROCESSES

Anaerobic technology has been used for over a century for the treatment of a variety of wastes and wastewaters (e.g., McCarty, 1982; Shieh and Li, 1989; Iza et al, 1991; Noike et al., 1985; Sundstrom and Klei, 1979; Metcalf and Eddy, 1991; and Huang et al., 1989). Anaerobic digestion is a complex, multi-step biological process during which the biodegradable portion of the waste is converted into bacterial cells, carbon dioxide, methane gas, and water. There are three basic stages involved in anaerobic digestion: 1) Hydrolysis, liquefaction, and fermentation; 2) Hydrogen and acetic acid formation; and 3) Methane formation. The three-stage scheme, involving possibly five groups of bacteria is shown in Figure 2-1.

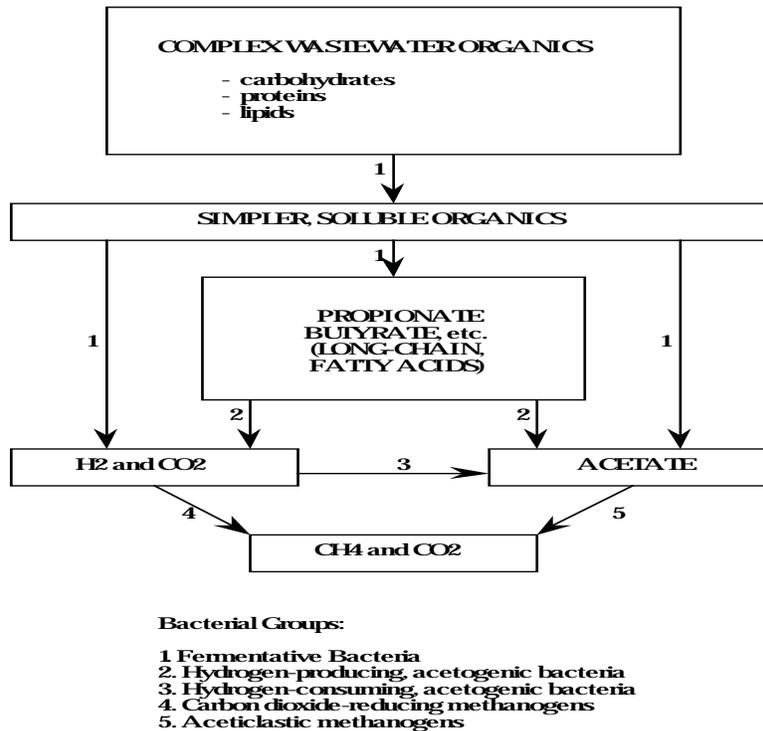


Figure 2.1. Methane Formation in Anaerobic Digestion (after Parkin and Owen, 1986)

2.1 Hydrolysis, Liquefaction, and Fermentation

Hydrolysis and liquefaction are necessary to convert complex organics that may be insoluble to a size and form that is readily usable by the bacteria as energy or nutrient sources. This is accomplished mainly by bacteria-exerted enzymes that promote the solubility of organic waste matter. No waste stabilization takes place during this step, this is merely a change in the form of the five-day biochemical oxygen demand (BOD₅) [or organic carbon]; the ultimate BOD_u [or total organic carbon (TOC)] remains unchanged. A properly functioning hydrolysis and liquefaction step is essential for subsequent waste stabilization, since particle size of the influent waste stream may affect the overall digestion efficiency.

Hydrolyzed complex organic waste is fermented to long-chain organic acids, sugars, amino acids and volatile organic acids (VAs) (Parkin and Owen, 1986). Fermentative acid-forming bacteria may be inhibited by the presence of anaerobic digestion by-products such as hydrogen (Hickey *et al.*, 1987; and Labib *et al.*, 1992). Thus, sufficient system assimilation capacity for hydrogen removal must be maintained to ensure continuous acid production. Stable, co-existing species of fermentative bacteria were found in mixed-culture experiments with carbon sources such as glucose, cellulose, and whey (Thiele, 1991). Rapid growth and metabolism of fermentative bacteria could lead to the accumulation of organic acids that can reduce pH levels. Low pH levels can result in a "sour digester". Though such an environment has little effect on the production of VAs, it can severely inhibit methane formation.

2.2 Hydrogen and Acetic Acid Formation

Hydrogen can be produced by fermentative and acetogenic bacteria. Acetic acid is also produced by these groups, as well as by hydrogen-consuming acetogenic bacteria. Hydrogen has been shown to play a key role in the production of methane gas. Parkin and Owen (1986) suggest that hydrogen partial pressures above 0.1 atm may inhibit methane production and cause VA accumulation. Thus, in order to maintain efficient digestion, a stable population of CO₂-reducing methanogenic bacteria is necessary to ensure sufficient assimilation of hydrogen.

Organic volatile acids that may accumulate during anaerobic digestion of easily hydrolysable or fermentable substrates include acetic acid (acetate), propionate and butyrate (Costello *et al.*, 1991a; Matsui *et al.*, 1993; Chynoweth, 1969; and Jeris and McCarty, 1965). Thus, a stable population of acetate-consuming bacteria is also necessary to maintain an effective anaerobic digestion, since accumulation of these acids would also inhibit the digestion process.

Acetogenic bacteria are often termed "syntrophic" since they are believed to metabolize and grow only in the presence of metabolically active hydrogen- and/or formate-consuming bacteria (Thiele, 1991). It is important to note that acetate is also an inhibitory by-product of anaerobic digestion; thus, the rate of acetate removal by methanogenic bacteria directly affects the metabolic rate of acetogenic bacteria. In fact, high organic acids levels may be used as an indicator of stressful operation of the AFB. Martin, et al. (1993) noted that acetate concentrations above 800 mg/L indicated impending failure of an anaerobic digestion system for swine manure. The same authors reported a ratio of 1.4 between propionic and acetic acid concentrations as a digester failure criterion.

2.3 Methane Formation

Final waste stabilization (organic material removal) occurs when CO₂-consuming and acid-using methanogens produce biogas (composed primarily of methane and carbon dioxide). Methane has a very low solubility in water and is readily separated and collected from the system. Carbon dioxide, on the other hand, is soluble in water (CO₂ solubility is influenced by many factors including partial pressure, pH, and temperature). The produced carbon dioxide either leaves the system as a gas or is converted to bicarbonate alkalinity in water. Thus, a carbon mass balance based on methane production would provide a better measure of the system's conversion efficiency than a balance based on CO₂.

Methanogenic bacteria only can use a specific group of substrates as an energy source. This group includes formic acid, acetic acid, methanol, hydrogen, and carbon dioxide (Parkin and Owen, 1986; and Zeikus *et al.*, 1985). Jeris and McCarty (1965) employed tracer studies to evaluate the direct contribution of acetate to methane production for anaerobic digestion of various substrates. They estimated that 67-100% of the methane production from fatty substrates is directly due to acetate cleavage. Carbohydrates, which are easier to digest than fats, showed 67% methane production from acetate. Proteins and sewage sludge had approximately 70% of their methane production directly attributable to acetic acid. The remainder of produced methane is a result of carbon dioxide reduction using hydrogen as an energy source. A schematic of the pathways for methane production from complex wastes is presented in Figure 2-2.

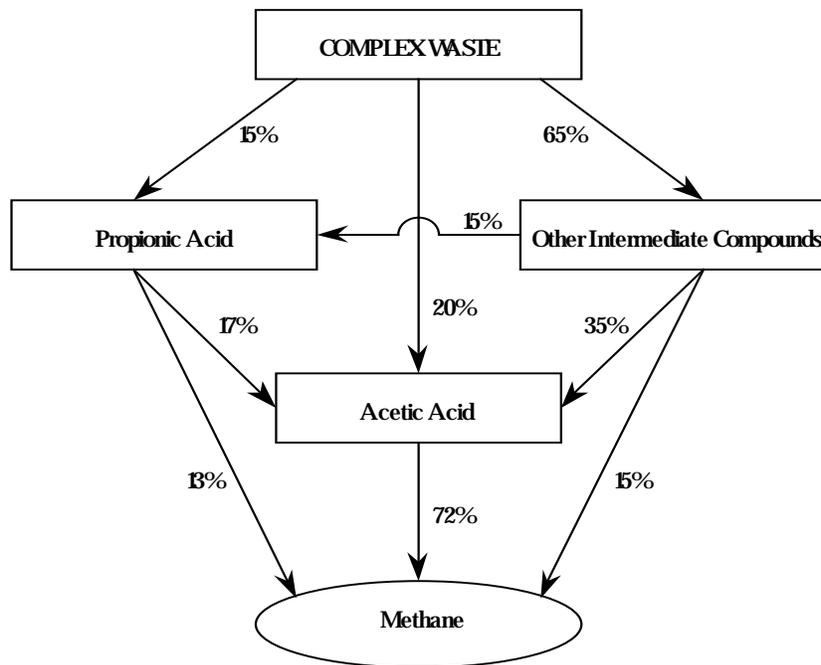


Figure 2.2. Pathways in Methane Fermentation of Complex Wastes. Percentages Represent Conversion of TOC by Various Routes. (McCarty and Smith, 1986)

Despite the complexity of the anaerobic digestion process, it is highly effective in degrading organic wastes and producing energy in the form of methane gas. Anaerobic digestion has been successfully used around the world to treat process-related wastewaters generated by food and beverage manufacturing facilities.

SECTION 3

DESCRIPTION OF ANAEROBIC DIGESTER SYSTEMS

Anaerobic digesters are primarily suspended growth or attached growth systems. In the suspended-growth system the anaerobic bacteria grow suspended in the bulk liquid matrix contained within the digester. In the attached-growth system the anaerobic bacteria grow on pellet or grain surfaces contained within the digester. Examples of suspended-growth digesters include plug-flow and completely-mixed digesters. In general, the kinetics of suspended-growth digester are limited by the slow growth rates of anaerobic bacteria. This limitation may result in: 1) reduced process stability; 2) high hydraulic retention time requirements; and 3) sensitivity of the microorganisms to toxic materials, temperature, and pH (Schraa and Jewell, 1984).

Recent research in anaerobic digestion has led to the development of packed-bed and fluidized bed attached-growth systems that provide many advantages over conventional suspended growth systems and are effective for treating a variety of waste streams. Attached-growth digesters typically have higher loading rates, enhanced process stability, and shorter hydraulic retention time requirements (see Table 3-1) than suspended-growth digesters, due to the inherent physics of the systems. First, due to attachment of bacteria to growth support media within the digester, bacteria washout is minimized resulting in a high cell retention capacity (and subsequently large microbial populations) within the digester. In addition to biodegrading wastes effectively, large microbial populations enhance process stability and facilitate system recovery from adverse operating conditions such as hydraulic and organic overloading. Second, fluidization of the growth support media further increases the cell retention capacity by increasing access to available surface area within the digester, which is especially important for slow-growing methanogenic bacteria.

Anaerobic fluidized-bed digesters (AFBDs) are robust systems that: 1) require a small area of land; 2) can handle high waste loading rates; 3) have high biogas production and capture rates; and 4) can tolerate variable loading rates while maintaining effective operation. AFBD systems are an established technology for waste treatment and methane gas generation in the food and beverage industry (Speece, 1996), and have been used successfully for treatment of brewery wastes (potentially high in sulfates), cheese-manufacturing wastes (high solids and organic content), and airport run-off water (high solids content). Depending on the characteristics of the raw waste stream, pre-treatment may be required.

Because high populations of anaerobic bacteria are developed and maintained in AFBD systems, their organic loading rate is approximately 10 to 40 times higher than completely-mixed and plug-flow digesters. Subsequently, AFBD systems can convert large amounts of waste in a small digester volume, which should be particularly beneficial for manure management at small farms. Most current manure anaerobic digesters have a hydraulic retention time (HRT) range of 12 to 90 days with an organic loading rate of less than 300 lbs. COD/1,000 ft³ digester/day. In comparison, AFBDs have a HRT range of 0.1 to 0.3 days and an organic loading rate between 1,500 and 3,000 lbs. COD/1,000 ft³ digester/day. A comparison of organic loading rates (expressed as lbs. COD/1,000 ft³ digester/day) for various digester designs is provided in Table 3-1.

Table 3.1. Comparison of Operating Parameters for Various Anaerobic Digester Designs.

Digester Design	Loading Rate (Lbs. COD/1,000 ft ³ digester/day)	Waste Source	HRT (days)	COD Removal Efficiency (%)	Reference
Completely-mixed	60-125*	Animal Waste	12-20	35-70	USEPA, 2001b
Horiz. plug flow	60-125*	Animal Waste	18-22	35-70	USEPA, 2001b
Covered first cell of two-cell lagoon	60-125*	Animal Waste	30-90	80-90	USEPA, 2001b
Completely-mixed	250-300*	Dairy-Cow Waste	23	NR	Wilkie, 2000
Fixed-Bed	1,250*	Dairy-Cow Waste	3	57-77	Wilkie, 2000
AFBD	2,200-3,000	Paper Mill (high solids)	0.35	88	Speece, 1996
AFBD	1,600	Brewery (high sulfates)	N/R	98	Speece, 1996
AFBD	2,200	Food Sweetener (high COD)	0.2	95	EMG Laboratory
AFBD	1,750	Cheese Plant (high COD)	0.1	93	EMG System

* Estimated from reported operational parameters

HRT – Hydraulic Retention Time, NR – Not Reported

AFBD systems are not expected to pose public safety issues that have not already been addressed by plug-flow and completely-mixed digester systems, and by use of AFBDs in the food and beverage industry. In fact, because AFBD systems have a small footprint, they can be installed away from “high traffic” areas, and be fenced-in to control accessibility. AFBD systems are likely to provide similar odor control to that provided by plug-flow and completely-mixed digesters. Finally, to reduce system operational tasks to the farmer, AFBD systems can be packaged units ready for operation, with farm operational tasks limited to basic sample collection/analysis and periodic equipment maintenance.

The effectiveness and efficiency of AFBD systems for treating manure digestion and biogas generation will be influenced by many factors including pH, solids-to-water ratio, carbon-to-nitrogen (C/N) ratio, digester temperature, average size of particulates being digested, and digester retention time. Compared to municipal wastewater, animal wastes generally have a neutral pH, potentially high sulfates, high volatile solids (VS), high COD content (which represent degradable materials), and high BOD₅ (which represents readily biodegradable materials). On a weight basis, dairy cow manure contains approximately 10% COD, 11.6% VS, and 1.9% BOD₅ (USEPA, 2002b). To efficiently apply the AFBD technology for manure digestion, pre-conditioning steps that reduce the solids-to-water ratio and increase the bioavailable COD in the raw manure are needed. In addition to laboratory-scale treatability studies to evaluate the technical feasibility of AFBDs for manure digestion and biogas generation, experiments were conducted to establish manure pre-conditioning requirements.

SECTION 4

FARM SELECTION AND WASTE CHARACTERIZATION

A small dairy farm in New York State (NYS) (N-Man Dairy Farm, Box 681, Route 284, Westtown, NY 10998) was selected to supply manure for the laboratory studies. The farm maintains 90-100 cows for milk and meat production. The herd is kept in a barn. Hay is chopped and spread to provide bedding material and maintain a dry area around and under the cows. Approximately 9 to 10 bales of hay (1' H x 1' W x 3' L) are used for the herd on a daily basis. Produced manure and hay are shoveled manually into a narrow trough (1' wide x 8" deep). The trough is fitted with steel scrapers that are operated by a conveyor belt. The produced manure and hay are collected into a tractor equipped with a spreader for field application. The manure collection setup at the farm is shown in Photos 1 and 2 below.



Photo 1. View of the N-Man Dairy Farm Barn with Manure and Hay in the Collection Trough



Photo 2. Chopper Used to Apply Hay in the Area Around and Under the Cows after the Troughs are Cleaned

EMG collected eight five-gallon buckets of manure for the waste characterization and treatability study. Prior to filling the buckets, manure was manually mixed and homogenized. After collection, samples were transported to EMG's laboratory and placed in cold storage. For waste characterization, each bucket was mixed before a sub-sample was collected for analysis. The samples were analyzed for physical characteristics (i.e., total solids, volatile solids (VS), moisture content) and chemical characteristics (i.e., COD, ammonia-N ($\text{NH}_3\text{-N}$), nitrate-N ($\text{NO}_3^-\text{-N}$), phosphate (PO_4^{3-}), and sulfate (SO_4^{2-})). For total solids and volatile solids analysis, a total of nine (9) sub-samples were collected from the manure sample, and were analyzed using Standard Method 2540 (Eaton et al., 1995). For chemical analyses, a total of twenty (20) sub-samples were collected from the manure sample. COD was analyzed using Hach method 8000, ammonia-N ($\text{NH}_3\text{-N}$) was analyzed using Hach method 10205, nitrate-N ($\text{NO}_3^-\text{-N}$) was analyzed using Hach method 10020, phosphate (PO_4^{3-}) was analyzed using Hach method 10127, and sulfate (SO_4^{2-}) was analyzed using Hach method 8051. Results from these analyses are summarized in Tables 4-1, 4-2, and 4-3. These results were used as a baseline for conducting the laboratory scale AFBD treatability studies. The average measured COD was 137,220 mg/L (i.e., 13.7%), VS was 12.6%, phosphorus was 2,214 mg/L, and ammonia-N was 1,954 mg/L. The baseline data are similar to existing data available from the USEPA (recognizing that different farms will produce manure with slightly different characteristics); COD of 10%, VS of 11.6%, phosphorus of 1,550 mg/L, and ammonia-N of 1,250 mg/L (USEPA, 2002b).

Table 4.1. Summary of Analyses (Total Solids and Volatile Solids) Performed on Manure Samples Collected from N-Man Dairy Farm.

Sample Number	Total Solids (mg/L)	Volatile Solids (mg/L)
1	148,681	124,835
2	150,462	127,319
3	148,901	127,143
4	150,769	125,736
5	150,418	125,297
6	148,747	126,659
7	149,824	127,231
8	148,549	126,989
9	148,308	127,495
Average Value (Std. Dev.)	149,407 (957)	126,523 (979)

Table 4.2. Summary of Analyses (Percent Solids and Percent Water) Performed on Manure Samples Collected from N-Man Dairy Farm

Sample Number	Percent Solids (%)	Percent Water (%)
1	15.5	84.5
2	14.3	85.7
3	14.2	85.8
4	14.6	85.4
5	14.5	85.5
6	14.6	85.4
7	15.2	84.8
8	14.9	85.1
9	14.7	85.3
10	15.1	84.9
11	15.3	84.7
12	15.4	84.6
13	14.9	85.1
14	15.0	85.0
15	15.0	85.0
16	14.9	85.1
17	15.1	84.9
18	14.9	85.1
19	15.0	85.0
20	15.2	84.8
Average Value (Std. Dev.)	14.9 (0.34)	85.1 (0.34)

Table 4.3. Summary of Analyses Performed on Manure Samples Collected from N-Man Dairy Farm

Sample Number	COD (mg/L)	NO₃⁻ - N⁻ (mg/L)	PO₄³⁻ (mg/L)	SO₄²⁻ (mg/L)	NH₃-N (mg/L)
1	124,600	760	2,300	30,000	1,872
2	107,800	890	2,120	28,500	1,908
3	115,200	460	2,080	26,500	1,896
4	145,800	745	1,900	30,000	1,776
5	162,400	630	2,032	29,000	1,800
6	147,400	570	2,152	28,500	1,860
7	141,400	505	2,228	31,000	1,848
8	138,400	505	2,316	30,500	1,800
9	182,200	810	2,896	31,000	1,824
10	138,800	610	2,412	30,500	1,812
11	132,600	670	2,428	29,000	2,088
12	155,800	565	2,484	29,000	2,232
13	144,600	695	1,976	30,000	2,208
14	131,800	635	2,004	32,500	2,148
15	127,800	645	1,904	31,500	2,196
16	142,800	715	1,872	32,500	1,956
17	148,000	605	2,392	29,000	1,968
18	120,000	760	2,232	31,500	1,956
19	122,600	730	2,276	31,000	2,064
20	114,400	720	2,280	30,000	1,872
Average Value (Std. Dev.)	137,220 (17,893)	661 (110)	2,214 (247)	30,075 (1471)	1,954 (149)

Table Notes:

- COD denotes Chemical Oxygen Demand

SECTION 5

WASTE PRE-TREATMENT AND PRE-CONDITIONING EXPERIMENTS

Laboratory-scale experiments to evaluate manure pre-treatment and pre-conditioning were conducted with a goal of producing a waste stream that had a high COD concentration and low suspended solids in the bulk liquid matrix, had a high degree of consistency, and was free of coarse solid matter. The manure pre-conditioning steps evaluated herein included:

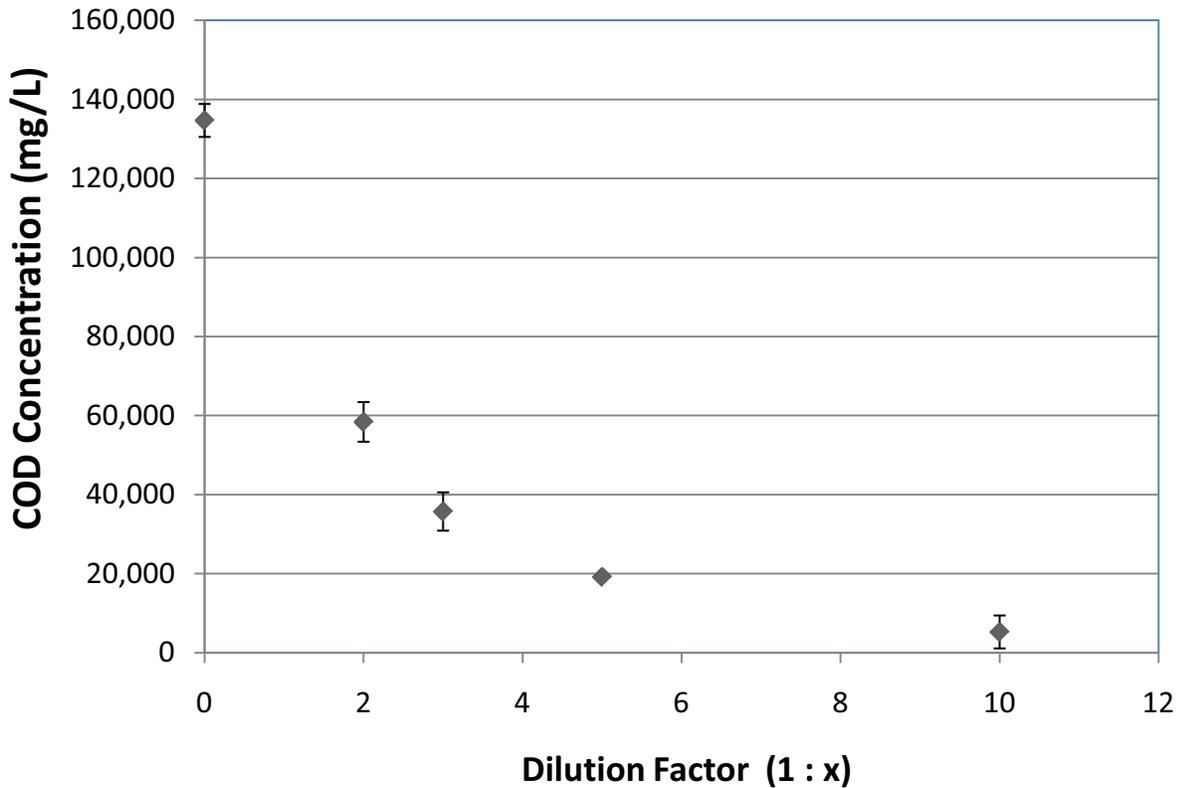
- a) Dilution - Raw manure was mixed with tap water to homogenize the waste stream and modify its physical characteristics so that the mixture could be directly pumped into the digester;
- b) Grinding and blending – A grinding blender (Sears, *CounterCraft*) was used to reduce and homogenize the manure particulate size prior to treatment;
- c) Solids Separation and Liquefaction - Raw manure was passed through a solids separator (Integrity Ag Systems, Chambersburg, PA) to remove large solids (e.g., bedding material) that can adversely affect the performance of the AFBD system, then mixed with water; COD concentration was measured over time;
- d) Hydrolysis - Manure pH was reduced to a point where soluble, bioavailable organics such as sugars, alcohols, peptides, and long-chain organic acids were produced; and
- e) Fermentation and acidification (early digestion steps) – Manure was placed in large waste holding containers with various hydraulic retention times (HRT) and evaluated to measure the break-down of long-chain carbon compounds into shorter-chain compounds that can be readily biodegraded to produce methane and carbon dioxide.

5.1 Dilution Experiments

These experiments were conducted to evaluate the effect of dilution on raw manure prior to treatment in the AFBD system. Raw manure samples (100 mls each) were diluted with tap water at four (4) sample-to-total-volume ratios: 1:2; 1:3; 1:5, and 1:10. The samples were mixed with a magnetic stir bar for approximately 20 minutes; no grinding blender was used. Dilution experiments were run in triplicate, and samples collected from the experiments were analyzed for COD.

At the 1:2 dilution, the measured COD concentration was approximately 44% of the concentration in the raw sample (as compared with a theoretical COD concentration of 50%). At the 1:3 dilution, the measured COD concentration was approximately 26% of the concentration in the raw sample (as compared with a theoretical COD concentration of 33.3%). For the 1:5 and 1:10 dilution, the measured COD concentrations were approximately 14% and 4%, respectively, of the COD concentration in the raw sample (as compared with theoretical COD concentrations 20% and 10%, respectively). [Note: The measured COD values were approximately 6% below the theoretical values for each dilution, which is likely due to the fact that a portion of the “larger” solids in the raw sample is not transferred to the different dilution containers, perhaps due to the sample transfer/analysis procedures.] The results are shown in Figure 5-1.

In summary, the measured COD concentrations in the liquid phase decreased as the dilution ratio increased. In other words, although the addition of water to the raw manure sample improved the pumping and handling of the manure, it had minimal benefits with regard to making the organic content of manure more available in the bulk liquid matrix (as compared to grinding and blending experiments discussed below).



**Figure 5.1. Measured COD Concentrations during Dilution Experimentation
(Error Bars Represent One Standard Deviation)**

5.2 Grinding and Blending Experiments

These experiments were conducted to evaluate the effect of fragmenting and homogenizing raw manure particulate size prior to treatment in the AFB system. Raw manure samples were blended with tap water in a grinding blender for 20 minutes at four (4) sample-to-total-volume ratios: 1:2; 1:3; 1:5, and 1:10. Blending experiments were run in triplicates, and samples collected from the experiments were analyzed for COD, alkalinity, and volatile acids.

Grinding and blending seemed to increase the measured COD concentration in the bulk liquid matrix (after correcting for dilution). As compared to the average raw manure COD concentration of 137,220 mg/L (see Table 4-3), the measured COD concentration increased by 25% in the 1:2 dilution and up to approximately 60% in the 1:10 dilution. This is most likely due to the fact that grinding reduces the particle size and increases the solubility of the

organics. On the other hand, measured VA and alkalinity concentrations remained relatively steady despite grinding and blending (after correcting for dilution). This is most likely due to the fact that the samples were analyzed within 20 minutes of grinding and were not allowed sufficient time to ferment and produce additional volatile acids. The results are shown in Figures 5-2 and 5-3.

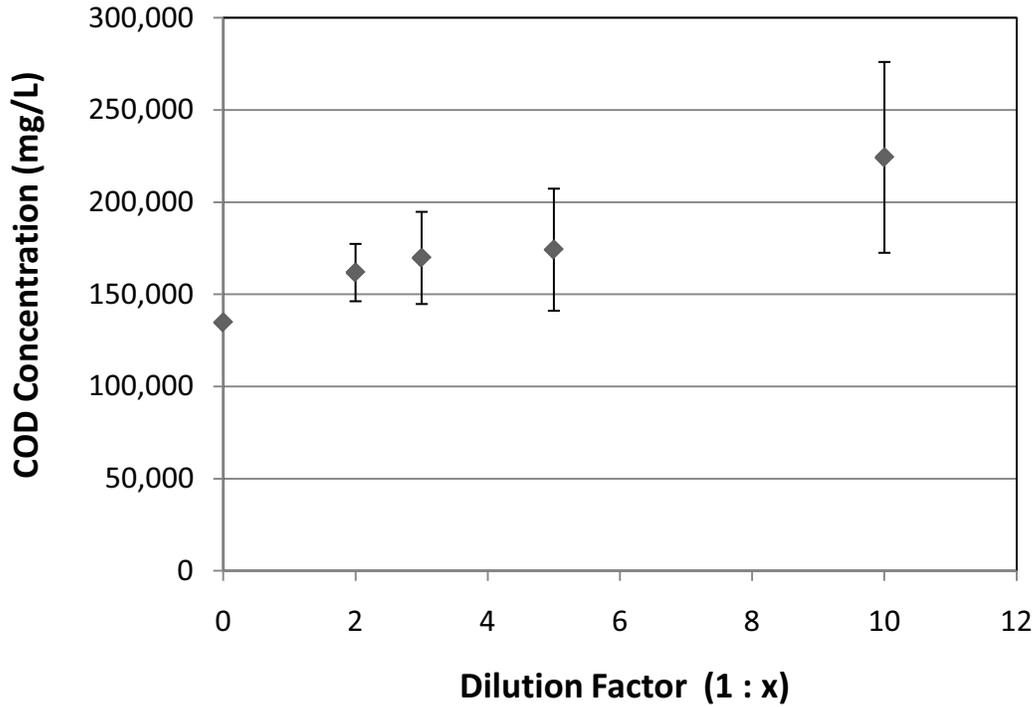


Figure 5.2. Measured COD Concentrations during Grinding and Blending Experimentation (Error Bars Represent One Standard Deviation)

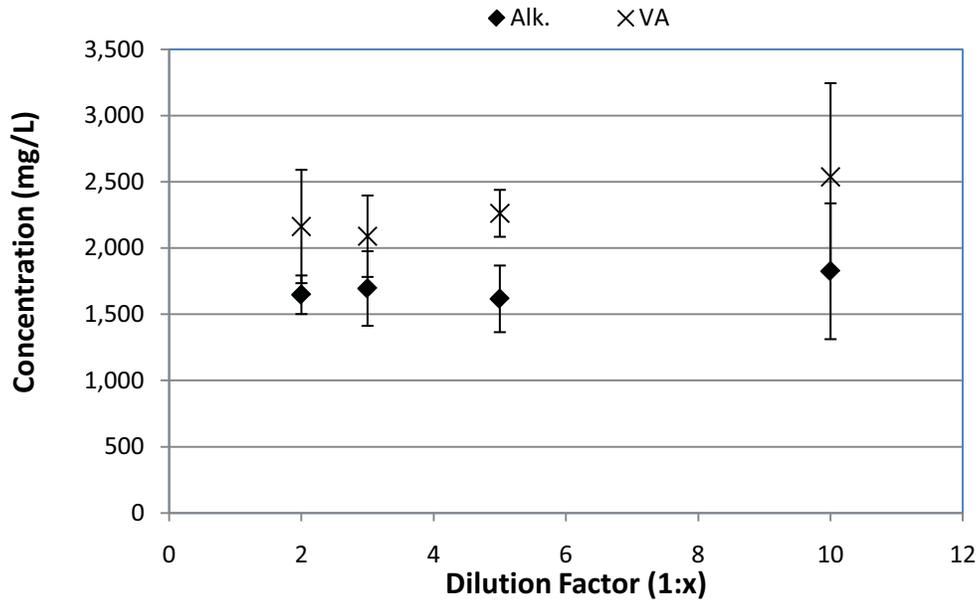


Figure 5.3. Measured Alkalinity and Volatile Acid Concentrations during Grinding and Blending Experimentation (Error Bars Represent One Standard Deviation)

5.3 Solids Separation and Liquefaction Experiments

These experiments were conducted to evaluate the kinetics of the liquefaction of separated raw manure. Note that liquefaction in this investigation is defined as the process during which larger manure particles are fragmented into smaller particles by solids separation and water addition, thereby changing the measured COD concentration in the bulk liquid matrix. Raw manure was passed through a screw-press solids separator (Integrity Ag Systems, Chambersburg, PA), then 100 milliliter (ml) sub-samples were diluted with tap water at four (4) sample-to-total-volume ratios: 1:2; 1:3; 1:5; and 1:10. The diluted samples were mixed with a magnetic stir bar; no grinding blender was used. The experiments were run in triplicate, and samples were collected from the batch after 10 minutes, 20 minutes, 30 minutes, 60 minutes, and 120 minutes from the start of the liquefaction experiment and analyzed for COD. No analyses were conducted on the separated solids stream during these experiments. Nevertheless, Gooch et al., 2005, presented data showing that conducting solids separation at a 100-cow dairy farm resulted in a separated liquid manure stream that represents 77.3% of the total raw manure volume (with the remaining 22.7% of the volume going to the separated solids stream) (Gooch et. al., 2005). That study also showed that for a raw manure stream from a 100-cow dairy farm with a Total Solids Concentration of approximately 10%, the separated liquid manure stream had a total solids concentration of approximately 5%, while the separated solids stream had a total solids concentration of approximately 25% (Gooch et. al., 2005).

For all the dilution ratios tested, the measured COD concentration in the bulk liquid reached steady state after approximately 60 minutes. Alkalinity concentrations remained mostly steady over the 120 minute duration of the experiments, while VA concentrations generally decreased during the first hour, then stabilized for the remainder of the experiment. Measured COD concentrations are shown in Figure 5-4. Measured alkalinity and VA concentrations (corrected for dilution) are shown in Figures 5-5 to 5-8.

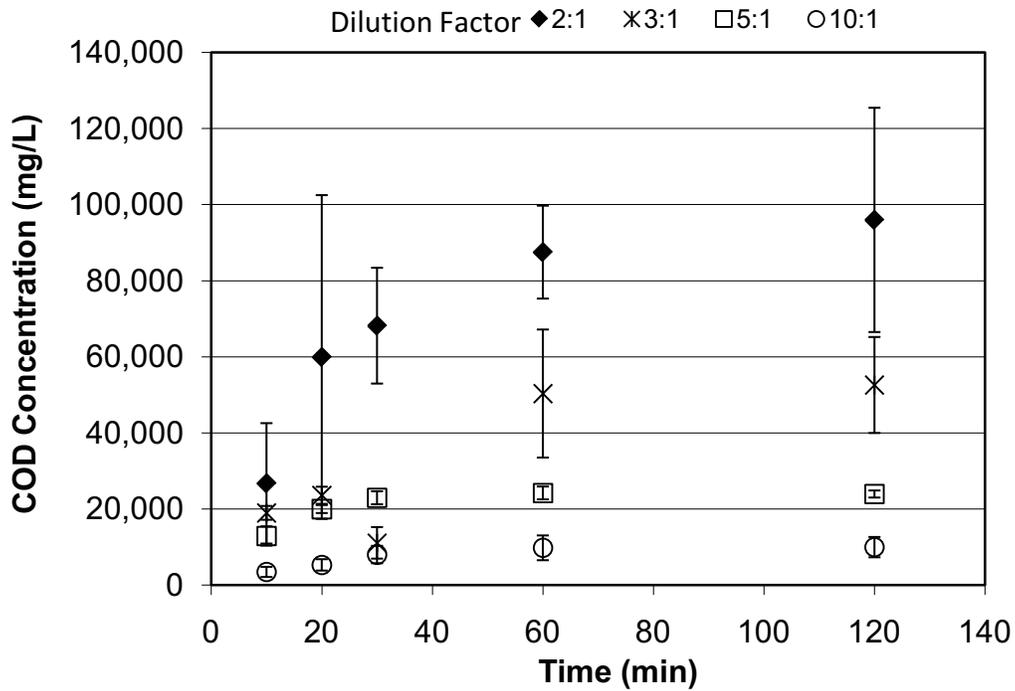


Figure 5.4. Measured COD Concentrations during Solids Separation and Liquefaction Experimentation (Error Bars Represent One Standard Deviation)

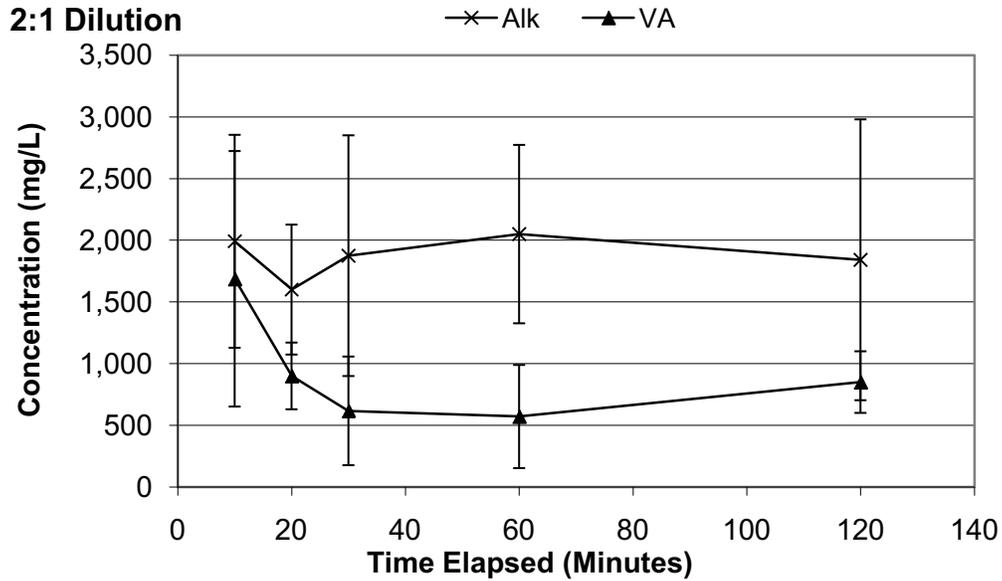


Figure 5.5. Measured Alkalinity and VA Concentrations during Solids Separation and Liquefaction Experimentation (Error Bars Represent One Standard Deviation)

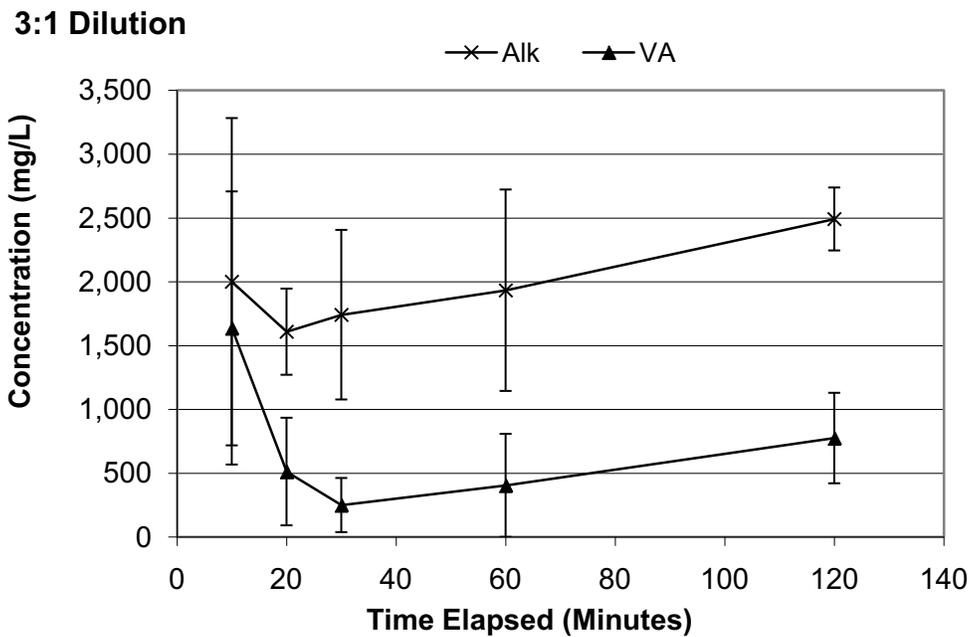


Figure 5.6. Measured Alkalinity and VA Concentrations during Solids Separation and Liquefaction Experimentation (Error Bars Represent One Standard Deviation)

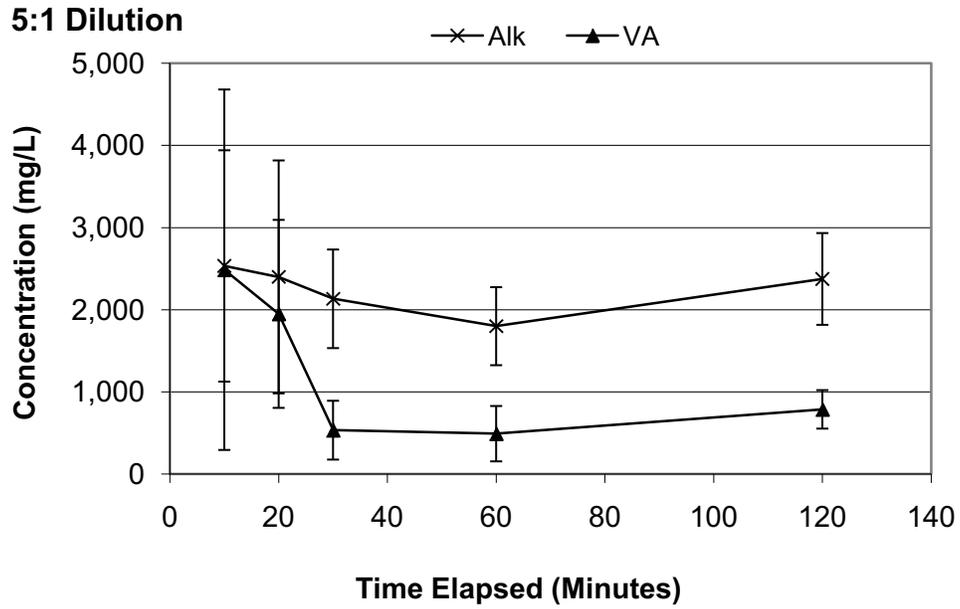


Figure 5.7. Measured Alkalinity and VA Concentrations during Solids Separation and Liquefaction Experimentation (Error Bars Represent One Standard Deviation)

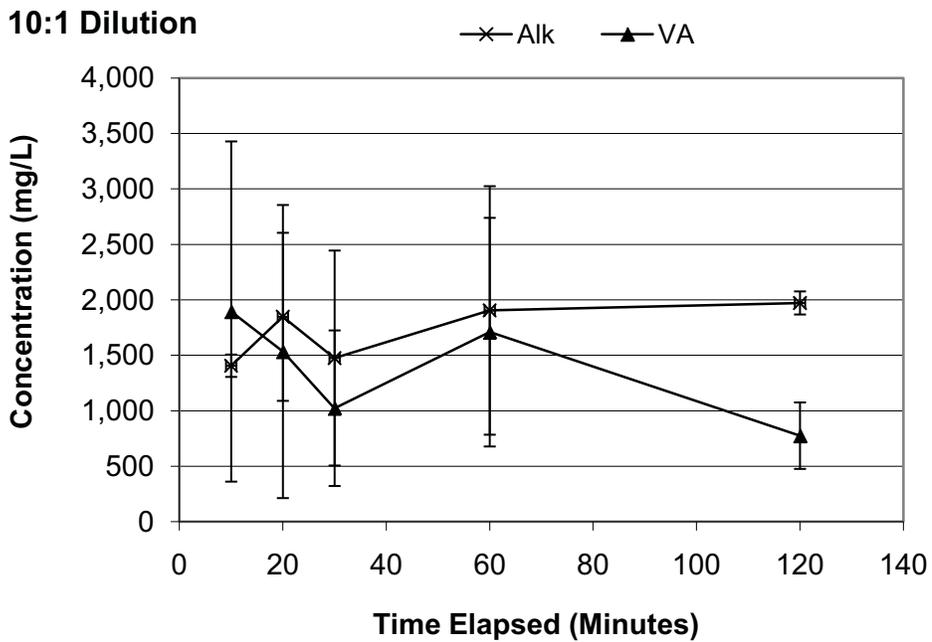
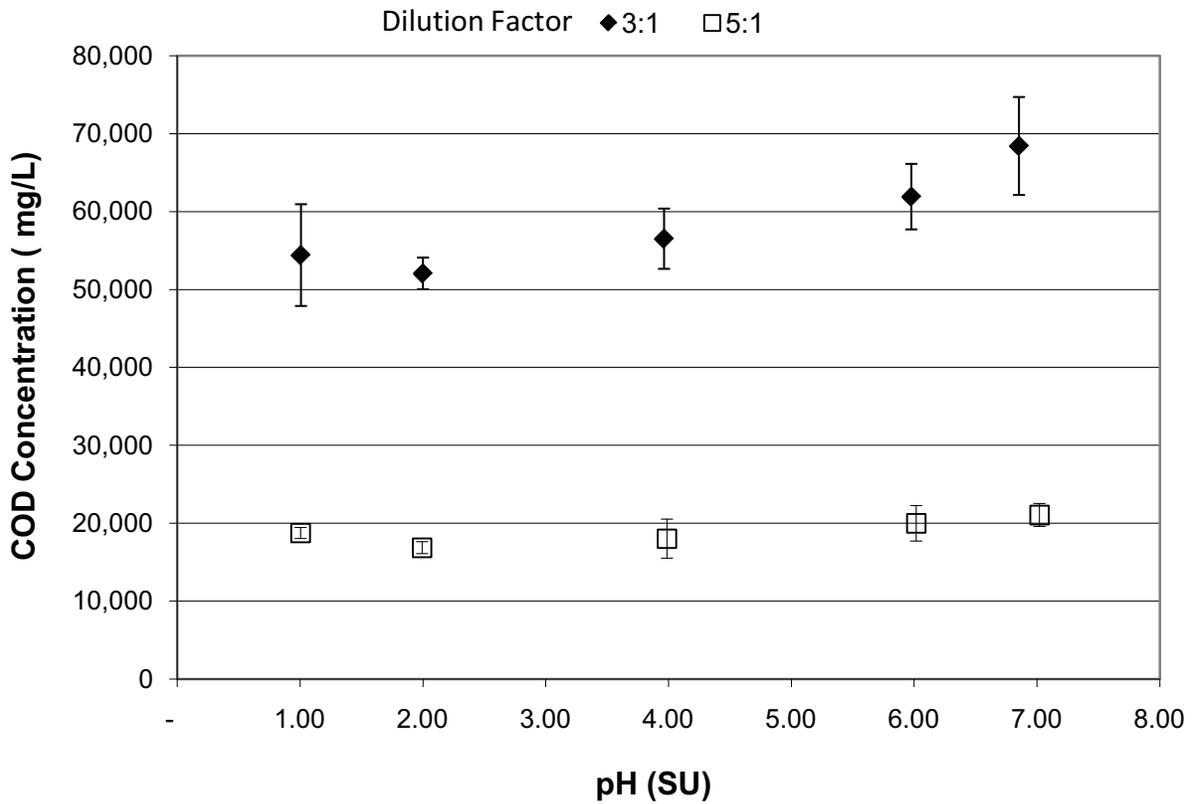


Figure 5.8. Measured Alkalinity and VA Concentrations during Solids Separation and Liquefaction Experimentation (Error Bars Represent One Standard Deviation)

5.4 Hydrolysis Experimentation

These experiments were conducted to evaluate the affect of pH on measured COD. Raw manure samples were passed through a solids separator (*Integrity Ag Systems*, Chambersburg, PA) then sub-samples (100 mls each) were collected and diluted with tap water at 1:3 and 1:5 sample-to-total volume ratios. These dilution ratios were selected because they resulted in the most desirable consistency for pumping and handling of the manure. Sulfuric acid was added to reduce the pH of each sample to four discrete pH levels (6, 4, 2, and 1) (pH was measured using a Thermo Fisher Scientific pH meter, Waltham, MA). Each pH level was run in triplicates. Lowering of the pH level did not increase the measured COD concentrations in the bulk liquid matrix (see Figure 5-9).



**Figure 5.9. Measured COD Concentrations during Hydrolysis Experimentation
(Error Bars Represent One Standard Deviation)**

5.5 Fermentation and Acidification Experimentation

These experiments were conducted to evaluate whether implementation of fermentation and acidification (an early-stage digestion step) can increase the available COD in the bulk liquid matrix. Raw manure samples were diluted with tap water at 1:3 and 1:5 water-to-total volume ratios, with subsequent solids separation. Each experiment was performed in large, sealed, one liter plastic bottles, and allowed to ferment at room temperature in an anaerobic environment for up to fifteen (15) days. Samples were collected from the experiments at various time intervals (1-hour, 2-hours, 6-hours, 24-hours, 5-days, 10-days and 15-days) and analyzed for COD, VA, and alkalinity concentrations in the bulk liquid matrix.

Subjecting raw manure samples to early digestion did not significantly change the COD concentrations in the bulk liquid matrix in either 1:3 or 1:5 dilution ratio experiments. After an initial increase in VA concentration in the bulk liquid matrix, VA concentrations stabilized for the remainder of the experiment. Similarly, alkalinity concentrations initially increased and then stabilized. Measured COD concentrations are shown in Figure 5-10. Measured VA and alkalinity concentrations are shown in Figure 5-11.

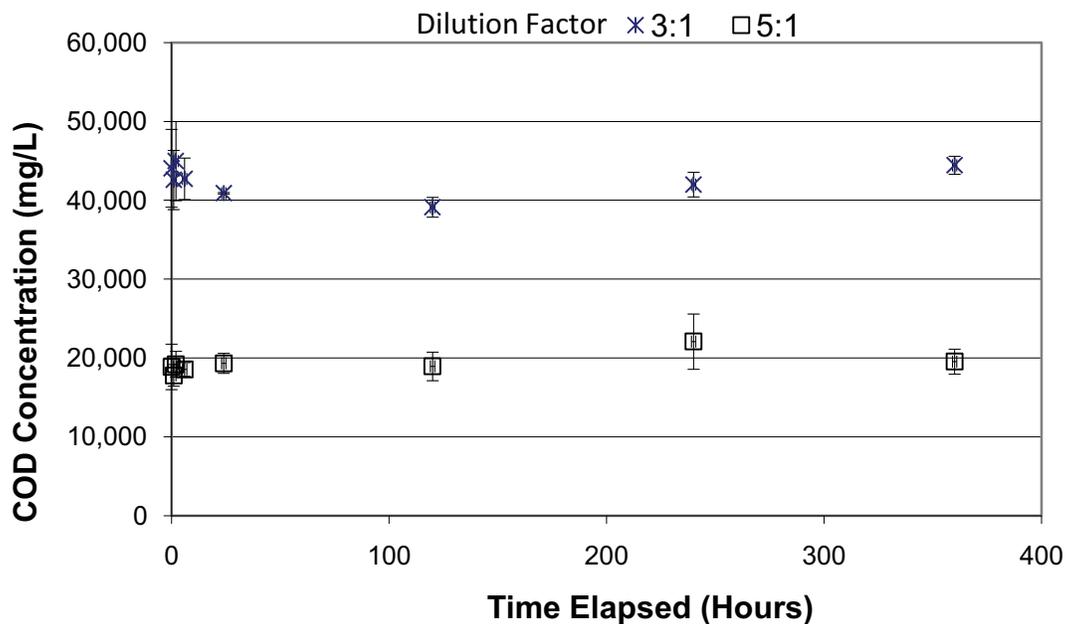


Figure 5.10. Measured COD Concentrations during Fermentation and Acidification Experimentation (Error Bars Represent One Standard Deviation)

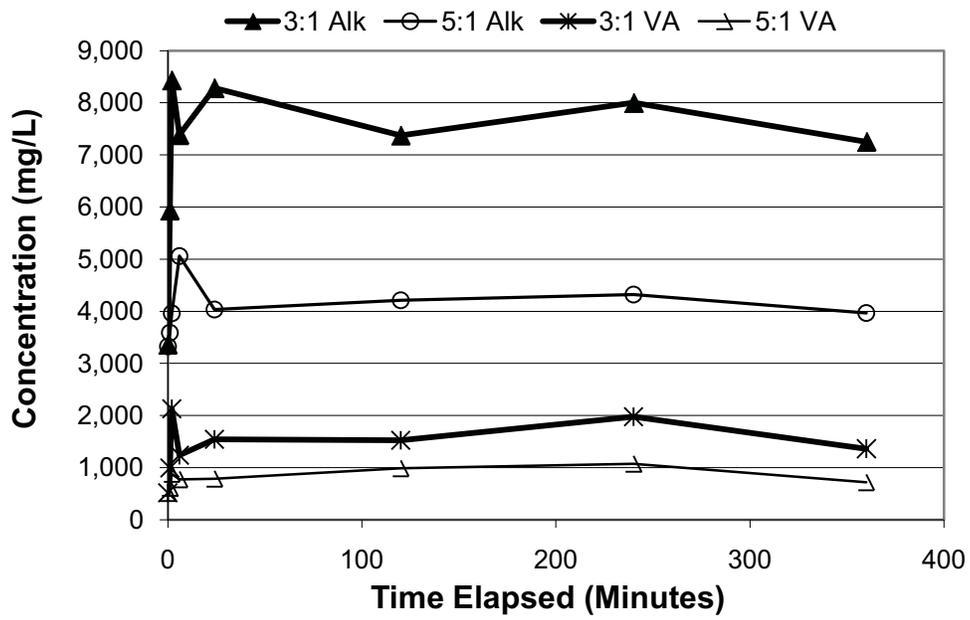


Figure 5.11. Measured Alkalinity and VA Concentrations during Fermentation and Acidification Experimentation

SECTION 6

BENCH-SCALE AFBD TREATABILITY STUDIES

Two bench-scale AFBDs were fabricated, each with an influent line, an effluent line, a water recycle line, and a biogas collection line. To start up the AFBDs, an anaerobic sludge sample was added as a bacterial seed, which was screened and homogenized prior to addition to the AFBDs. One digester was fed unconditioned (raw) manure and the other pre-conditioned (solids separation; 1:3 dilution ratio) manure. This was done so that the effects of pre-conditioning on AFBD performance could be evaluated. In the field-scale system, a portion of the AFBD effluent (rather than tap water) can be used as dilution water. As noted previously, solids separation and dilution pre-treatment conditioning was shown to produce a desirable consistency for pumping and handling of the manure. Manure was fed continuously into the AFBDs until a pseudo steady-state for biomass and chemical concentrations were achieved. Digester temperature was monitored and maintained between 90°F - 100°F. Biogas volume was measured using a gas flow totalizer (Gas Meter Co., Nashville, TN). A gas probe (RKI Instruments, Union City, CA) was used to periodically monitor biogas composition.

Measured influent/effluent COD concentrations and alkalinity/VA concentrations in the AFBD that was fed raw manure are shown in Figures 6-1 and 6-2, respectively. Soon after start up, this unit clogged. After multiple unclogging/reclogging cycles during the first ten days of operation of the unit, it became apparent that the AFBD system could not be operated using raw manure without any solids separation.

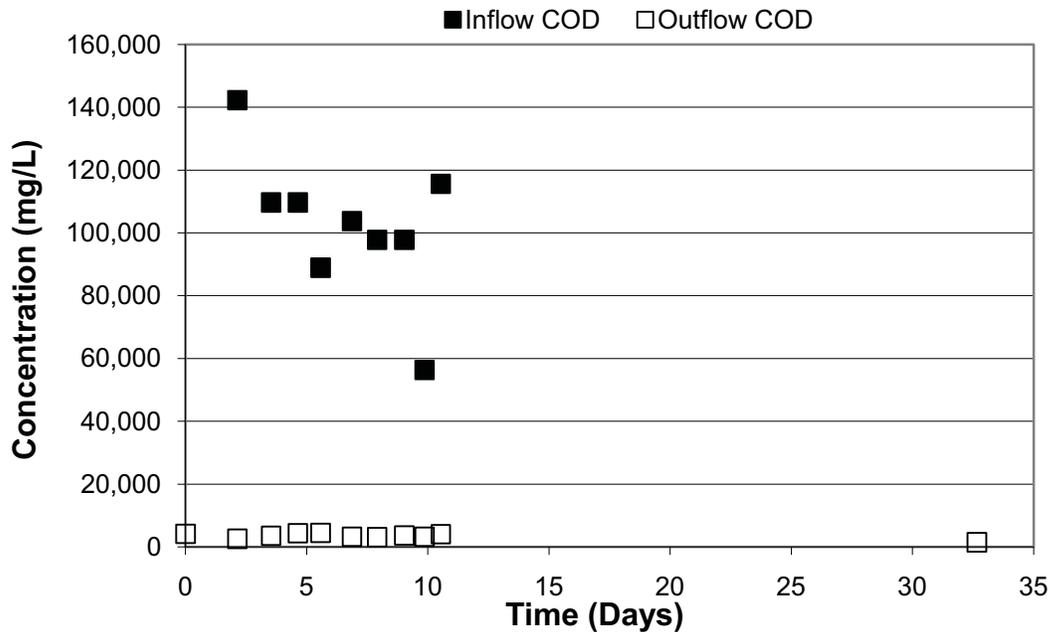


Figure 6.1. Measured Influent and Effluent COD Concentrations in the Bench-Scale AFBD System Fed with Raw Manure without Solids Separation.

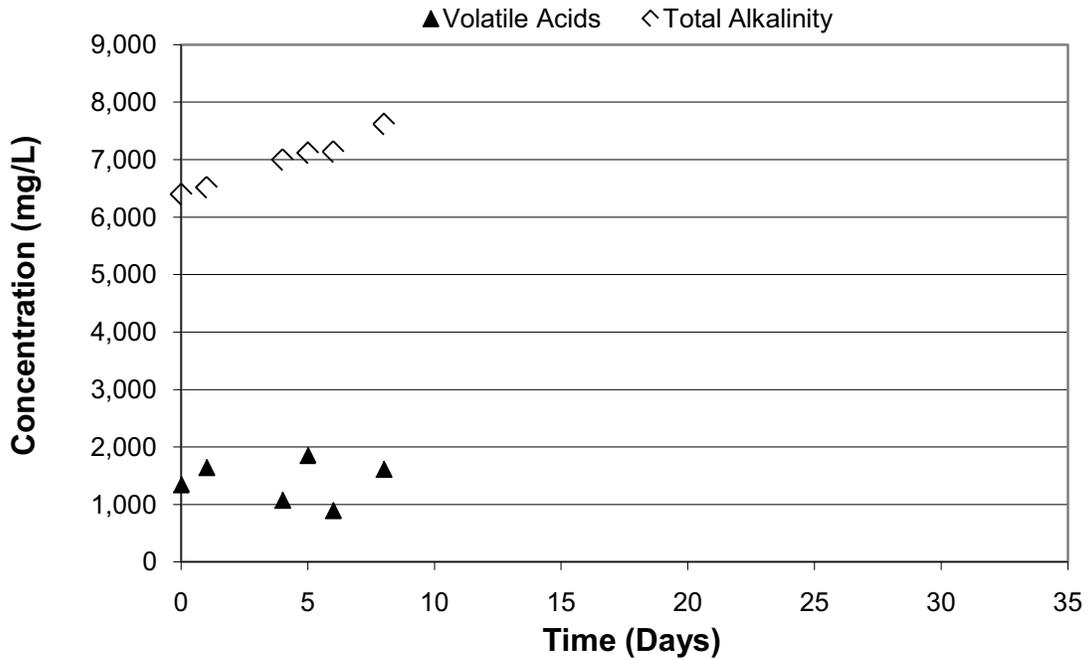


Figure 6.2. Measured Alkalinity and VA Concentration in the Bench-Scale AFBD Fed Raw Manure without Solids Separation.

Measured influent/effluent COD concentrations in the AFBD that was fed pre-conditioned manure are shown in Figure 6-3. Prior to starting this experiment, manure feed was pre-conditioned by separating the solids first then diluting the liquid manure using a 1:3 dilution ratio. The pre-conditioned feed manure was prepared in several buckets and placed in cold storage for this experiment. For use as feed for the digester unit, each bucket was placed on a magnetic stirrer and continuously mixed as it was fed. Over the duration of the study, this AFBD unit maintained consistent removal of COD from the influent manure stream (Figure 6-3). On average, the incoming manure stream had a COD concentration of approximately 98,045 mg/L, whereas the average COD concentration in the effluent was 7,756 mg/L. This represents an average COD removal efficiency of approximately 92%. Unlike the AFBD fed raw manure, this unit operated consistently for approximately one month with minimal down time. Measured alkalinity and VA are shown in Figures 6-4; alkalinity remained steady at approximately 8,000 mg/L and the VA concentration ranged between 2,000 mg/L and 3,000 mg/L.

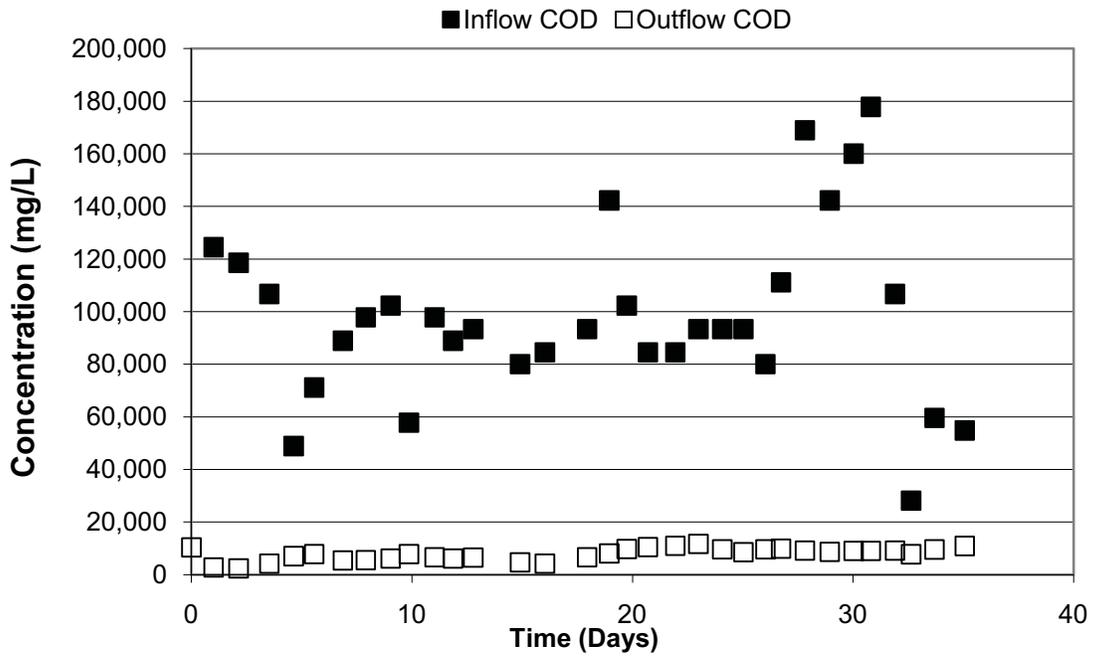


Figure 6.3. Measured Influent and Effluent COD Concentrations in the Bench-Scale AFBD System Fed with Pre-Conditioned Manure

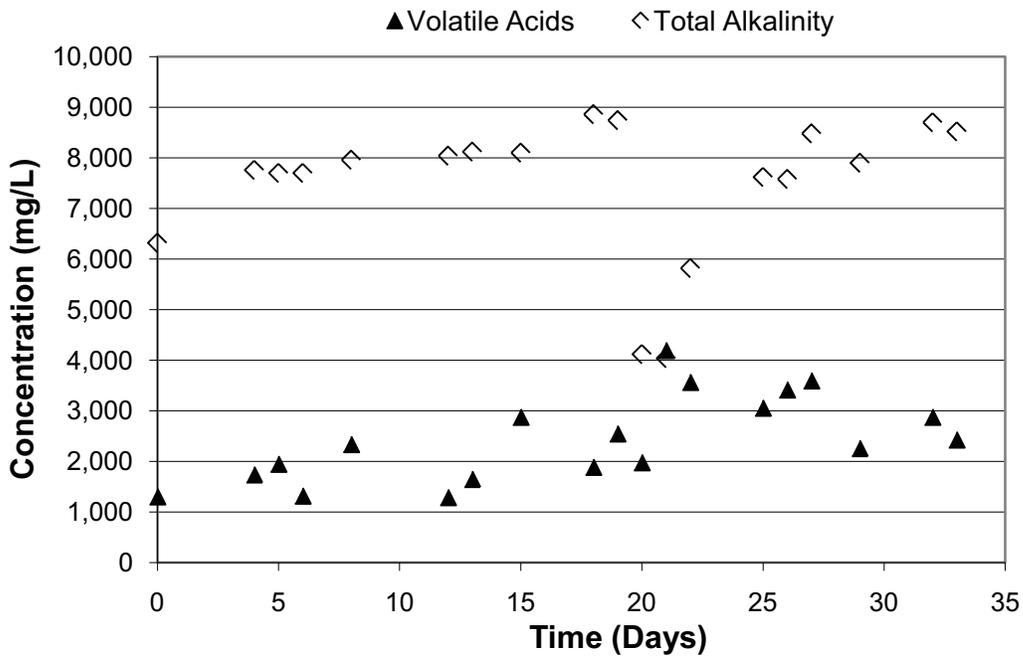


Figure 6.4. Measured Alkalinity and VA Concentration in the Bench-Scale AFBD Fed Pre-Conditioned Manure

The calculated daily COD removal efficiency and the cumulative biogas generation from the AFBD unit fed pre-conditioned manure are shown in Figure 6-5. This figure shows both steady COD removal efficiency and biogas generation during operation of the unit.

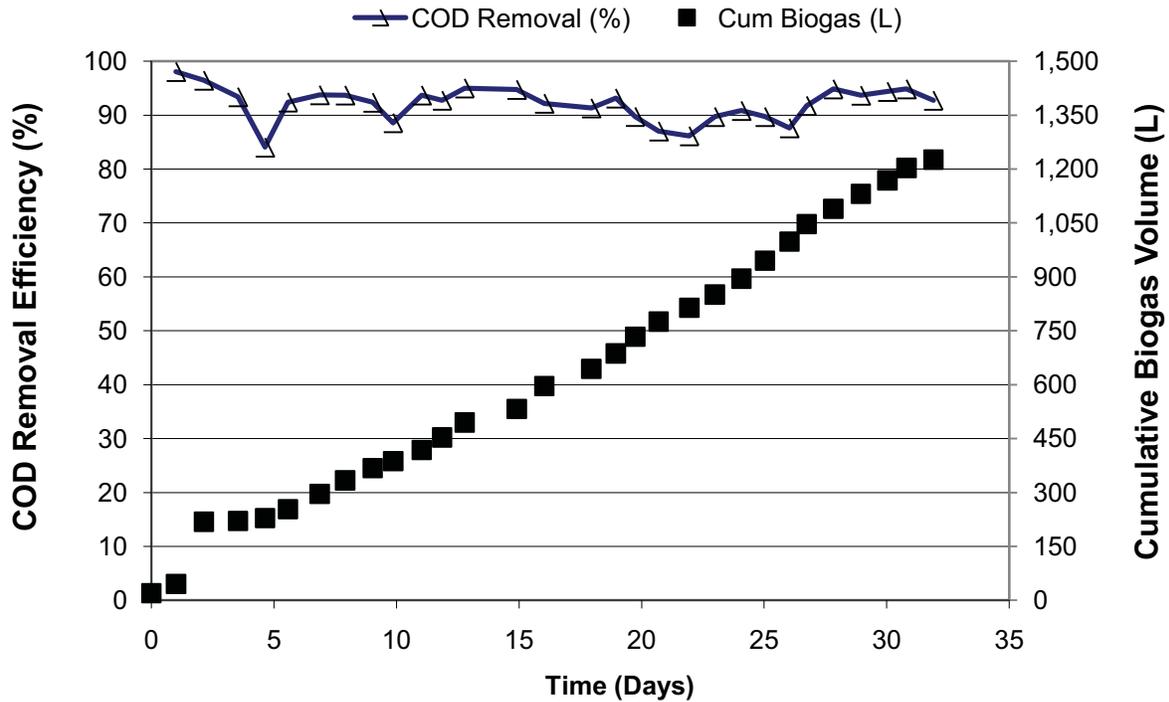


Figure 6.5. Measured Biogas Generation and Calculated COD Removal Efficiency in the Bench-Scale AFBD Fed Pre-Conditioned Manure

Additional parameters measured in the AFBD system fed pre-conditioned manure are shown in Table 6-1. Based on data shown in the table, the AFBD system resulted in a reduction in total solids and volatile solids, but did not affect ammonia and sulfide levels in the manure stream. Sulfide levels in the biogas exceeded the maximum detection limit of the instrument (1,250 ppmv), which warranted measuring sulfide levels in the bulk liquid matrix. The biogas methane content ranged from 59% to 68%, with an average value of 65%. The biogas CO₂ content ranged from 32% to 41% with an average value of 35%.

Table 6.1. Selected Parameters Measured in the Bench-Scale AFBD System During Operation.

Parameter	Influent	Effluent
Total Solids (n)	3.95% (2)	2.88% (2)
Volatile Suspended Solids (n)	20,790 (2)	16,460 (2)
Total phosphate (PO_4^{3-}) (n)	2,880 (4)	Not Measured
Total Nitrogen (n)	1,822 (5)	Not Measured
pH (n)	7.3 (3)	Neutral
Nitrate-N (NO_3^- -N) (n)	244 (1)	205 (1)
Ammonia-N (NH_3 -N) (n)	1,450 (2)	1,417 (2)
Sulfate (SO_4^{2-}) (mg/L) (n)	4,350 (2)	4,600 (2)
Sulfide (mg/L) (n)	18.9 (3)	25.6 (2)
Alkalinity (mg/L) (n)	7,953 (11)	See Figure 6-4

Table notes: n denotes the number of samples analyzed.

The volumetric loading rate (VLR) of the AFBD fed pre-conditioned manure, defined as the mass of organic material expressed as pounds of COD applied per 1,000 cubic feet of digester volume per day (lbs COD/1,000 ft³-day), was calculated at 1,963 lbs COD/1,000 ft³-day. This value compares well with AFBD loading rates shown in Table 3-1. This value will be used for design of a field-scale AFBD demonstration system at a small farm in NYS.

SECTION 7

PROJECTED AFBD TECHNOLOGY BENEFITS FOR NEW YORK STATE

Based on results from this investigation, use of the AFBD technology for manure digestion and electricity generation at small dairy farms in New York State can reduce this sector’s electricity costs and usage, environmental impact on NYS water resources and the atmosphere, and improve the dairy sector’s overall economic viability. The following subsections discuss potential energy, economic, and environmental benefits from application of the AFBD technology at small farms in New York State. Note that system benefits provided below (including organics removal efficiency, biogas production rates, electricity generation, and bedding material production) are based on the data obtained from this Feasibility Investigation, available literature, and EMG’s operating experience from full-scale AFBD system applications.

7.1 Energy Benefits

Application of the AFBD technology is expected to provide energy benefits to a small dairy farm such as N-Man Dairy, as well as, potential energy benefits to New York State overall as follows:

7.1.1 BTU Generation

Completing an AFBD system at a small dairy farm is expected to generate over 2,200 standard cubic feet of usable biogas per day (SCFD), or 800,000 SCF per year. The produced biogas composition will be approximately 65% methane gas and 35% carbon dioxide. Using a heating value of 1,000 BTUs per cubic foot of methane, the BTU value of the biogas is $2,200 \times 65 \times 1,000,000 = 1.43$ million BTUs per day (approximately 520 million BTUs per year).

State wide, New York has about 3,100 *Small Dairy Farms* (farms having 50 to 500 cows), maintaining in excess of 350,000 dairy cows and heifers (USDA, 2009). Therefore, the calculated average NYS small dairy farm herd size is 113 cows. Projected BTU generation benefits from wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-1 below.

Table 7.1. Projected BTU Generation Benefits from State-Wide Application of the AFBD Technology at Small Dairy Farms in New York^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Biogas Generation (million SCF/Year)	BTU Generation (MMBTU/Year)
1%	31	28	18,280
5%	155	141	91,420
10%	310	281	182,840
25%	755	685	445,300
40%	1,240	1,125	731,360
50%	1,550	1,406	914,200

Table Notes: ^{*1} Assumes an average small dairy farm herd size of 113 cows
SCF denotes Standard Cubic Feet, MMBTU denotes million BTU.

As can be seen from Table 7-1, application of the AFBD technology for 10% of *Small Dairy Farms* in New York State could generate 281 million SCF/Year of biogas, with a heating value of 182,840 MMBTU/Year. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York State could result in the generation of 1,406 million SCF/Year of biogas, with a heating value of 914,200 MMBTU/Year.

7.1.2 KW-H Generation

Using a generator set with an efficiency of 30%, and a conversion factor of 293 KW-H per million BTU, the amount of KW-H generated each day for a small dairy farm such as N-Man Dairy = $1.43 \times 0.3 \times 293 = 126$ KW-H per day (approximately 45,880 KW-H per year).

Projected electricity generation benefits from state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-2 below.

Table 7.2. Projected MWH Generation from State-Wide Application of the AFBD Technology at Small Dairy Farms in New York^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Electricity Generation (MWH per year)
1%	31	1,610
5%	155	8,040
10%	310	16,070
25%	755	39,140
40%	1,240	64,290
50%	1,550	80,360

Table Notes: ^{*1} Assumes an average small dairy farm herd size of 113 cows

MWH denotes MegaWatt-Hour

As can be seen from Table 7-2, application of the AFBD technology for 10% of *Small Dairy Farms* in New York State can result in electricity generation of 16,070 MW-H per year. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York State can generate 80,360 MWH per year. Using the USEPA’s equivalent emissions calculator, generating 80,360 MWH/year of renewable energy is equivalent to a reduction in gasoline use of approximately 6.5 million gallons per year (USEPA, 2010).

7.2 Environmental Benefits

Application of the AFBD technology is expected to provide environmental benefits to a small farm such as N-Man Dairy, as well as, potential environmental benefits to New York State overall as follows:

7.2.1 Organics Removal

As shown in Figure 6-5 herein, the observed COD removal efficiency using the AFBD technology for this investigation was approximately 92%. Still, based on EMG’s operating experience with full-scale AFBD systems treating dairy farm manure streams, a conservative COD removal efficiency of 50% will be used for the purposes of this evaluation.

Based on a manure generation rate of 12,000 lbs per day at N-Man Dairy farm, a measured pre-conditioned manure COD concentration of 98,045 mg/L, and a COD removal efficiency of 50%, the estimated mass of COD that would be removed by an AFBD system from the manure stream is 590 lbs/day. Thus, an AFBD system at a small dairy farm such as N-Man Dairy is estimated to remove approximately 214,700 pounds of COD annually from the manure stream before it is land-applied or discharged into the soil/water environment.

Projected benefits to the environment from removal of organics as a result of state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-3 below.

Table 7.3. Projected Amount of Organics Removed from the Environment from State-Wide Application of the AFBD Technology at *Small Dairy Farms* in NYS*¹

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Annual Amount of COD Removed from Manure Streams Across NYS (million lbs COD/year)
1%	31	7.5
5%	155	37.6
10%	310	75.2
25%	755	183.2
40%	1,240	300.9
50%	1,550	376.1

*¹ Assumes an average small dairy farm herd size of 113 cows

As can be seen from Table 7-3, application of the AFBD technology for 10% of *Small Dairy Farms* in New York could result in the removal of over 75 million lbs COD/year from manure streams across the state. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York could result in the removal of over 376 million lbs COD/year from manure streams across the state.

7.2.2 Odor Removal

Odors generated from manure are primarily due to un-controlled emission of organic acids, hydrogen sulfides, and ammonia. AFBD digester systems will convert most of the organic acids into methane gas, and produce a biogas stream that is fully contained. Once combusted, odorous compounds such as ammonia and sulfides are oxidized to significantly less odorous compounds. As discussed herein, farms that use anaerobic digestion for manure management have attained up to 97% odor reduction (Wilkie, 2000). Wide application of the AFBD technology is expected to provide similar odor reduction benefits at *Small Dairy Farms* across New York State.

7.2.3 Air Emissions

Although combustion of the biogas stream in a generator set will result in emission of CO₂, SO₂, and NO_x gases into the atmosphere, digester systems are considered to be net zero carbon emitters. This is due to the fact that emissions by digester systems do not represent a “new” source of emissions for these gases. In contrast to fossil fuel combustion, digester systems emit gasses that originate from elements (C, N, or S) and gases (CO₂, SO₂, or NO_x) that were recently (i.e., over the plant growing season) captured from the soil or air environments by plant material. Thus, chemicals emitted by digester systems are compounds that existed in the environment 12-months earlier and are simply recycled back to the digester by plants used as animal feed.

Using the USEPA’s equivalent emissions calculator, generating 45.88 MWH/year of renewable energy at a small dairy farm such as N-Man Dairy is estimated to result in a reduction of 33 metric tons of carbon-dioxide-equivalent emissions per year (USEPA, 2010). Projecting those benefits over the long-term; application of the AFBD technology in 10% of *Small Dairy Farms* in New York State is estimated to result in a reduction of 11,540 metric tons of carbon-dioxide-equivalent emissions per year. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York is estimated to result in a 57,700 metric ton reduction of carbon-dioxide-equivalent emissions per year.

7.3 Economic Benefits

The AFBD treatment technology is expected to provide economic benefits to small dairy farms such as N-Man Dairy, as well as, projected economic benefits to New York State from wider application of the technology as described in Sections 7.3.1 through 7.3.4, and summarized in Section 7.3.5 below.

7.3.1 Electricity Generation

Using the current rate of \$0.135 per KW-H, the value of 45,880 KW-H per year produced by an AFBD system at a farm similar in size to N-Man Dairy translates to combined savings/sales in electricity of approximately \$6,200 per year.

Projected economic benefits from electricity generation as a result of state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-4 below.

Table 7.4. Projected Economic Benefits from Electricity Generation from State-Wide Application of the AFBD Technology at *Small Dairy Farms* in NYS^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Annual Income from Electricity Generation from AFBD Systems^{*2} (\$/year)
1%	31	\$217,000
5%	155	\$1,085,000
10%	310	\$2,170,000
25%	755	\$5,284,000
40%	1,240	\$8,679,000
50%	1,550	\$10,848,000

Table Notes: ^{*1} Assumes an average small dairy farm herd size of 113 cows

^{*2} Based on a Rate of \$0.135 per KW-H

As can be seen from Table 7-4, application of the AFBD technology for 10% of *Small Dairy Farms* in New York State could generate renewable electricity revenues with a value of \$2,170,000/year. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York State would generate renewable electricity revenues with a value of \$10,848,000/year.

7.3.2 Manure Handling Costs and Bedding Material Generation

Currently, N-Man Dairy estimates that it spends approximately \$12,000 annually on manure disposal through land application. The propose AFBD system is expected to lower annual manure management costs at small dairy farms such as N-Man by approximately 25% due to: (i) reduced overall manure stream volume through solids separation, and (ii) ease of handling for the treated manure stream (enabling use of tank spreaders rather than farm tractors equipped with a trailer). This would translate into savings of approximately \$3,000 annually for small dairy farms such as N-Man Dairy. In addition, N-Man Dairy estimates that it spends approximately \$15,000 annually on bedding material for its herd. Based on EMG’s experience with AFBD systems at larger dairy farms, the AFBD system at N-Man Dairy is expected to generate twice the amount of bedding material used by the Farm annually. Thus, small dairy farms such as N-Man Dairy can realize \$30,000 in annual savings and sales to neighboring farms from generation of re-usable bedding material by the AFBD system. Therefore, the total projected savings and income for small dairy farms such as N-Man Dairy from manure handling and bedding material generation from the AFBD system is approximately \$33,000 annually.

Projected economic benefits from manure handling, disposal, and bedding material cost savings as a result of state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-5 below.

Table 7-5: Projected Economic Benefits from Manure Handling and Bedding Material Cost Savings from Wide Application of the AFBD Technology in NYS^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Annual Manure Handling (MH) Savings (\$/year)	Annual Bedding Generation (B) Savings (\$/year)	Total Annual Savings (MH+B) (\$/year)
1%	31	\$105,000	\$1,051,000	\$1,156,000
5%	155	\$525,000	\$5,255,000	\$5,780,000
10%	310	\$1,051,000	\$10,509,000	\$11,560,000
25%	755	\$2,559,000	\$25,595,000	\$28,154,000
40%	1,240	\$4,203,000	\$42,036,000	\$46,239,000
50%	1,550	\$5,255,000	\$52,545,000	\$57,800,000

^{*1} Assumes Average Dairy Farm Head Size of 113 Cows

As can be seen from Table 7-5, application of the AFBD technology for 10% of *Small Dairy Farms* in New York State could generate manure handling and bedding material savings that exceed \$11.5 million annually. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York State would generate manure handling and bedding material savings of \$57.8 million annually. These estimates are conservative when compared with results presented by Gooch et al., 2005. In that study, pre-digester solids separation at a 100-cow dairy produced approximately 2.3 wet tons per day of separated solids (which is equivalent to 840 tons per year of bedding) (Gooch, 2005). Based on an approximate cost of \$100 per ton, this amounts to bedding generation worth \$84,000 per year for 100-cow dairy farm, or 2.5 times the estimated benefits from Table 7-5 Above. For the analysis presented in Table 7-5, it is assumed that bedding generated from the AFBD system would be used at the farm with excess bedding material sold to neighboring farms.

7.3.3 Carbon Credit Generation

The number of carbon credits from digester systems is typically determined based on actual KW-Hs or BTUs generated during operation. Energy generated from digester systems is converted into carbon credit equivalents. The value of carbon credits generated will depend on market trading value in the Chicago Climate Exchange Market (Native Energy, Inc., Personal Communication, 2009, www.nativeenergy.com).

As described herein, operating an AFBD system at a small dairy farm such as N-Man Dairy can produce 45,880 KW-H per year or 45.88 Megawatt-Hour (MWH) per year in renewable electricity. Through June 30, 2008 NYSERDA and the Department of Public Service completed three Main Tier competitive solicitations, with average contract award prices ranging from \$15.00 to \$22.90 per MWH (NYSERDA, September, 2008). Thus, an AFBD system at a small dairy farm such as N-Man Dairy would be expected to generate between \$690 and \$1,050 per year in carbon credits (\$870 on average).

Projected carbon credit benefits from state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-6 below.

Table 7.6. Projected Carbon Credit Benefits from State-Wide Application of the AFBD Technology at Small Dairy Farms in New York^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Annual Carbon Credit Benefits to New York State Economy (\$/year)
1%	31	\$30,000
5%	155	\$152,000
10%	310	\$305,000
25%	755	\$742,000
40%	1,240	\$1,219,000
50%	1,550	\$1,524,000

^{*1} Assumes Average Dairy Farm Head Size of 113 Cows

As can be seen from Table 7-6, application of the AFBD technology for 10% of *Small Dairy Farms* in New York could generate approximately \$305,000 in annual carbon credit benefits to the state’s economy. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York could generate approximately \$1,524,000 in annual carbon credit benefits to the state’s economy.

7.3.4 Job Creation

In addition to benefiting the viability of *Small Dairy Farms* in New York, several permanent and temporary jobs would be created in the state during construction, installation, and long-term operation of AFBD manure treatment systems. EMG estimates that construction and installation of the AFBD treatment systems in New York would create one (1) full-time job and three (3) part-time jobs in the state for every fifteen (15) systems installed at *Small Dairy Farms*. EMG also estimates that on-site service and technical support would create one (1) full-time job and two (2) part-time jobs in New York for every twenty five (25) AFBD systems installed at *Small Dairy Farms* in the state.

7.3.5 Summary of Total Economic Benefits

Overall, EMG expects that installing and operating an AFBD system at a farm similar in size to N-Man Dairy translates to combined economic benefits of approximately \$40,000 per year from electricity generation, manure handling savings, bedding generation, and carbon credits. A Summary of total annual expected economic benefits from state-wide application of the AFBD technology at *Small Dairy Farms* in New York are outlined in Table 7-7 below.

Table 7.7. Projected Total Economic Benefits from State-Wide Application of the AFBD Technology at Small Dairy Farms in New York^{*1}

Percent of Small Dairy Farm Market in NYS Using the AFBD Technology (%)	Number of Farms	Projected Total Annual Economic Benefits to New York State Economy
1%	31	\$1,403,000
5%	155	\$7,017,000
10%	310	\$14,034,000
25%	755	\$34,180,000
40%	1,240	\$56,137,000
50%	1,550	\$70,172,000

^{*1} Assumes Average Dairy Farm Head Size of 113 Cows

As can be seen from Table 7-7, application of the AFBD technology for 10% of *Small Dairy Farms* in New York could generate approximately \$14 million of total annual economic benefits to the state’s economy. Over the next 20 years, wider application of AFBD technology for 50% of *Small Dairy Farms* in New York could generate approximately \$70 million of total annual economic benefits to the state’s economy.

SECTION 8

SUMMARY AND CONCLUSIONS

Given that 95% of dairy farms in NYS have fewer than 500 cows (USEPA, 2001a), and that use of manure as a renewable resource of energy remains significantly under-used, developing AFBD systems for manure digestion and biogas generation at small dairy farms could greatly benefit New York State. Developing AFBD systems for small dairy farms will greatly enhance their economic viability and power efficiency, and reduce their environmental impact on air and water resources in the state.

The cash income of the agricultural sector in NYS totaled approximately \$3 billion in 2000 (NYSERDA, 2003), with energy costs (fuel and electricity) accounting for approximately 34 percent of net farm income, or approximately \$200 million. NYS has approximately 3,100 dairy farms with 50 to 500 cows housing a total of approximately 350,000 dairy cows (USDA, 2009). The total amount of manure generated from small dairy operations in NYS exceeds five million gallons each day. Conversion of manure generated in by small dairy farms alone could result in approximately 2,400 million ft³ of biogas per year in NYS, (which is equivalent to approximately 160,000 MW-H/year). Clearly, successful development of the AFBD system for efficient manure conversion and biogas generation at small dairy farms could create a large resource of renewable energy in NYS.

The goal of this project was to develop and evaluate a compact, high-rate anaerobic digester system that is economically feasible for energy generation and manure management at small farms in NYS. Specifically, this project evaluated AFBD systems and several potential pre-treatment and pre-conditioning processes that produce a waste stream high in liquid-phase COD content, low in suspended solids, with a high degree of consistency, and free of coarse solid matter. The manure pre-treatment and pre-conditioning steps evaluated included:

- Dilution
- Grinding and blending
- Solids separation and liquefaction
- Hydrolysis
- Fermentation and acidification

Two bench-scale AFBD units were fabricated and operated to treat pre-conditioned manure samples collected from a small dairy farm. Based on results from this project, the following observations and conclusions are noted:

1. For the manure samples collected from a small NYS dairy farm (100 cows), the average measured COD was 137,220 mg/L (i.e., 13.7%), VS was 12.6%, phosphorus was 2,214 mg/L, and ammonia-N was 1,954 mg/L. The baseline data collected under this project are similar to existing data available from the USEPA (recognizing that different farms will produce manure with slightly different characteristics).

2. The dilution experimentation performed herein shows that although water addition to raw manure improved the physical characteristics of the manure for pumping and handling, it had minimal benefits with regard to making the organic content of manure more available in the bulk liquid matrix.
3. Grinding and blending of raw manure samples increased the measured COD concentrations in the bulk liquid matrix. The increase in measured COD concentration due to grinding varied from 25% in the 1:2 dilution ratio to approximately 60% in the 1:10 dilution ratio.
4. Solids separation and liquefaction of raw manure samples increased the measured COD concentrations in the bulk liquid matrix. Approximately one hour is needed to reach steady COD concentrations in the bulk liquid when raw manure samples are mixed with dilution water following solids separation.
5. Lowering the pH below neutrality does not appear to increase the measured COD concentrations in the bulk liquid matrix for the samples analyzed.
6. Subjecting the manure samples to early digestion (i.e., fermentation and acidification for up to fifteen days) did not significantly change the COD concentrations in the bulk liquid matrix.
7. Overall, using the proper pre-conditioning steps, the AFBD system effectively and consistently digested manure collected from a 100-cow dairy farm.
8. Steady COD removal efficiencies (above 90%), along with steady biogas generation were achieved and maintained by the AFBD system.
9. Bench-scale AFBDs can be operated at a volumetric loading rate near 2,000 lbs COD/1,000 ft³-day.
10. Application of the Anaerobic Fluidized Bed Digester (AFBD) technology for manure treatment and biogas generation at *Small Dairy Farms* in New York offers significant energy, environmental, and economic benefits to the state. For example, application of the AFBD technology for 10% of *Small Dairy Farms* in New York State is expected to produce the following benefits:
 - A usable biogas stream of 281 million SCF/Year, with a heating value of 182,840 MMBTU/Year
 - Electricity generation of 16,070 MW-H per year, which is equivalent to a reduction of approximately 1.3 million gallons per year in gasoline use, and a reduction of 11,540 metric tons per year of carbon-dioxide-equivalent emissions
 - The removal of over 75 million lbs. of COD/year from manure streams across the state
 - Significant odor reduction from *Small Dairy Farm* operations
 - Total annual economic benefits of approximately \$14 million to the state's economy from electricity generation, manure handling savings, bedding generation, and carbon credit revenues
 - Create 33 full-time jobs and 86 part-time jobs in NYS

SECTION 9

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info@nysesda.org
www.nysesda.org



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Andrew M. Cuomo, Governor

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