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Technologies for Dairy Nutrient Recovery

Evaluation of Low-impact Ammonia Stripping with Bio-Fertilizer Recovery and Support for Technology Decision Making

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EVALUATION OF LOW-IMPACT AMMONIA STRIPPING WITH BIO-FERTILIZER RECOVERY AND SUPPORT FOR TECHNOLOGY DECISION MAKING

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Abstract and Benefits

Abstract:

Presently, most U.S. dairies manage manure through fiber separation and long-term lagoon storage of liquid effluent before application to nearby cropland. The use of anaerobic digestion systems for treating dairy manure produces renewable energy and reduces manure pathogens and odors, but does not on its own address nutrient-related concerns. This study assessed the use of pilot- and commercial-scale ammonia stripping systems within the context of a proposed sequential manure treatment system of anaerobic digestion, coarse fiber separation, fine solids separation, and ammonia stripping.

At the commercial scale, total ammonia nitrogen (TAN) removal was 3.7±3.3% for primary solids separation. An additional 34.0±1.8% TAN was removed during fine solids separation, likely contained in moisture associated with the solids. For the higher-performing pilot-scale system, batch and continuous flow systems, removed 74% and 49% TAN, respectively, after five-hour hydraulic retention times. Economic analysis to evaluate the feasibility of ammonia stripping within the context of sequential manure treatment indicated a net loss for the full biorefinery system of $688,708 over 10 years of operation for a 100,000-gallon per day system, not considering potential economic benefits to manure management costs. Analysis also indicated that ammonia stripping provided a net positive cash flow for the operator each year, available to offset some operational costs of the full treatment process. Further analysis of the pro forma examined the economic impacts of changes in several global parameters, including electricity rate paid, substrate tipping fee, and co-digestion volumetric flowrate. A 17.8% increase in electrical rate to $0.0766/kW, from an initial estimate of $0.065/kW, or an increase in substrates for co-digestion by 31.0%, each led to breakeven over a 10-year timeframe.

Offsets to manure management costs resulting from implementation of nutrient recovery technologies are likely also to be important to dairies considering adopting these technologies. The technological and economic evaluations indicate a need for ongoing technology development focused on improving performance levels and consistency, and on reducing costs. Development of more desirable form and consistency of nutrient recovery products and viable markets for use, as well as development of nutrient crediting markets, may also be important pathways to support adoption. Ongoing independent evaluations are important to supporting improved decision making related to nutrient recovery technologies, as these technologies develop.

Benefits:

- Tests and further develops a novel low-input ammonia stripping technology suitable for application to dairy wastewater.
- Improves understanding of the full nutrient and economic impact of a system of manure management technologies through the use of ammonia stripping technology within the context of a dairy biorefinery comprising an anaerobic digester, primary and fine solids separation, and ammonia stripping,.
- Improves understanding of the life cycle and nutrient management impacts of these technologies when used on dairies through a complementary analysis (Integrated Management of Animal Manure Wastes; Nutrient Recovery, Bio-fertilizers, Enhanced Biomethane Production and Management Tools).
- Provides support for improved decision making by dairy-allied industry, and agencies relative to nutrient recovery technologies on dairy farms.

Keywords: Ammonia stripping, dairy, nitrogen recovery, phosphorus recovery, biorefinery.

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Acronyms and Abbreviations

AD	Anaerobic digestion
ASABE	American Society of Agricultural and Biological Engineers
cfm	Cubic feet per minute
CH_4	Methane
COD	Chemical oxygen demand
DAF	Dissolved air flotation
EPA	Environmental Protection Agency
GHG	Greenhouse gas
GPD	Gallons per day
HRT	Hydraulic retention time
HP	Horsepower
K	Potassium
kW	Kilowatt
kWh	Kilowatt hour
N	Nitrogen
NH^{4+}	Ammonium
NH_3	Ammonia
NR	Nutrient recovery
NRCS	Natural Resources Conservation Service
P	Phosphorus
TK	Total potassium
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TAN	Total ammonia nitrogen
TKN	Total Kjeldahl nitrogen
USDA	United States Department of Agriculture
VS	Volatile solids
WSU	Washington State University

Executive Summary

Presently, most U.S. dairies manage manure through long-term lagoon storage of liquid effluent before application to nearby cropland. Manure management on large agricultural facilities in the U.S. has become a major issue due to concerns about air, water, and soil quality and releases of greenhouse gases (GHGs). The use of anaerobic digestion systems for treating dairy manure produces renewable energy and reduces manure pathogens and odors but does not on its own address nutrient-related concerns. Adoption of these systems has been relatively low across the U.S., serving less than 6% of the U.S. dairy herd as of early 2018 (U.S. EPA AgStar 2018).

To address these concerns and better target the application of nutrients from the manure to cropland, there are active efforts to develop technologies that can practically and economically recover and redistribute concentrated forms of the primary nutrients - nitrogen (N), phosphorus (P), and potassium (K) (Galinato et al. 2015, 2016; Szogi et al. 2015).

This study assessed the use of ammonia stripping systems within the context of a proposed sequential manure treatment system of anaerobic digestion, with the digester effluent then undergoing coarse fiber separation (i.e., primary solids separation), dissolved air flotation (DAF) for fine solids separation, and ammonia stripping (Figure ES-1). Unfortunately, due to installation decisions beyond the control of the study authors, the entire series of technologies under study were not available at a single commercial dairy. Therefore, individual stepwise processes were investigated on multiple Washington State dairies, with most testing done at commercial scale. Due to variation in absolute nutrient values between dairies related to variation in manure characteristics, evaluation focused on the percentage difference in nutrient flows between input and output streams.

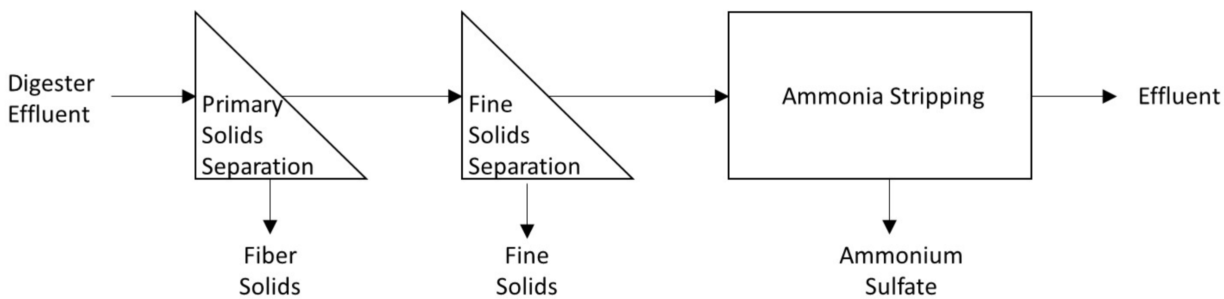


Figure ES-1. Conceptual Overview of the Anaerobic Biorefinery Process Under Study.

Primary solids separation measurements were taken at two commercial-scale dairy installations, each with solids separation occurring after anaerobic digestion. At the first installation, the composite primary solids separator was comprised of a GEA/Houle Slope Screen with rollers elevated within a solids processing and storage building with concrete pad and was coupled with a dewatering auger. At the second installation, primary solids separation was carried out with a U.S. Farm slope screen, coupled with a US Farm dewatering auger. Duplicate grab samples were collected daily over two five-day trials from the digester effluent exit point, the post-separation liquid stream, and the separated solids pile. Total ammonia nitrogen (TAN) removal averaged 3.7±3.3% for primary solids separation.

The fine solids separation system tested utilized dissolved air flotation (DAF) with a polymer from Hychem Incorporated (Tampa, FL) called Hyperfloc CP 904 HH, which is a very high molecular weight, low charge density, cationic polymer. Initially, two one-day trials were completed at pilot scale utilizing manure from a dairy in Outlook, WA. Samples were analyzed at the WSU Water Quality Laboratory for total solids, total phosphorus, and total Kjeldahl nitrogen (TKN). Complementing this initial study, an evaluation of a DAF system using the same polymer was subsequently carried out with complementary funding in fall 2017 at a dairy in Lynden, WA that had newly installed a commercial-scale DAF system. The modified DAF system (DVO, Chilton, WI) was designed for a flow rate of 100,000 gallons per day, and was located in its own dedicated building, with an equalization pit, and a solids processing area. After DAF treatment at a polymer dosing rate of 136.5 mg/L, solids were dewatered with a moving disc press. For this complementary study, duplicate grab samples were collected twice daily six days per week for two weeks. Morning and evening samples were combined for n=12 samples with duplicates. An additional 34.0±1.8% TAN was removed during fine solids separation, likely contained in moisture associated with the solids.

Investigation of the ammonia stripping and ammonium sulfate recovery system was conducted in four trials. The first two trials were conducted at commercial scale (Figure ES-2), under batch operation for trial 1 and continuous operation for trial 2. Initial evaluation of the ammonia stripping system at commercial scale indicated a need for process improvements and these improvements were subsequently tested at pilot scale. The commercial-scale ammonia stripping system achieved 64% TAN removal when batch operated, but only 31-36% TAN removal when in continuous operation (Table ES-1).

Figure ES-2. Commercial Ammonia Stripping Installation, Lynden, WA.

Table ES-1. Summary of Ammonia Stripping Trials.

	Influent TAN	Hydraulic Retention Time (HRT)	Effluent TAN	TAN Removal	pH	Temperature	Production Rate
	(mg N/L)	(hours)	(mg N/L)	(%)			(mg N/L hour)
Trial 1 batch commercial	1400	24	500	64	8.45 - 9.7	50°C	37.5
Trial 2 continuous commercial	1200-1400	31.9	768-966	31-36	7.0 - 10.6	50.6 - 60.6°C	13.6
Trial 3 batch pilot	993	5	258	74	8.02 - 9.25	46.1 - 56.1°C	147.0
Trial 4 continuous pilot	1145	5	516	49	8.98 - 9.42	44 - 47.8°C	125.8

A pilot system with micro-aerators instead of the macro-aerators used during the initial commercial-scale trials, attempted to improve performance by achieving higher air to liquid ratios, requiring less retention time and therefore lower costs and reactor heights (Figure ES-3). The goal was to achieve high air to liquid ratios, requiring less retention time, therefore lowering costs and reactor heights. An optimum operating gas to liquid aeration ratio of 600 and five-hour hydraulic retention time (HRT) were targeted. Results showed that the pilot-scale system achieved higher rates of TAN removal, with 74% removal when batch operated (Table ES-1). Performance was still substantially lower when operated continuously, achieving 49% TAN removal at five hours HRT. Variability of performance was high (Figure ES-4).

Figure ES-3. The Micro-Aeration Box Added with a Goal of Maximizing Stripping Performance.

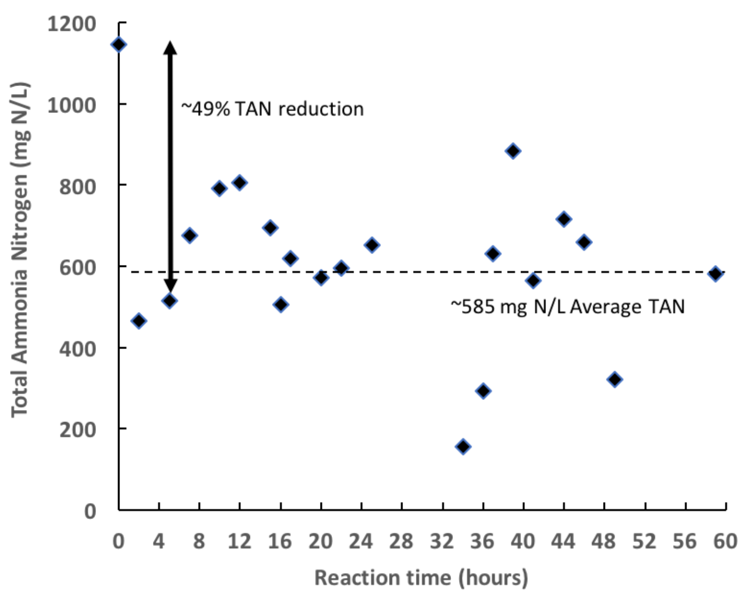


Figure ES-4. Pilot Continuous System Total Ammonia Nitrogen (TAN) Reduction Performance.

Economic analysis to evaluate the feasibility of ammonia stripping within the context of sequential manure treatment indicated a net loss for the full biorefinery system of $688,708 over 10 years of operation for a 100,000-gallon per day (GPD) system, not considering potential economic benefits to manure management costs (Table ES-2). Analysis also indicated that ammonia stripping provided a net positive cash flow for the operator each year, available to offset some operational costs of the full treatment process. Further analysis of the pro forma examined the economic impacts of changes in several global parameters, including electricity rate paid, substrate tipping fee, and co-digestion volumetric flowrate. A 17.8% increase in electrical rate to $0.0766/kW, from an initial estimate of $0.065/kW, or an increase in substrates for co-digestion by 31.0%, each led to breakeven over a 10-year timeframe.

Table ES-2. Summary of 10-Year Composite Biorefinery Pro Forma Analysis.

Term	Estimation
Capital cost	$5,325,760
Operation & maintenance costs	$6,318,176
Total revenues	$9,590,028
Gross earnings (before taxes)	-$688,708
Net profit as % of investment	-1.29%
Net available for capital repay after interest expenses	$1,974,172
Return based on repay potential	3.71%

Based on the core estimates and assumptions described above and the size of the system, the economic analysis indicates several challenges to overcome to push the full system economics to be a net positive for dairy producers. These challenges include a need for additional cost reductions and enhancements in performance and reliability of the technology. They also indicate a critical need for product refinement and market development to generate revenues that offset at least some of the costs. Finally, additional work related to supporting the development of viable nutrient crediting may have an important role to play in catalyzing future technology adoption, particularly considering recent economic challenges for dairies.

Despite these challenges, there is ongoing and increasing interest from dairy producers in nutrient recovery technologies, including both the fine solids separation and the ammonia stripping technologies explored here, and other technological approaches. This interest is likely to continue to grow given environmental, regulatory, and legal pressures with respect to dairy nutrient management.

To support improved decision making within the context of emerging technologies, this project also incorporated extension efforts targeting a wide range of decision makers, including dairy producers and representatives from dairy-allied industry and state and federal agencies. The major effort under this comprised a peer-reviewed extension manual that provides an overview of the major nutrient recovery (NR) approaches emerging or currently in use for recovery or removal of P, N, K, and other salts from dairy manure, particularly after anaerobic digestion (AD) (Frear et al. 2018). For each of the more common technical approaches being used or considered by the dairy industry, the publication aimed to summarize important indicators, including approximate performance, capital and operating and maintenance (OPEX) expenses, co-product form and price, and potential impacts on manure management. While this is clearly a time-sensitive and changing snapshot, our goal was to gather existing information in a way that was accessible to non-academic stakeholders, to support their understanding of a rapidly changing field, and to provide a starting point for additional investigation into technology approaches most likely to be of interest. Meanwhile, complementary extension efforts carried out with support from both the Water Research Foundation and complementary funding sources included a five-part webinar series that had a combined 341 live attendees, with an additional 1595 views of recordings; a video providing an overview of nutrient recovery efforts and the main opportunities and challenges (viewed 282 times over eight months); and two in-person field days.

CHAPTER 1

Introduction

Manure management on large agricultural facilities in the U.S. has become a major issue due to air, water, and soil quality concerns as well as environmental releases of greenhouse gases (GHGs). To address these concerns and better target the application of needed primary nutrients from the manure, there are active efforts to develop technologies that can practically and economically recover and redistribute concentrated forms of the primary nutrients, including nitrogen (N), phosphorus (P), and potassium (K) (Galinato et al. 2015, 2016; Szogi et al. 2015).

In addition to technological development, a number of other factors are contributing to changes in manure management strategies. First, ongoing increases in the size of dairy farms (USDA-NASS 2010) results in more manure, bedding, and urine being produced in concentrated areas. Annually, a dairy cow produces liquid and solid manure containing 58 lbs. phosphorus, 168 lbs. ammonia (a form of nitrogen), and 336 lbs. total nitrogen (ASAE 2005). Many large farms do not have the land necessary to utilize the amount of manure being produced (Ribaudo et al. 2011). In addition, liquid manure is expensive and costly to transport to distant fields (Ribaudo et al. 2003) for final land application.

Second, during land application of liquid manure, several factors can encourage over-application of nutrients beyond what plants can readily take up, despite a risk of nutrient losses to the environment. The receiving land for manure is generally limited to forage fields, due to food safety concerns (MacDonald et al. 2009). The ratio of nitrogen, phosphorus, and potassium (NPK) in manure does not match that required by crops, so applying manure based on N results in over-application of P and K. Inconsistencies in nutrient form and content can lead to over-application of nutrients. Broadcast or surface application, which are most frequently used, can contribute to nutrient overloading in the environment through loss to the atmosphere and surface runoff (Ribaudo et al. 2011). Lastly, farmers may apply nutrients at a rate needed for high yields (in case weather conditions are favorable), which results in over-application during years with average or below average yields (USDA-ERS 2011).

Third, nutrient-related air, water, and soil quality issues are an increasing public concern in many areas of the U.S. that have significant concentrations of livestock, which has increased pressure on dairies to ensure proper management of nutrients (Rieck-Hinz et al. 2012). The Yakima Valley in Washington State has concerns about nitrogen enrichment of surface and ground water as well as air quality (U.S. EPA 2012; Palmer 2014). The Chesapeake Bay, which includes more than 83,000 farms and 13 million acres of farmland, is another example where poor manure management has contributed to water and air quality issues. Evidence suggests that livestock manure is the largest source of phosphorus and is one of the largest sources of nitrogen affecting this area (Chesapeake Bay Commission 2012).

Though not driving dairy producer's interests in nutrient recovery technologies, manure-derived forms of N, P, and K also have the potential to meet crop needs, while reducing reliance on fertilizers from non-renewable resources (Mendonça et al. 2017). Synthetic fertilizers are made using mined, non-renewable P and K, while N fertilizer is obtained from the energy-intensive Haber-Bosch process (Vaccari 2009; Ciceri et al. 2015; Cherkasov et al. 2015). To highlight the current risks of continuing to utilize non-renewable fertilizers, it has been estimated that global phosphate rock reserves for the production of P could essentially be depleted within 100 years (Cordell et al. 2009). While global supplies of K from potash reserves are expected to continue to be available for longer, there are only a finite number of countries with these reserves, which could significantly alter production costs in the future (Ciceri et al. 2015). Finally, fertilizer N can be produced from plentiful atmospheric nitrogen; however, the Haber-Bosch process contributes to GHG production and N fertilizer could become prohibitively expensive if future energy markets become more volatile (Narbel and Hansen 2014; Razon 2014).

1.1 Overview of Nutrient Recovery and its Use in a Sustainable Dairy Biorefinery

The potential for nutrient recovery to ameliorate a range of existing sustainability concerns relating to animal and cropland agriculture has not yet been realized, with few systems currently deployed at commercial scale in the U.S. At present, a number of different technological approaches are under consideration, with many under ongoing development. Each technological approach is aiming to provide the operational stability and low costs that are needed for success in an agricultural context.

While it is possible for nutrient recovery technologies to be used as the core manure management technology, there are some potential advantages to their use in conjunction with anaerobic digestion (AD) (Figure 1-1).

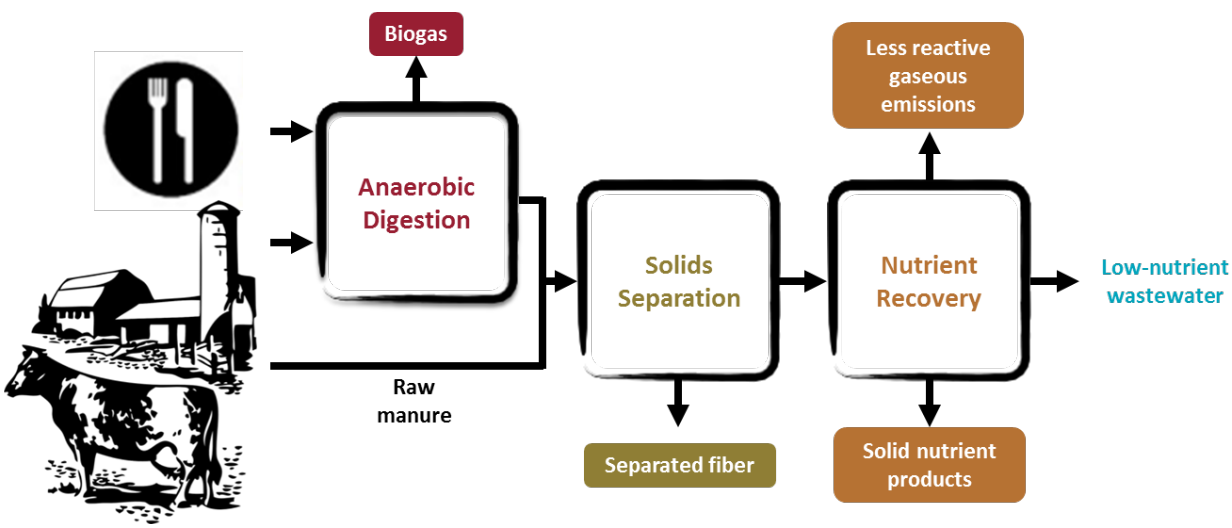


Figure 1-1. Generalized Schematic of the Phosphorus and Nitrogen Recovery Process.
Image created by Sonia Hall and Timothy Ewing.

Anaerobic digestion (AD) is a biological process for stabilizing liquid and solid organic matter by the production of a methane containing biogas and a stabilized digestate that has reduced odors and pathogens (Mitchell et al. 2015). The AD process is a mature technology in wide-scale use at municipal wastewater treatment facilities (Ganidi et al. 2011). During the AD process, four distinct species of bacteria act synergistically to break down complex organic matter into various organic compounds, including volatile fatty acids (VFAs), before final conversion to biogas (Figure 1-2) (Stams 1994; Gerard, 2003).

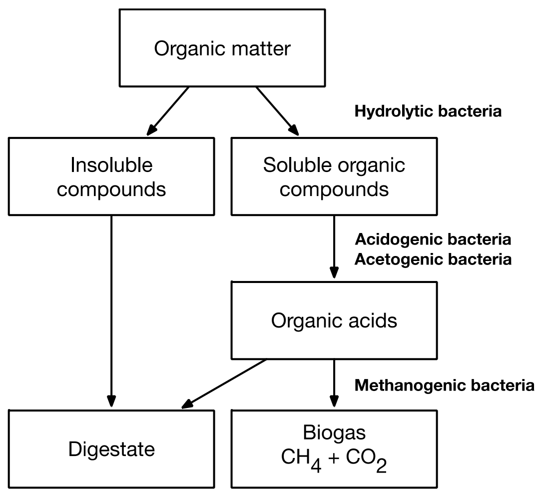


Figure 1-2. A Simplified Diagram of Metabolism During Anaerobic Digestion.
Adapted from Gerardi 2003; Stams 1994.

During AD, the form of nitrogen and phosphorus is changed but the amounts of the two nutrients are not appreciably reduced. As dairies have adopted AD technologies, some have also co-digested food scraps and other organic waste materials with the manure (Zhang et al. 2013). The process of co-digestion can produce more biogas which increases revenue, but also brings more organic materials onto the facility, increasing the overall nutrient load and possibly increasing nutrient management challenges (Zhang et al. 2013; Camarillo et al. 2013; Ma et al. 2017). Used in conjunction with AD, nutrient recovery systems can contribute to the economic feasibility of an AD project and lessen overall nutrient concerns (Yorgey et al. 2014). Anaerobic digestion of animal manures alone provides for public benefits of reduced odor emissions, reduced GHG emissions and reduced digestate pathogen counts, but it struggles to be economically viable and may not be considered cost-effective in some U.S. locations. Thus, the development of viable nutrient recovery technologies that work in conjunction with AD could synergistically increase the adoption of AD facilities by both providing these public benefits while also addressing the priority concern of nutrient management for dairy operators through nutrient recovery.

Together, anaerobic digestion and nutrient recovery technologies can be described as components of a sustainable biorefinery, designed to convert biomass into value-added products and energy (Aresta 2012). The biorefinery concept was previously described for the production of ethanol from corn stock (Humbird et al. 2011). More recently, the concept has been applied to dairy-based anaerobic digestion systems. In this context, unit operations of the biorefinery can include pretreatment, biogas conditioning and upgrading, solids separation and soil amendment production, nutrient recovery and biofertilizer production, and water treatment and reuse (Figure 1-3) (Kennedy et al. 2013; Yorgey et al.

in review). Other elements of an AD biorefinery, not related to nutrient recovery, may include the upgrading of methane-rich biogas to pipeline quality natural gas and the use of torrefaction, pyrolysis, and composting technologies to treat recalcitrant lignocellulosic materials (Mitchell et al. 2015).

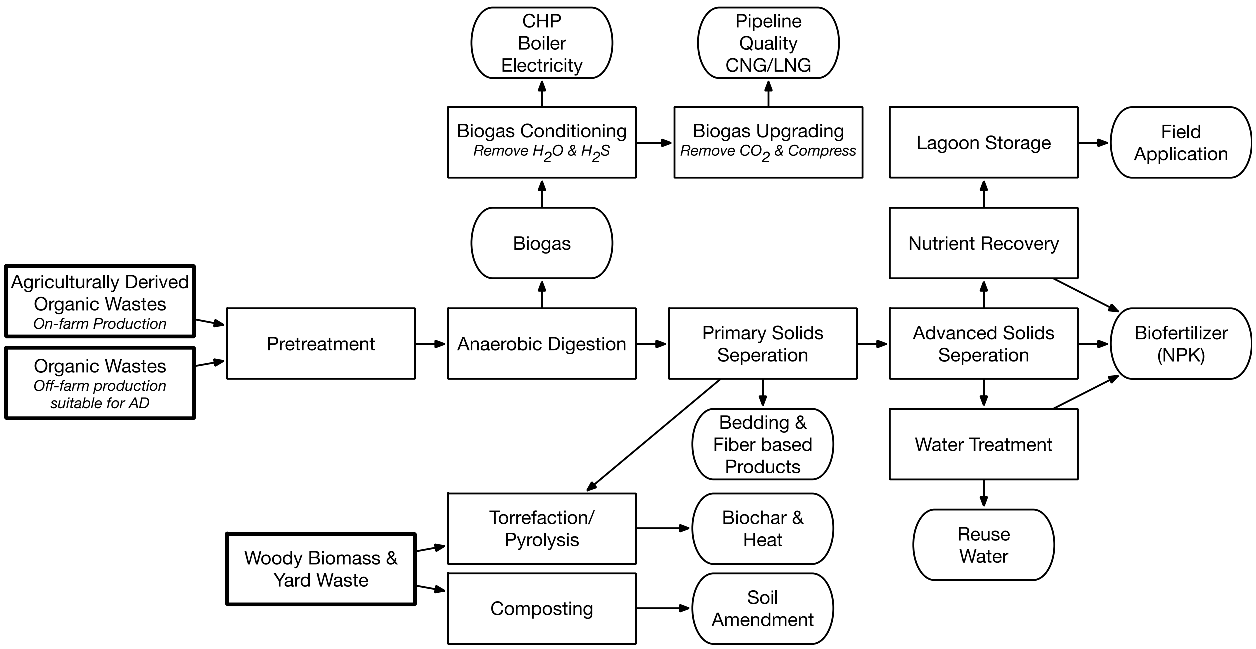


Figure 1-3. Sustainable Anaerobic Biorefinery Concept.
Adapted from Kennedy et al. 2013.

A number of potential nutrient recovery strategies may be viable paired with anaerobic digestion. Most advanced approaches rely on multiple technologies, applied sequentially. In most cases, nutrient recovery is preceded by primary solids separation, a technology that is highly commercialized and can be used on dairies with or without AD technology. Up to 40% of total solids and moderate amounts of nutrients can be removed during primary separation and recovered fiber is most commonly used as livestock bedding (Pelaez-Samaniego et al. 2017). The various competing nutrient recovery technologies are different in terms of the form of manure with they treat (dry, scrape, flush) and in whether they 1) yield concentrated nutrient products more efficient to transport than liquid manure, or 2) yield non-reactive nutrients (usually N) in forms that can be released directly into the environment without negative impacts.

1.2 Ammonia Stripping as an Approach for Dairy Nutrient Recovery

Among the various approaches currently under investigation (Ma et al. 2013), ammonia stripping is a known process that has been utilized for both industrial and municipal wastewater treatment. Process modifications have recently been proposed to allow the application of this technology to recover ammonia from livestock manure to produce an ammonia solution or ammonium salt fertilizer (Jiang et al. 2014). At the correct temperature and pH, the equilibrium between liquid and vapor shifts from ammonium ions (NH_4^+) to gaseous ammonia (NH_3) which can then be readily separated. Adding alkali chemicals or heat to produce favorable conditions to drive the equilibrium shift can be costly, which is why using ammonia stripping with AD is of particular interest. Anaerobic digestion effluent is naturally alkaline, and AD is a source of thermal energy (Jiang et al. 2014).

Lab-scale ammonia stripping systems had been thoroughly investigated through previous work (Jiang 2010; Jiang et al. 2014; Zhao et al. 2015). A very broad range of conditions including pH, temperature, HRT, liquid depth, bubble size, and airflow rate have been explored (Zhao et al. 2015), with those results informing the conditions chosen for the current study. Temperature and pH were identified as the most cost sensitive ammonia stripping parameters (Jiang 2010; Jiang et al. 2014). Raising the pH of the dairy wastewater to 11 required 63% more alkali than raising the pH to 10 because of the abundance of bicarbonates. The ammonia stripping temperature and pH were economically optimized by combining the ammonia stripping efficiency with the titration correlation. After optimization, the cost of ammonia stripping was substantially lower than that estimated from other reports for a similar process.

Though the approach is promising, ammonia stripping is not without its concerns (Jiang et al. 2010). Although AD raises the pH of the effluent, facilitating ammonia stripping, Bicarbonate/carbonate, phosphate, and ammonia buffers are elevated by 50-60% during AD, which can raise the requirements for alkali chemicals when further pH adjustments are needed. Non-chemical air stripping can be used to reduce the carbon dioxide content of the effluent and help overcome these alkalinity issues, reducing chemical cost. Another significant concern is that not enough thermal energy is produced by AD to raise the temperature to desired levels, leading to increased costs (Liao et al. 1995). Finally, for systems that use a stripping tower, clogging is a concern. Potential strategies for addressing this concern include pre-treatment with advanced solid separation, the use of hot air stripping, and the use of thermophilic anaerobic digestion with its higher temperatures.

The work described in this report aimed to evaluate a series of commercial- and pilot-scale nutrient recovery trials that utilized anaerobically digested dairy manure effluent to produce ammonia sulfate, a potential value-added product, from low-impact ammonia stripping. For efficiency of testing and to reduce overall costs, the conditions of the commercial- and pilot-scale trials including HRT, temperature, and pH were determined from the results of previous lab-scale studies. Along with the reported results from these nutrient recovery trials, an economic pro forma was completed to estimate the magnitude of capital and operation and maintenance costs associated with developing an industrial-scale sustainable anaerobic biorefinery treating 100,000 gallons per day with AD, primary solids separation, DAF, and ammonia stripping.

Complementing this work, and to support improved decision making by dairies and other dairy-allied stakeholders relating to emerging commercial nutrient recovery technologies, extension efforts focused on improving knowledge related to a wide range of technological approaches. This was accomplished using a video that provides an overview of the opportunities and some of the remaining challenges related to dairy nutrient recovery, a peer-reviewed extension publication that summarizes known performance and costs associated with approaches suitable for dairy manure, and a field day that provided an opportunity for in-person exploration of dairy nutrient recovery. Webcasts and conference talks also provided an opportunity to share the work with a national audience.

CHAPTER 2

Ammonia Stripping Evaluation in the Context of a Dairy Biorefinery

Working with dairy producers and industrial collaborators, Washington State University (WSU) researchers investigated the use of ammonia stripping in the context of complementary sustainable biorefinery processes at both pilot- and commercial-scale deployed on Washington state dairies. The composite anaerobic biorefinery process investigated involved anaerobic digestion, a primary separation of fibrous settled solids using a slope screen with dewatering screw press, a dissolved air floatation (DAF) system for fine solids separation, aeration through a dedicated ammonia stripping and ammonium sulfate solution recovery system (Figure 2-1). Additional economic information is provided in the pro forma section for a Washington State-based composite anaerobic biorefinery treating 100,000 gallons per day of manure with co-substrates. The pro forma section includes cost and product revenue estimates for AD, primary solids separation, DAF, and ammonia stripping.

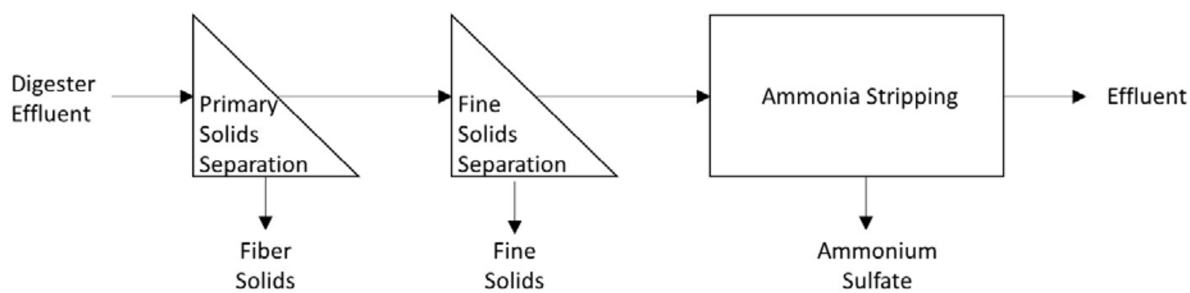


Figure 2-1. Conceptual Overview of the Anaerobic Biorefinery Process Under Study.

Unfortunately, due to installation decisions beyond the control of the study authors, the entire series of technologies under study were not available at a single commercial dairy. Therefore, individual stepwise processes were investigated on multiple Washington state dairies, with testing at commercial scale where possible. For ammonia stripping, initial testing at commercial scale indicated a need for process improvements; these were subsequently tested at pilot scale. Because individual dairies show variation in absolute values relating to manure characteristics, this report focuses on the percentage difference between input and output streams with regard to nutrient flow for each discussed unit operation. While testing a single commercial scale dairy with all operations installed at scale would have been ideal, reporting the differences allows a coherent picture to be formed of a single composite anaerobic biorefinery and its potential application in Washington State.

2.1 Dairy Manure and Anaerobic Digestion

Ammonia stripping-produced dairy manure falls outside the scope of this report. However, for completeness and as a general reference, the American Society of Agriculture and Biological Engineers (ASABE) provides a standard reference on manure production and characteristics. For a lactating dairy cow fed a U.S. high energy diet, total manure production, total solids, volatile solids, chemical oxygen demand (COD), N, P, K, and moisture content are summarized in Table 2-1.

Table 2-1. Summary of Ammonia Stripping-Produced Manure for Lactating Dairy Cow (kg/day/cow).
Adapted from ASAE 2005.

Total Manure	Total Solids	Volatile Solids	COD	N	P	K	Moisture Content
kg/day/cow							% mass
68	8.9	7.5	8.1	0.45	0.078	0.103	87

Anaerobic digestion of dairy manure as a standalone technology has been well described in the literature, and results in volatile solids (VS) reduction of approximately 40% over a 20-30-day hydraulic retention time (HRT) at mesophilic temperatures (38°C) (US EPA 2004; Demirer and Chen 2004). This results in the production of approximately 0.23 m^3 methane (CH_4)/kg volatile solids (VS) destroyed (Møller et al. 2014). The AD process results in the production of biogas, which contains methane and carbon dioxide, with corresponding reduction of carbon content in the resulting digester effluent and leads to pathogen reduction due to HRT and temperature parameters (Mitchell et al. 2015). However, other than a conversion of organic nitrogen to ammonia or ammonium and conversion of organic phosphorus to inorganic form, there is no change in total mass of nutrients, N, P, and K, during this process (Yilmazel and Demirer 2013).

2.2 Materials and Methods

This section discusses the materials and methods used in this study.

2.2.1 Primary Solids Separation

Primary solids separation measurements were taken at two commercial-scale dairy installations. At the first site, (Lynden, WA), influent to primary solids separation was collected at the exit point from an existing full-scale commercial two-stage mixed plug flow mesophilic (38°C), anaerobic digester with a working capacity of 220,559 cubic feet, designed for a flow rate of 75,000 gallons per day and a hydraulic retention time (HRT) of 22 days (patented by DVO, installed 2012). The digester was designed to digest either dairy manure alone or to support co-digestion of up to 30% by volume organic substrates. Samples were collected at a sampling port at the effluent exit point from the digester. At this site, the composite primary solids separator was comprised of a GEA/Houle Slope Screen with rollers elevated within a solids processing and storage building with concrete pad. (Figure 2-2). The slope screen was coupled with a dewatering auger.

Figure 2-2. Rollers of GEA/Houle Slope Screen (L), and Wide View Showing Installation at One of the Commercial Dairies Sampled in this Study.

At the second site (also in Lynden, WA), influent to primary solids separation was collected at the exit point from an existing full-scale commercial two stage mixed plug flow TM mesophilic (38°C, anaerobic digester with a working capacity of 132,335 cubic feet, designed for a flow rate of 45,000 gallons per day and a hydraulic retention time (HRT) of 22 days (patented by DVO, installed 2004). The digester was designed to digest either dairy manure alone or to support co-digestion of up to 30% by volume organic substrates, and generally operates near 30% by volume organic substrates, the limit allowed under Washington State law while still allowing for an exemption from solid waste permit requirements. At this site, primary solids separation is carried out with a U.S. Farm slope screen. Solids fall into a U.S. Farm dewatering auger, while the combined press water and effluent flow into a storage lagoon. Solids are stacked under a building until use as bedding.

At both sites, duplicate samples were collected as grab samples daily over two five-day trials from the digester effluent exit point, the post-separation liquid stream, and the separated solids pile. Samples were analyzed by Exact Scientific Services, Inc. (Ferndale, WA) for total solids, total volatile solids, potassium, phosphorus, ammonia, and total nitrogen.

2.2.2 Fine Solids Separation

Dissolved air flotation (DAF) was used for the composite fine solids separator using a polymer from Hychem Incorporated (Tampa FL) entitled Hyperfloc CP 904 HH, a very high molecular weight, low charge density, cationic polymer. Two trials were completed at pilot scale utilizing manure at a dairy in Outlook, WA. For trial 1, duplicate samples were collected for a one-day period. For trial 2, triplicate samples were collected for a one-day period. Samples were analyzed at the WSU Water Quality Laboratory as described in Standard Methods for total solids, total phosphorus, and TKN.

Complementing this initial study, an evaluation of a DAF system using the same polymer was subsequently carried out with complementary funding in fall 2017 at a dairy in Lynden, WA that had newly installed a commercial-scale DAF system. The modified dissolved air flotation (DAF) system (DVO, Chilton, WI) was designed for a flow rate of 100,000 gallons per day, located in its own dedicated building, with equalization pit, and solids processing area. After DAF treatment at a polymer dosing rate of 136.5 mg/L, solids were dewatered with a moving disc press. For this complementary study, duplicate grab samples were collected twice daily, six days per week for two weeks. Morning and evening samples were combined for n=12 samples with duplicates. Samples were analyzed by Exact Scientific Services, Inc. (Ferndale, WA).

2.2.3 Nitrogen Recovery via Ammonia Stripping

Investigation of the ammonia stripping and ammonium sulfate recovery system was conducted in four trials. The first two trials were conducted at commercial scale, under batch operation for trial 1 and continuous operation for trial 2. The following two trials were conducted at pilot-scale, under batch operation for trial 3 and continuous operation for trial 4.

For influent to the ammonia stripping system, simulated DAF effluent was made by collecting fiber-separated manure from a commercial scale system in a 250-gallon tote and treating with polymer to simulate the DAF operation. Supernatant from the DAF simulation was then stored in another large vessel and allowed to settle for two days, until enough volume from multiple DAF batch simulations could be produced. For all ammonia stripping trials, the influent was grab sampled immediately prior to operation of the continuous or batch test.

All samples, influent and effluent were taken in 250 mL polyethylene bottles, properly labeled and stored in coolers until transport to Exact Scientific (Ferndale, WA) for analysis of TKN.

2.2.3.1 Commercial-Scale Ammonia Stripping System

The commercial scale ammonia stripping system comprised a 24’ by 40’ by 9.5’ rectangular pit outfitted with internal heat exchangers to elevate the influent to an average stripping temperature of 55.56 +/- 5°C using recovered heat from the generator engines associated with the AD system, a gas recirculation system with duckbill nozzles to induce a plug-flow pattern through the pit, macro-aerators arrayed at a height of 5’ across the surface area of the pit to maximize air flow, an internal piping system and de-foaming pit for foam control, and a 60-horsepower (HP) blower providing 1,800 cubic feet per minute (cfm) of air to the system run through an air to air heat exchanger to recover waste blower heat for warming the influent air (Figure 2-3, Part I). The array of aerators was comprised of: 1) 240 Flex Caps capable of 7.5 cfm/diffuser with dimensions of 1.625 inches in height with a polypropylene base and a 4.2-inch EPDM cap and 2) 85 tubular diffuser with maximum 30 cfm/diffuser.

Figure 2-3. Commercial Ammonia Stripping Installation, Lynden, WA.
Rectangular solids/phosphorus settling pit (part I), ammonia stripping tower (part III), and storage tanks for produced ammonium sulfate solution (part II).

The acid stripping tower for production of ammonium sulfate slurry comprised a 5,000-gallon concentrated sulfuric acid tank with concrete secondary containment, 1/3 HP acid dosing pump, slurry mixing pump, a 173” by 60” by 48” stainless steel, two-stage stripping tower filled with 3.5” gas-stripping media and outfitted with a lower liquid reservoir and two pH meters for high/low end pH control (Figure 2-3 Part III, Figures 2-4 and 2-5). Two 10,000-gallon poly-tanks were used for storage of produced ammonium sulfate solution.

Batch Operation (Trial 1)

The commercial unit described above was operated in batch mode by filling the vessel to capacity, allowing the temperature to attain a working level of 50°C and operating the blower at 1,800 cfm for a 24-hour period. Polyethylene 250 mL bottles were used to collect an initial manure influent sample (digested, fiber separated manure) as well as effluent samples at hours 1.5, 12, 14, 16, 17, 18, 20, 22, and 24. All samples were transported in a cooler and then stored at 4°C until measurement of TAN. Operating temperature, pH for both the aeration system and the stripping tower were monitored while a hydrometer and tank levels were used to monitor product density and volume of ammonium sulfate product produced. Ammonia dragger tubes were used to periodically monitor ammonia gas concentration in the pipe leading from the aeration vessel to the stripping tower.

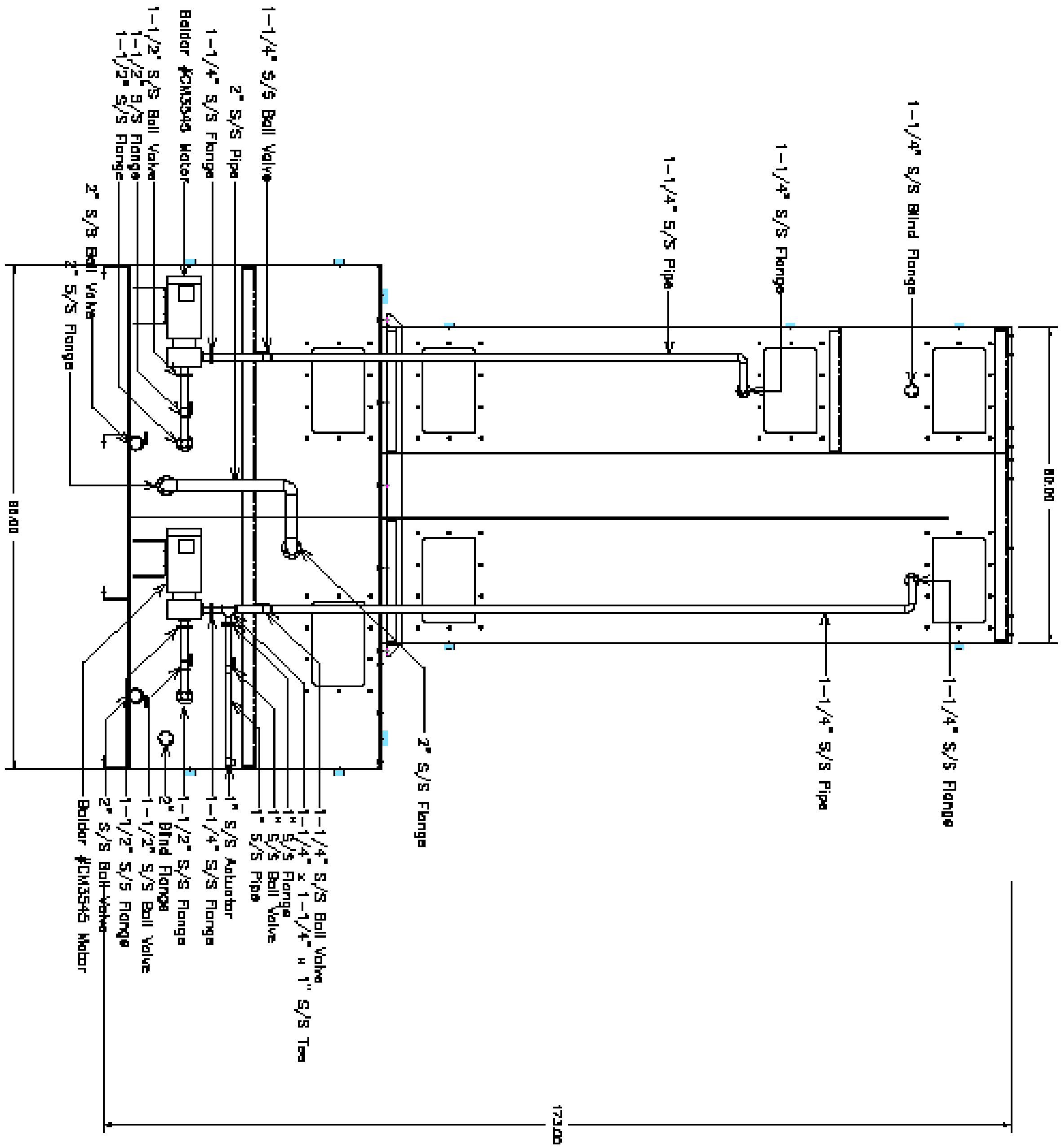


Figure 2-4. Ammonia Stripping Tower.

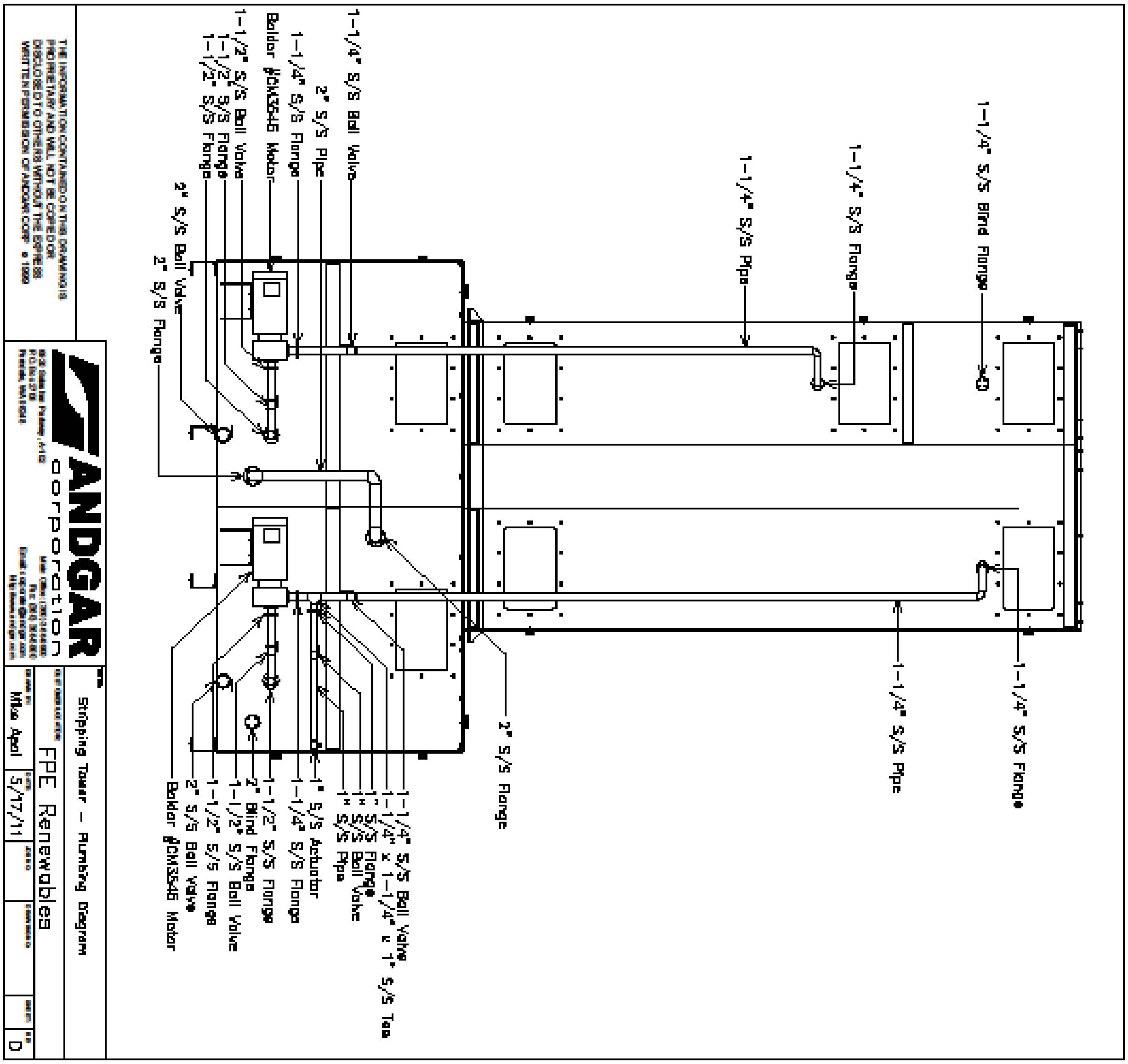


Figure 2-5. Plumbing for the Ammonia Stripping Tower.

Lastly, at start-up, manure volume loss due to gas hold up was calculated. Gas hold up was determined by filling the commercial aeration basin to maximum height and from known dimensions determining the initial volume. After the gas blowers were turned on to expected operating capacity a new liquid height was determined after overflow of removed volume had ceased and achieved equilibrium. The change in volume due to height difference was the volume loss to gas holdup.

Continuous Operation (Trial 2)
The commercial unit described above was periodically monitored for key recorded data during an approximate 10-month period of continuous operation, with samples of both influent and effluent taken. Data recorded included: 1) time between recordings, 2) aeration tank temperature, 3) aeration effluent pH, 4) ammonium sulfate production, 5) ammonium sulfate specific gravity, 6) acid usage, and 7) manure influent flow rate. All recorded data was normalized to a 24-hour period, with means and standard deviations recorded for the n = 41 data points.

2.2.3.2 Pilot-Scale Ammonia Stripping System
Based on the results obtained from trials 1 and 2, a pilot micro-aeration box was designed and constructed to test new concepts aimed at maximizing stripping performance and reducing or at least maintaining cost, but within a much smaller hydraulic retention time and footprint. A box of 250 gallons working volume and dimensions of 8’ 2 ¼” x 1’11” x 4’ 3 15/16” was constructed with two stacked trays that cascade from one to the next in an overall u-shaped flow (Figures 2-6 and 2-7). Two 4” outer diameter tubular micro-aerators were positioned in each tray with a regenerative blower used to supply air capable of supplying 120 cfm by controlling the blower pressure drop to 30 inches of water column. Foam was controlled by allowing the pressure of the foam to build up and collapse upon itself as it could rise through a stand pipe and then drop back down into the end of the second tray. Heat exchanger coils were placed in each tray to control temperature.

Figure 2-6. The Micro-Aeration Box Added with a Goal of Maximizing Stripping Performance.

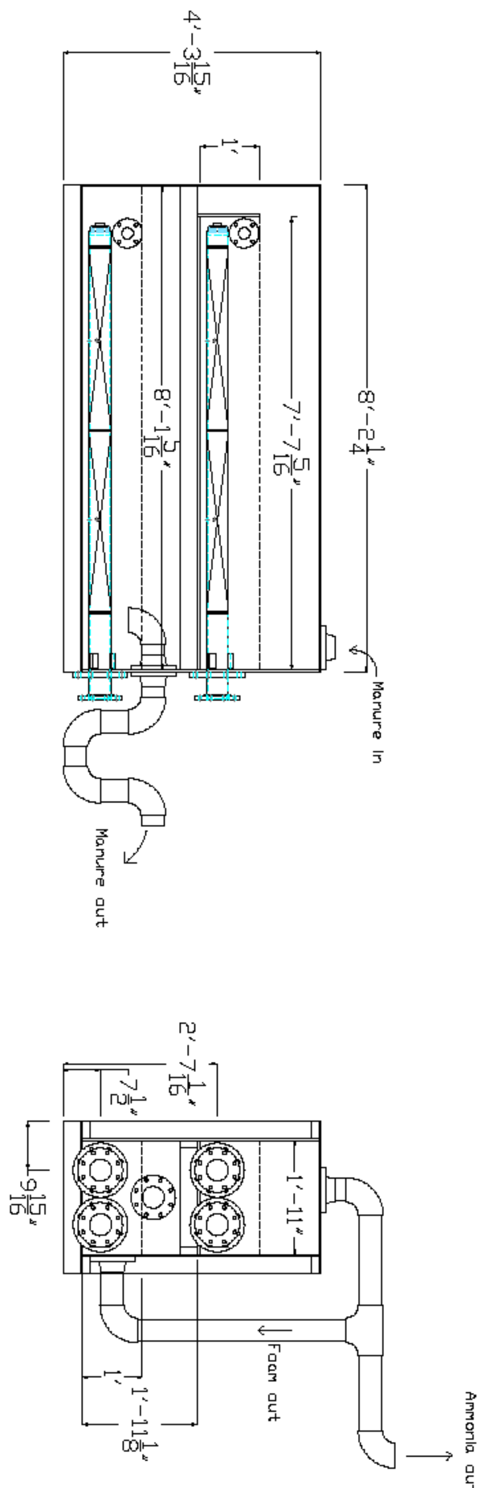


Figure 2-7. Diagram of Pilot Micro-Aerator.

Batch Operation (Trial 3)

The pilot unit described above was operated in batch mode by filling the vessel to capacity with simulated DAF effluent (DAF treatment of AD, fiber-separated manure as described above). At the beginning of the trial the simulated DAF effluent was heated to 48.89°C. A sample of the simulated DAF effluent (influent to this process) was taken and stored at 4°C until analysis. The process blower was set to 60 cfm and samples of the liquid leaving the pilot system were taken every hour for eight hours, and the time, temperature and pH were recorded. The trial was repeated in triplicate.

Continuous Operation (Trial 4)

The pilot unit described above was operated in continuous flow mode. The simulated DAF effluent was heated to 48.89°C in an outside tank equipped with a heat exchanging coil. When the simulated DAF effluent was at temperature, a transfer pump was used to supply manure to the box at the appropriate flow rate for the particular experimental design. Both the transfer pump manure flow rate of 45 gallons per hour and the blower pressure drop were controlled to produce desired air/liquid ratio of 600 being studied. Influent samples were taken at the beginning of each air/liquid ratio trial using 250 mL polyethylene bottles, which were then stored at 4°C until analysis. Multiple effluent samples were taken within the AR vessel at hours 2, 5, 7, 10, 12, and 15 during continuous operation and collected and stored in a similar manner. Temperature and pH were recorded during each sampling. The trial was repeated in triplicate.

2.3 Results and Discussion

A more detailed discussion of primary solids separation, fine solids separation, and ammonia stripping follows.

2.3.1 Primary Solids Separation

Dairy manure contains a high concentration of partially digested fibrous solids (Liao et al. 2010). Primary solids separation comprised a slope screen coupled in trial 1 with a dewatering auger and in trial 2 a roller press. Trial 1 showed 24.8% TS removal and trial 2 showed 22.0% TS removal (Table 2-2). This is somewhat lower than expected, as previous studies have shown that single screen systems can remove approximately 40% total solids from dairy wastewater (Hobson 1998; Husfeldt et al. 2012). Results for N, P, and K removal are also given in Table 2. Note that TAN and K are highly water soluble but are reduced during the solids separation steps as the solids are roughly 75% moisture and the ammonia in particular has a tendency for adhesion to solid particles. The characteristics of the resulting separated fiber product are summarized in Table 2- 3.

Table 2-2. Primary Solids Separation, Solids and Nutrient Removal.

	Trial 1			Trial 2		
	Influent	Effluent	Removal %	Influent	Effluent	Removal %
TS (%)	3.62 ± 0.57	2.72 ± 0.09	24.8	4.04 ± 0.15	3.15 ± 0.07	22.0
VS (% of TS)	75.84 ± 3.58	71.14 ± 4.24	6.2	72.53 ± 1.25	67.14 ± 0.60	7.4
TN (%)	0.27 ± 0.04	0.25 ± 0.01	7.4	0.23 ± 0.01	0.22 ± 0.03	4.3
TAN (mg N/L)	1730 ± 185	1626 ± 188	6.0	1367 ± 42	1349 ± 68	1.3
TP (mg P/L)	259 ± 64	223 ± 10	14.1	322 ± 21	330 ± 32	-2.4*
TK (mg K/L)	1362 ± 30	1342 ± 47	1.4	1869 ± 25	1920 ± 42	-2.7*

* Negative removal % are within the error range for the analysis

Table 2-3. Separated Fiber Solids and Nutrient Content.

	Trial 1 Solids	Trial 2 Solids
TS (%)	28.89 ± 1.65	25.67 ± 0.47
VS (% of TS)	90.60 ± 1.51	89.29 ± 0.72
TN (%)	2.68 ± 0.22	2.56 ± 0.27
TAN (mg N/L)	4071 ± 506	4696 ± 389
TP (mg P/L)	5241 ± 1464	5049 ± 974
TK (mg K/L)	4359 ± 588	7175 ± 179

2.3.2 Fine Solids Separation

After fiber is removed during primary solids separation, the effluent still contains a large fraction of suspended solids in the form of small irregularly shaped particles that take a long time to settle out (Zhang et al. 2010, Huang et al. 2013). The majority of the remaining total phosphorus is present in these small suspended particles in the form of either calcium or magnesium salts (Chapuis-Lardy et al. 2004, K. Güngör and Karthikeyan 2005). Phosphorus is primarily found in particles with characteristic length from 0.5-125 microns (Zhao et al. 2013). At 1.5 microns, particles are considered colloidal material (Hamilton 1998), so targeting phosphorus recovery requires technologies capable of removing suspended particles less than 1.5 microns.

The composite anaerobic biorefinery under review utilized dissolved air flotation (DAF) for fine solids separation. The central idea of utilizing a flotation process is to produce aggregated particles that are lighter than the surrounding liquid. The DAF process introduces pressurized air to a mixture containing the liquid effluent and a polymer. This polymer destabilizes colloidal solids into particulate solids to aid in their separation from water. Due to the difference in bubble pressure and vapor pressure of the liquid effluent, these bubbles rise and get trapped in the aggregated particles which floats them to the top. A mechanical skimming system removes the suspended particles from the tank. Trial 1 showed 67.5% TS removal and trial 2 showed 47.4% TS removal (Table 4). P removal was 94.0% (trial 1) and 95.8% (trial 2). N removal was predictably lower, but not inconsequential, 35.3% (trial 1) and 32.7% (trial 2).

Table 2-4. Fine Solids Separation.

	Trial 1			Trial 2		
	Influent	Effluent	Removal %	Influent	Effluent	Removal %
TS (%)	4.35	1.41 ± 0.01	67.5	2.35 ± 0.09	1.24 ± 0.01	47.4
TKN (mg N/L)	2850	1843 ± 16	35.3	2276	1532	32.7
TP (mg P/L)	2003	121 ± 6	94.0	1183 ± 66	50.0 ± 2.5	95.8

As described in the methods, in fall 2017, complementary funding allowed for a more comprehensive evaluation of DAF performance at commercial scale, at a newly built commercial-scale installation on a dairy in Lynden, WA. Results for TS and N from this evaluation indicated a lower P recovery rate of 86.7%, but similar TS and N recovery of 58.5% and 34.3%, respectively (Bronstad, Frear et al. unpublished data).

Additional suspended solids removal processes have been investigated and described in the literature including settling basins, decanting centrifuges, vibrating screens, membranes, and ultrafiltration systems. In comparison to the DAF system, a case study using a vibrating screen system showed 35-40%

TS removal with 12-18% TP recovery (Ma et al. 2013). In another case study using a decanting centrifuge showed 30-35% TS removal with 40-50% TP recovery (Ma et al. 2013). A struvite approach achieved 75% total P removal and 10% N removal from fiber-separated AD effluent (Ma et al. 2013).

2.3.3 Ammonia Stripping

Ammonia stripping is a thermochemical process that allows nitrogen in the form of ammonium ions to be removed from liquid manure effluent as free ammonia (Guštin and Marinšek-Logar 2011). As excreted dairy manure contains about 0.6% N on a wet basis. During AD, between 25-40% organic N is converted to an inorganic soluble form, giving a range of 75-90% of the TN as an inorganic form that could be recovered (Uludag-Demirer et al. 2008). Ammonia stripping is a mature process first developed for treating industrial and municipal wastewaters (U.S. EPA 2000). As a coupled thermochemical process, both pH and temperature can affect the equilibrium of the process for a given total ammonium nitrogen (TAN) concentration. The pH of liquid effluent required for ammonia stripping decreases with increasing temperature (Emerson et al. 1975). In Zhao et al. (2015), 70% TAN removal was demonstrated at temperature and pH values of 35°C and 9.32, 55°C and 8.78, and 70°C and 8.41. In addition to temperature and pH considerations, the gas to liquid ratio coupled with liquid height is an important factor in ammonia stripping as the air bubbles contribute to removal of carbon dioxide and associated increase in pH (U.S. EPA 2000; Jiang et al. 2014). A study by Zhao et al. (2015) determined that smaller bubble size contributed to more TAN removal compared to higher gas to liquid ratios. Higher gas to liquid ratios have been shown to detrimentally impact TAN removal due to uncontrolled foaming issues (Liao et al. 1995). The following sections detail the results of the four trials.

2.3.3.1 Trial 1, Commercial-Scale Batch Ammonia Stripping System

Results from Trial 1 indicated that the produced ammonium sulfate stabilized at 4.5. TAN concentrations went from 1,400 to 500 mg/L over the course of the 24-hour batch run, with a total 64% reduction in TAN during stripping. Ammonium sulfate production during the batch run was 140 gallons at a density of 1.24 g/mL, which translates to 42% concentration and 95.7% of theoretical, stoichiometric production. Ammonia concentrations in the gas stream measured an immediate high of 2,000 mg/L ultimately lowering to 800 mg/L at the end of the batch process.

During the process, aeration raised the room temperature pH of the effluent from 8.45 to 9.7 for the non-chemical stripping process achieved in batch mode. The calculated air/liquid ratio for the batch process, when factoring in the 8% loss of manure due to gas holdup, was 370, which is a quite low ratio (Guštin and Marinšek-Logar 2011). This low ratio in conjunction with the slightly lower than desired operating temperature and the low operating pH due to no chemical addition, still led to a moderate removal percentage, albeit at high retention times.

2.3.3.2 Trial 2, Commercial-Scale Continuous Ammonia Stripping System

Results showed an aeration tank temperature of 55.56 +/- 5°C, aeration effluent pH of 8.8 +/- 0.18, ammonium sulfate production of 231 +/- 53 gallons/day, ammonium sulfate specific gravity of 1.22 +/- 0.14 g/mL, acid use of 51.66 +/- 31 gallons/day, and manure flow rate of 55,834 +/- 24,368 gallons/day. Calculations, considering the manure loss due to gas hold up, indicated a theoretical HRT, assuming no short-circuits and perfect plug-flow action, of 31.88 hours. The corresponding air/liquid operating ratio was 378, or very similar to the batch operation but at higher operating temperatures. Notably, the pH of the effluent was lower, only achieving 8.8 on average (range of 8.62 -8.98), as compared to batch tests that achieved a high of 9.7. Influent manure sampling showed a consistent TAN concentration of between 1400-1200 mg N/L. Using stoichiometric calculations, and assuming 100% conversion to ammonium sulfate, the range of TAN removal was 31-36%, far lower than the batch study. The reduced performance as compared to batch mode, despite operating parameters that were the same or higher, was hypothesized to be due to 1) ineffective manure mixing/flow patterns that deviated from plug-flow behavior and much nearer complete-mix with short-circuiting and 2) continuous dilution of liquid with influent manure of low pH, that prevented the pH from rising to the desired minimum.

The results from trial 1 and trial 2 indicated operation below performance targets. The air to liquid ratio utilized required extensive retention times, leading to a large required basin with large depth and pressure losses to the compressor. These led to high compressor/electrical costs as well as high capital costs (Table 2-5). Acid consumption was 53.5 gal/day, 128% of the calculated theoretical consumption of 41.8 gal/day. While one would expect the actual consumption to be higher than the theoretical consumption, this substantial increase was likely the results of either inefficiency, or of error-prone reading of the tank line in the commercial system.

Table 2-5. Summary of Major Inputs and Outputs from Trial 2 Continuous Commercial System.

	Manure Treated	Sulfuric Acid Consumption[1]	Electrical Consumption	Ammonium Sulfate Solution Produced[2]
	gal/day	gal/day	kwh/h	gal/day
	56,130 +/- 19,111	53.3 =/- 30[1]	55.24	234 +/- 38

[1] Sulfuric acid was 15.36 lbs./gallon density 98% purity acid.
[2] AS solution had a density of 1.22 +/- 0.14 g/mL, corresponding to a 35% AS concentration.

Worse, the results were not inline with previous laboratory outcomes or with desired performance, with TAN removal less than 40%, rather than the targeted 70-80% removal.

2.3.3.3 Trial 3, Pilot-Scale Batch Ammonia Stripping System

Utilizing the lessons learned through trials 1 and 2, as well as information from additional laboratory-scale work, a pilot-scale system was designed and built utilizing micro-aerators, instead of the macro-aerators used during the initial commercial-scale trials. The goal was to achieve high air to liquid ratios, requiring less retention time and therefore lower costs and reactor heights. An optimum operating gas to liquid aeration ratio of 600 and five-hour HRT was targeted. Results showed that the micro-aeration process raised the pH of the effluent from 8.02 to 9.25 with temperatures varying from 46.1°C to 56.1°C. Average influent TAN was 993 mg N/L. After five hours of operation, a TAN reduction of approximately 74% was observed. After eight hours, average effluent TAN was 177 mg N/L, an 82.2% TAN reduction. The concentrations of TS and TP increased by 7.4 and 7.9% respectively, indicating some small amount of evaporation, which artificially reduced the actual TAN reduction. Reductions by hour are shown in Figure 2-8.

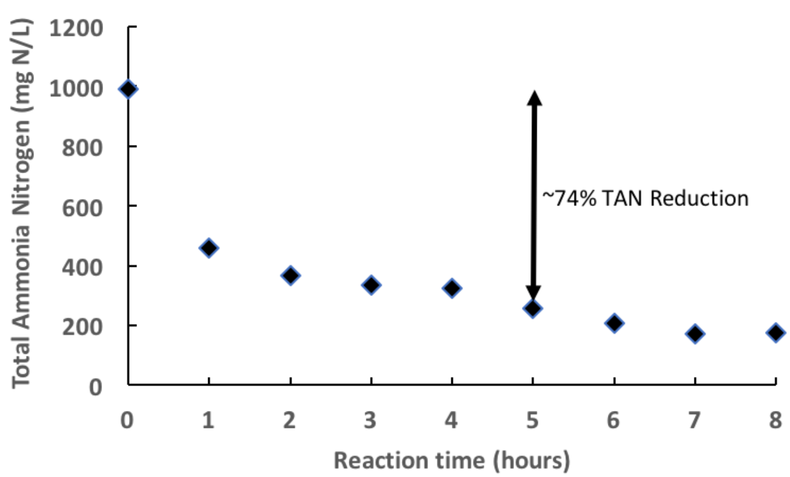


Figure 2-8. Pilot Batch System Total Ammonia Nitrogen (TAN) Reduction Performance.

Overall, the pilot system resulted in reduced pressure losses and similar capital and electrical costs (lower structural costs but more expensive aerators as well as more air flow, compensated for with reduced pressure loss). Performance was also improved, presumably through enhanced mass transfer.

2.3.3.4 Trial 4, Pilot-Scale Batch Ammonia Stripping System

For trial 4, a gas to liquid aeration ratio of 600 was targeted and an HRT of five hours was set, similar to targets during trial 3. While most of the reduction in TAN occurred after just one hour in the pilot batch system (Figure 11), this targeted five-hour retention time was used to allow for robust performance, user flexibility to operate with a shorter or longer HRT depending on performance needs, and to compensate for any sampling or data error. After startup, the pH and temperature varied from 8.98 to 9.42 and 44.4°C to 47.8°C, respectively. After the first five hours, the TAN reduction was approximately 49%. Experimental TAN values by hour are shown in Figure 2-9.

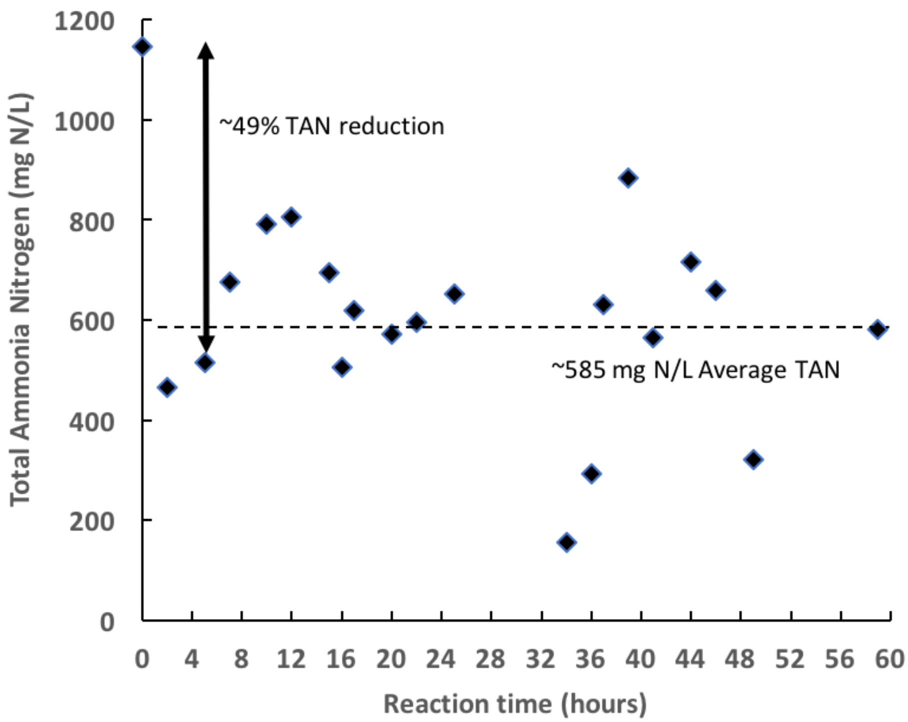


Figure 2-9. Pilot Continuous System Total Ammonia Nitrogen (TAN) Reduction Performance.

Starting TAN was 1,145 mg N/L while average effluent TAN during course of the 60-hour experiment was 585 +/- 177 mg N/L, giving a mean 48.9% TAN reduction. Meanwhile, the concentrations of TS and TP decreased by -4.8 and -3.7%, respectively, showing limited evaporation over the course of the trial. Nitrate concentrations rose 7.2% over time, averaging 1.44 +/- 0.5 mg N/L.

Variability of effluent TAN was quite high (Figure 2-9). This may correspond somewhat to difficulty obtaining representative samples due to the physical configuration of the unit. It also likely corresponding to several potential design issues which include difficulty controlling the pump rate, inadequate foam control, short circuiting of influent manure that changed influent TAN over time, and lack of process and equipment optimization. Given lower performance during continuous operation for both the commercial- (trials 1 and 2) and pilot-scale units, there may also be that variations in temperature, partial pressures, or concentrations are causing complex equilibrium to shift away from gas release during continuous operation. Finally, underlying variability of manure inputs and TAN concentrations may have also been a factor. These design flaws will need to be further explored and addressed in future work.

While it is not possible to directly compare the costs for the pilot scale system with the commercial scale system tested in Trials 1 and 2, we anticipate that the Trial 3/4 system would likely have similar capital costs at commercial scale, due to less concrete needed due to the smaller volume, but additional aerators. Electrical costs are likewise estimated to be roughly similar, due to the impacts of doubling the aeration rate, but reducing the depth from 12 feet to 1 foot, with reduced head pressure loss. Sulfuric acid requirements would be higher, but with overall improvements in economics, due to the additional revenues from increased ammonium sulfate production.

2.3.3.5 Ammonia Stripping Summary

The maximum recovery of TAN achieved in this study was 82.2% for the trial 3 batch pilot system, which would generally correspond to roughly 62-74% recovery of TN in the digester effluent; however, this was given an HRT of eight hours, considerably longer than the targeted five hours of operation. The performance of each trial at the targeted HRT is summarized in Table 2-6.

Table 2-6. Summary of Ammonia Stripping Trials.

	Influent TAN	HRT	Effluent TAN	TAN Removal	pH	Temperature	Production Rate
	(mg N/L)	(hours)	(mg N/L)	(%)			(mg N/L hour)
Trial 1 batch commercial	1400	24	500	64	8.45 - 9.7	50℃	37.5
Trial 2 continuous commercial	1200-1400	31.9	768-966	31-36	7.0 - 10.6	50.6℃ - 60.6 ℃	13.6
Trial 3 batch pilot	993	5	258	74	8.02 - 9.25	46.1℃ - 56.1℃	147.0
Trial 4 continuous pilot	1145	5	516	49	8.98 - 9.42	44. ℃ - 47.8℃	125.8

The reported 74% TAN recovery for trial 3 corresponds to a range of 56-67% total N removal. In laboratory tests, Jiang et al. (2014) demonstrated that 90% TAN recovery was possible with a system operating at pH of 10.3 and temperature of 35°C. While this performance is significantly better than the results obtained here, they used chemical pH adjustment through addition of 3.3 g/L lime, which increases both the complexity and cost of the associated system (Jiang et al., 2014). Using only aeration in a similar lab-scale study, Zhao et al. (2015) demonstrated 90% TAN recovery in a batch system with an HRT of six hours at 55°C. In comparison, for an air ammonia stripping system treating liquid swine manure, at a pH of 9.5 and temperature of 22°C, it took 55 hours to reach 91% TAN removal (Liao et al. 1995). In this same system, they chemically increased pH to 11.5 to get 90% TAN removal in only seven hours (Liao et al. 1995).

In a case study at a poultry operation, Ma et al. (2013) reported that AD of poultry liter followed by ammonia stripping resulted in 55-65% TN removal. While this is relatively similar to the above demonstrated system treating digested dairy manure effluent, anaerobic digestion of poultry litter is more susceptible to ammonia inhibition; therefore, a nutrient recovery technology that targets TN removal is essential in combination with AD in this system, whereas its role in a dairy system is more dependent on the overall nutrient balances of the dairy (Sims and Wolf 1994; Sakar et al. 2009; Yilmazel and Demirer 2013; Budych-Gorzna et al. 2016).

CHAPTER 3

Economic Analysis of Ammonia Stripping in the Context of a Dairy Biorefinery

To examine the current viability of ammonia stripping within a biorefinery context, a pro forma analysis was carried out. The analysis relied on previous commercial data relating to anaerobic digester performance, thus that data is reviewed first. Pro forma analysis of the complete biorefinery follows, followed by a separate economic analysis of the ammonia stripping unit on its own.

3.1 Anaerobic Digester Performance Overview for Pro Forma

Bio-methane potential (BMP) studies done by Labatut et al. (2011) give an indication of what the potential biogas/methane performance is for manure under ideal conditions: 0.243 +/- 0.06 m^3 CH4/kg VS input. What is meant by ideal conditions is that: the manure is batch digested, thus not experiencing bacterial washout or short-circuiting during organic loading; the mixing and temperature control are consistent and suitable for suspension and bacterial/substrate interaction without shearing, and bacterial and organic loading conditions are set so as to avoid inhibition or poor biological activity. Labatut et al. (2011) showed a large standard deviation in performance, with some samples obtaining a standard deviation high of 0.30 and a low of 0.18 m^3 CH_4/kg VS input to the system.

Obtaining total solids (TS) and volatile solids (VS) data over an extended period of time to obtain an accurate mass balance for an operating digester can be expensive and logistically problematic, thus the most commonly available data is simply biogas flowrate and wet cow equivalents to estimate manure production. Also, most on-farm digester projects in Washington State are performing co-digestion, thus obtaining a manure-only baseline can be problematic.

Performance and flow data has been made available from an anaerobic digester over an approximate three-year period of observation (Figure 3-1). Fortunately, this project had an extended period of manure-only digestion (7/30/2013 to 6/25/2014) in between periods of co-digestion. The average biogas production during manure-only feed was 229,251 +/- 41,108 cubic feet per day, yielding an average electrical production with its engine/generator sets of 408 +/- 37 kW. The average flow was 83,004 +/- 27,057 gallons per day from 1,700 wet cow equivalents. Thus, inputs on a per wet cow basis were 48.8 +/- 15.9 gallons per cow per day, yielding 134.9 +/- 24.2 cubic feet biogas per cow per day; and roughly 4.2 cows per KW electrical production. Using ASABE manure characteristics (150 lbs. manure per cow per day and 11.0% VS) (ASAE 2005) and Labatut et al. 2011 data (0.243 +/- 0.06 m3 CH_4/kg VS), the expected biogas production rate on a per cow basis would be 117 cubic feet biogas per cow per day.

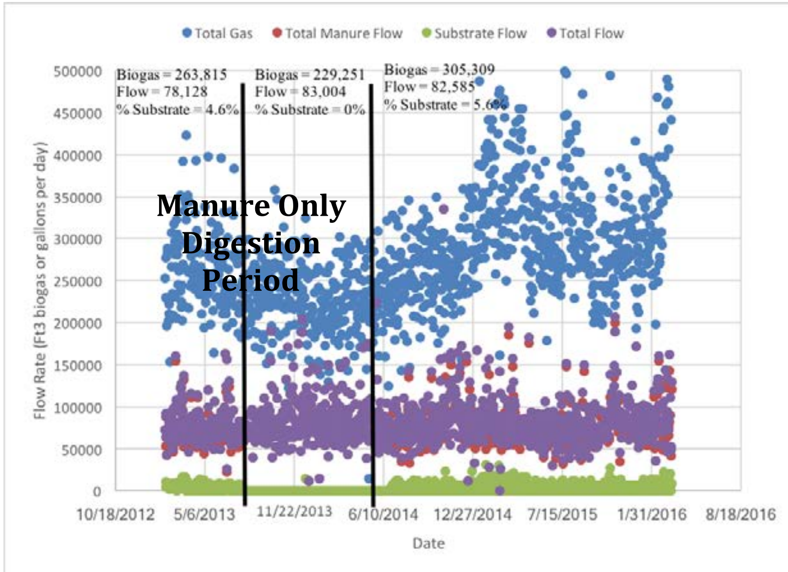


Figure 3-1. Biogas, Flow Data for Anaerobic Biorefinery from Early 2013 Through Early 2016.

3.2 Baseline Pro Forma Specifics

The baseline composite biorefinery utilized for the pro forma analysis includes an anaerobic digester, mechanical building and generator, slope screen separator and stand, DAF unit, and an ammonia stripping system (Figure 3-2). This system is sized to treat 100,000 gallons total flow per day with 90% from dairy manure and 10% from off-farm substrates for co-digestion. The anaerobic digester was assumed to be the same design sampled in the research study, a modified plug-flow design with biogas mixing and sludge recycle operating at mesophilic temperature (38°C).

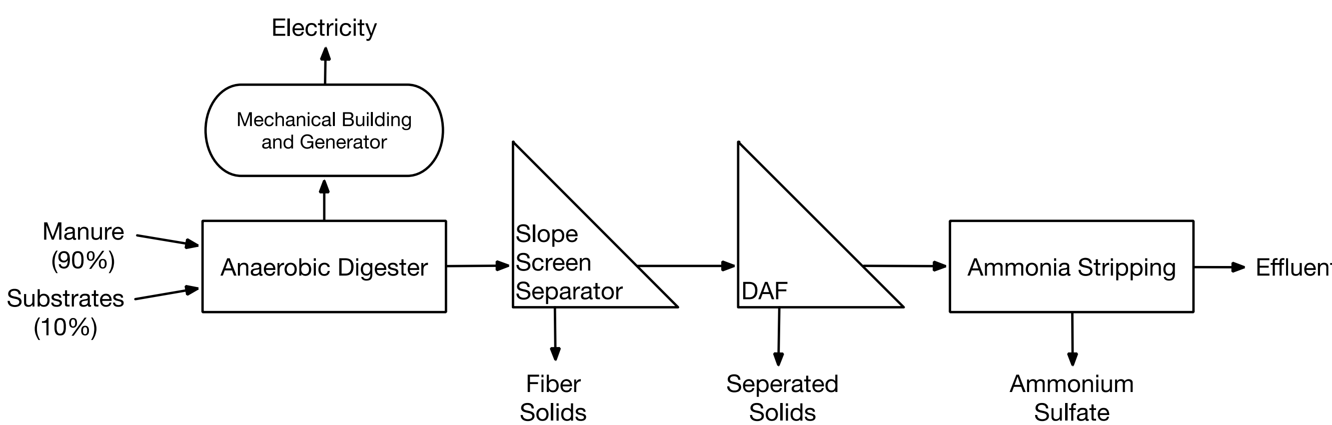


Figure 3-2. Baseline Composite Biorefinery for Pro Forma.

With the greater performance seen from the smaller footprint pilot-scale ammonia stripping operation, Pro forma analysis used these translated performances and costs to carry out the analysis. Capital for the installed commercial systems as well as estimated scale-up of pilot AR system were completed by Regenis Corporation (Ferndale, WA) who constructed as well as operates the commercial systems studied in this report. The capital cost for this baseline system is estimated at $5,325,760.00 with costs for each unit provided in Table 3-1.

Table 3-1. Estimated Capital Costs for the Composite Biorefinery (2017 Dollars).

Item	Units	Cost ($)
Anaerobic Digester	1	3,000,000.00
Mechanical building and generator	1	1,000,000.00
Slope Screen Separator and Stand	1	125,000.00
DAF Unit	1	375,760.00
Ammonia Stripping System	1	825,000.00
Total for 100,000 GPD System		**5,325,760.00**

Based on experience from our industrial collaborator, who supplied many capital, operating and pricing assumptions, a Pro forma analysis was completed. Key assumptions include those regarding important operating cost parameters. Energy is necessary to keep the digester heated, run pumps and motors, and drive the main separation systems. It was estimated that a parasitic load of 22% from the energy produced from the biogas would be needed. The DAF unit operates most effectively when used in combination with a chemical polymer, which was estimated at 30,466 lbs/year. To produce ammonium sulfate, chemical addition of acid is necessary and estimated at 446 tons/year. For feedstocks, manure was set at 90,000 GPD with 7% TS, 80% VS and a specific methane potential of 0.23 m^3 methane/kg VS. The substrates for co-digestion were set at 10,000 GPD with 15% TS, 95% VS and a specific methane potential of 0.43 m^3 methane/kg VS. This results in an average electricity production of 821 KWh/h. Important cost and revenue elements are explained in Tables 3-2 and 3-3 and are based on prices as of spring 2017.

Table 3-2. Key Cost Parameters Used for the Pro Forma Analysis, Based on Industry Experience of Regenis Corporation (Ferndale, WA).

Item	Notes
Daily monitoring	Estimated at 2 hours per day, with labor at $60/hour, and 2% escalator.
Digester system maintenance	Based on many years of industry experience, estimated at $0.017/kWh/h minus parasitic load with 2% escalator.
Separator maintenance	Based on industry experience, primary separation with slope screen estimated at 2 hrs/week cleaning, 2 hrs/week maintenance, and $1,000 per year parts and cleaning supplies.
Fine solids polymer chemical	Calculated usage of polymer based on flow rate, solids concentration, dissolved solids concentration at end, polymer dosing rate).
Fine solids maintenance	Assumed to be 5% of capital equipment costs for parts plus 5 hrs/wk labor at $60/hr, with 2% annual escalator.
Sulfuric acid for ammonia stripping	Estimated at $200/ton, with usage as required for the assumed cows, flow rate, TAN concentration, Removal %, and acid type/density.
Ammonia stripping maintenance	Assumed to be 5% of capital equipment costs for parts plus 5 hrs/wk labor at $60/hr, with 2% annual escalator.
Electrical use	Usage based on industry experience.

Table 3-3. Key Revenue Parameters Used for the Pro Forma Analysis, Based on Industry Experience of Regenis Corporation (Ferndale, WA).

Item	Rate	Notes
Rate paid for electricity generated, with green tags	$0.065 per kW	Estimated conservatively based on considerable variability across the U.S.
Carbon credit	$10/MT	Average California price of $8-12 per MT, 55% brokerage split, $8000 annual cost for verification.
Tipping fee for organic wastes	$12.00/ton	Based on industry experience for tipping fees received for the types of wastes currently received by on-farm digesters.
Offset bedding	$5/ cubic yd	Based on industry experience.
Soil amendment	$7/ cubic yd	Conservative pricing for soil amendment bulk product to wholesaler less production costs and trucking.
Fine solids	$25/dry ton	Fertilizer value on dry weight is estimated at $100 for retail pricing, with discount for wholesale and shipping, processing.
Ammonium sulfate slurry	$80/ton	Dry AS crystals sale wholesale at $250/ton but this is 35% slurry plus some discount for shipping.

3.3 Baseline Pro Forma Analysis

From the above estimates, assumptions of nutrient product revenue based on similar commercial products, and including an escalating rate paid for electricity, a 10-year pro forma was generated (Table 3-4). Key elements of financial performance are summarized in Table 3-5.

Table 3-4. Baseline Composite Biorefinery Pro Forma.

15-Jun-17	PROJECTED COSTS & REVENUES - DIGESTER					
SCENARIO - WITH ELECTRICITY PRODUCTION	Digester, Electricity, Primary Screening, Fine Solids Polymer, Ammonia Stripping					
ASSUMED START UP IN 2018	DIGESTER SIZED FOR 2500 WET HOLSTEIN COW EQUIVALENT					
Project Cost	$ 5,325,760					
USDA Grant 25% of Cost up to $500,000	$ -					
Owner net investment			$ 5,325,760.00			
WET COW EQUIVALENT	2500	2500	2500	2500	2500	GRAND
REVENUE	Year 1	Year 3	Year 5	Year 7	Year 10	10 YEARS
ELECTRICITY SALES	$347,390	$364,977	$383,454	$402,866	$433,843	$3,891,947
Gross kWh/h total output	821	821	821	821	821	
Wh/h output (gross less parasitic and 95% runtime)	610	610	610	610	610	
Rate paid per kW w/Green Tags (1.025 escalator)	$0.0650	$0.0683	$0.0717	$0.0754	$0.0812	
CARBON CREDITS	$50,600	$50,600	$50,600	$50,600	$50,600	$506,000
Rate for Carbon Credit (currently $8 - $12)	$10.00	$10.00	$10.00	$10.00	$10.00	
TIPPING FEE	$183,958	$183,958	$183,958	$183,958	$183,958	$1,839,582
Tons Per Year	15,330	15,330	15,330	15,330	15,330	
Average Price Per Ton	$12.00	$12.00	$12.00	$12.00	$12.00	
FIBER SALES	$145,000	$145,000	$145,000	$145,000	$145,000	$1,450,000
Annual Fiber Production (yards/year)	25,000	25,000	25,000	25,000	25,000	
Average Price Offset Bedding ($/yard)	$5.00	$5.00	$5.00	$5.00	$5.00	
Average Price Soil Amendment ($/yard)	$7.00	$7.00	$7.00	$7.00	$7.00	
FINE SOLIDS SALES	$62,500	$62,500	$62,500	$62,500	$62,500	$625,000
Annual Fine Solids Production (dry tons/year)	2,500	2,500	2,500	2,500	2,500	
Average Price Fine Solids ($/dry tons)	$25.00	$25.00	$25.00	$25.00	$25.00	
AMMONIUM SULFATE SOLUTION SALES	$127,750	$127,750	$127,750	$127,750	$127,750	$1,277,500
Annual AS Slurry Production (tons/year)	1,597	1,597	1,597	1,597	1,597	
Average Price AS Slurry ($/ton)	$80.00	$80.00	$80.00	$80.00	$80.00	
TOTAL PROJECT REVENUE	$917,198	$934,785	$953,262	$972,674	$1,003,651	$9,590,028
EXPENSES						
DAILY MONITORING	$43,800	$45,570	$47,411	$49,326	$52,345	$479,598
DIGESTER SYSTEMS MAINTENANCE	$116,133	$120,825	$125,706	$130,785	$138,790	$1,271,626
SEPARATOR MAINTENANCE	$13,480	$14,162	$15,025	$15,940	$17,418	$153,164
FINE SOLIDS MAINTENANCE	$34,388	$35,777	$37,223	$38,726	$41,097	$376,539
AMMONIA STRIPPING MAINTEANCNE	$56,850	$59,147	$61,536	$64,022	$67,941	$622,492
ENGINE GENERATOR SET MAINTENANCE	$152,998	$165,483	$178,986	$193,591	$217,764	$1,836,911
Maintenance agreement cost / kW 2% inflat.	$0.0090	$0.0097	$0.0105	$0.0114	$0.0128	
Periodic maintenance sinking fund 2% inflat.	$0.0110	$0.0119	$0.0129	$0.0139	$0.0157	
FINE SOLIDS POLYMER CHEMICAL	$68,549	$68,549	$68,549	$68,549	$68,549	$685,489
Price of Polymer ($/lb.)	$2.25	$2.25	$2.25	$2.25	$2.25	
AMMONIA STRIPPING ACID CHEMICAL	$89,236	$89,236	$89,236	$89,236	$89,236	$892,359
Price of Acid ($/ton)	$200	$200	$200	$200	$200	
CAPITAL DEPRECIATION - 20 year straight	$266,288	$266,288	$266,288	$266,288	$266,288	$2,662,880
Interest Expense @ 4.50% Term 10 years	$230,831	$190,274	$145,904	$97,363	$15,866	$1,297,680
TOTAL NET PROJECT EXPENSES	$1,072,553	$1,055,310	$1,035,863	$1,013,826	$975,293	$10,278,736
PROJECTED INCOME/LOSS BEFORE TAXES	-$155,355	-$120,524	-$82,601	-$41,152	$28,358	-$688,708
Net Profit as % of investment	-2.92%	-2.26%	-1.55%	-0.77%	0.53%	-1.29%
RECOUPING OF CAPITAL (Excluding depreciation)						
Net Available for Capital Repay After Interest Exp.	$110,933	$145,764	$183,687	$225,136	$294,646	$1,974,172
Return Based On Repay Potential	2.08%	2.74%	3.45%	4.23%	5.53%	3.71%

Table 3-5. Summary of 10-Year Composite Biorefinery Pro Forma Analysis.

Term	Estimation
Capital cost	$5,325,760
Operation & maintenance costs	$6,318,176
Total revenues	$9,590,028
Gross earnings (before taxes)	-$688,708
Net profit as % of investment	-1.29%
Net available for capital repay after interest expenses	$1,974,172
Return based on repay potential	3.71%

Although the project does begin to generate a net revenue in year 10 at the end of the debt service, the overall projected income/loss before taxes shows that over the 10-year operational period, the composite biorefinery would cost the operator a total of $688,708. Additional analysis showed that only when depreciation has been excluded is the system profitable through the full 10 years of operation. It is important also to note that this analysis does not examine impacts on manure management costs, which, depending on a variety of factors, might be reduced through implementation of nutrient recovery. Reductions in total solids and in total volume of manure wastewater may also result in reduced costs of cleaning, maintaining, or adding required long-term storage capacity, benefits also not captured in this analysis.

At this size and based on the core estimates and assumptions described above, this analysis shows that there are a number of challenges to overcome to push the full system economics to be a net positive for the producers. These challenges include not only a need for cost reductions but also a critical need for product refinement and market development. The development of a bio-economy that revolves around the production and sales of these renewable nutrient rich products could be the basis for the buildout of more facilities and increasing the value compared to non-renewable fossil fuel derived current fertilizers.

3.4 Baseline Biorefinery Parameter Estimation and Effect on Net Revenue

Given the baseline pro forma, several parameters can be immediately investigated to determine effect on the overall profitability of the composite biorefinery. The starting electricity rate paid, the substrate tipping fee, and the co-digestion volumetric flowrate were changed to reach break-even after 10 years of operation (Table 3-6). A change is electricity rate paid from $0.065/kW to $0.0766/kW would result in essentially break-even after 10 years of operation. A change in tipping fee for off-farm organics from $12.00/ton to $16.50/ton would also result in essentially break-even at 10 years. Finally, a change from 90,000 GPD manure and 10,000 GPD substrates to 86,900 GPD manure and 13,100 GPD substrates would again result in near break-even after 10 years. This analysis highlights the fact that the overall economic performance of the entire biorefinery is dependent not only on the performance and costs of the incorporated unit operations, but also on global factors including open energy market prices and the value and availability of waste organics.

Table 3-6. Parameter Change Required to Breakeven After 10 Years of Operation.

	Baseline	Alternative	Percentage change
Electricity rate paid	$0.065/kW	$0.0766/kW	17.8%
Substrate tipping fee	$12.00/ton	$16.50/ton	37.5%
Substrate volumetric flowrate	10,000 GPD	13,100 GPD	31.0%

3.5 Pro Forma Analysis for Ammonia Stripping System Alone

Considering that additional treatment steps may be added sequentially by a dairy, we also carried out a pro forma analysis for the ammonia stripping operation on its own. The assumption in this case is that the dairy may already have the prior treatment steps and is considering whether to install an ammonia stripping unit operation. The major results of this pro forma analysis are presented in Table 3-7. While capital costs are substantially lower than for the full biorefinery, losses are also greater, $970,770 over 10 years. The net loss is nearly 12% of investment, and the return based on repay potential is -6.77%. As above, this analysis does not consider the potential for reductions in manure management costs.

Table 3-7. Summary of 10-Year Pro Forma Analysis of Ammonia Stripping System.

Term	Estimation
Capital Cost	$825,000
Operation & maintenance	$1,634,750
Total revenues	$1,277,500
Gross earnings (before taxes)	-$970,770
Net profit as % of investment	-11.77%
Net available for capital repay after interests Exp.	-$558,270
Return based on repay potential	-6.77%

3.6 Economic Analysis Summary

As the economic analysis in this report illustrates, the revenues from these systems may not currently be great enough to offset operating and maintenance costs, let alone the capital costs associated with installing them on dairies. This is also true for several other emerging approaches to nutrient management (Frear et al. 2018). Technological advancements that reduce costs are likely to be important for future viability, as will development of more robust markets for the nutrient recovery products.

However, our experience through this project and our discussions with dairy producers throughout the region suggest that nutrient recovery technologies are often best seen as part of the costs of managing manure effectively on dairies, rather than as a stand-alone technology that should be evaluated based solely on its own revenues and costs.

As such, one of the most important financial impacts of nutrient recovery technologies can be to offset existing manure management costs of the dairy. These costs vary substantially from dairy to dairy, and there is little available data relating to either the amounts of manure trucked by dairies, the distances trucked, or the costs of manure management. Among the limited data that exists, in 2010, Hadrich et al. estimated equipment ownership and operating costs ranging from 0.32¢/L (1.18¢/gal) for a 175-cow dairy using a 11400-L (3000-gal) spreader with an average hauling distance of 1.6 km (one mile) and broadcast application with tillage incorporation to 0.50¢/L (1.91¢/gal) for a 1400-cow dairy using slurry injection and an average hauling distance of 6.4 km (4 miles) with two 34100-L (9000-gal) spreaders and four nurse trucks for over-the-road transport.

Utilizing the information in Hadrich et al. (2010) and updating to 2017 prices, the potential for avoided costs for the ammonia stripping technology can be illustrated. In this scenario, it is assumed that manure management is based on meeting crop needs for nitrogen (and the dairy nutrient management plan was, thus, based on nitrogen). Data from Hadrich et al. were used to determine costs, inclusive of long-term liquid manure storage, agitation, pumping, hauling, land application, and injection to the soil. Of the total manure volume generated, 40% was assumed to be trucked to distant fields five miles from the dairy at a cost of \$229 cow^{-1} year^{-1}, while 60% was applied to nearby fields at a cost of \$100 cow^{-1} year^{-1}.

Avoided costs were calculated assuming that the concentrated ammonium sulfate product is exported from the dairy, allowing for a removal of nutrients associated with the product. This nutrient export from the farm, alongside reductions in manure volume requiring land application, lead to corresponding reductions in manure management costs. Since the approach results in greater than 25% N removal, effluent can be applied only to surrounding fields (at a cost of \$100 cow^{-1} year^{-1}) instead of hauling to five-mile distant fields (\$229 cow^{-1} year^{-1}). Under these assumptions of a baseline involving a fairly high rate of manure hauling, sequential implementation of additional nutrient recovery reduces the amount of hauling needed, with benefits to manure management costs of up to \$79.60 cow^{-1} year^{-1} for full implementation. However, note that the bulk of the savings comes from implementation of the earlier nutrient recovery steps. This would be particularly true for dairies that are practicing lower rates of manure hauling in the baseline case.

Table 3-8. Summary of Avoided Manure Management Costs Resulting from Implementation of Ammonia Stripping System to Dairy with 2500 Cows, and 40% of Manure Hauled Under the Baseline Scenario.

	Cumulative Nitrogen Reduction	Cumulative Volume Reduction	Manure Hauled	Manure Applied Nearby	Manure Hauled	Total Avoided Cost	Avoided Cost
	%	%	cows	cows	%	year^{-1}	cow^{-1} year^{-1}
Baseline (no nutrient recovery)	–	–	1000	1500	40	–	
Primary Solids	5.9	10	911	1589	36	\$48,175	\$19.27
Primary Solids + Fine Solids (DAF)	38	28	432	2068	17	\$158,914	\$63.57
Primary Solids + Fine Solids (DAF) + Ammonia Stripping	65	28	0	2500	0	\$199,000	\$79.60

CHAPTER 4

Extension to Support Improved Decision Making Related to Emerging Nutrient Recovery Technologies

Nutrient recovery is a relatively new and still evolving area of technology within the dairy industry. While primary solids separation has been implemented on many dairies in the U.S., technologies for more advanced nutrient separation and were being used at only a few dozen of the largest dairies across the U.S. as of mid-2017 (Newtrient personal communication). As such, there is a need for objective, independent information about nutrient recovery for a variety of individuals who have interest in this emerging area.

Extension efforts within this project targeted a wide range of decision makers, including dairies, dairy-allied industry, and agencies including those at the federal and state level. The efforts carried out in support of this project are part of a long-standing extension strategy related to organic waste management led by the Center for Sustaining Agriculture and Natural Resources in collaboration with others at Washington State University, including a strong focus on dairy anaerobic digestion systems and dairy nutrient recovery. Links to extension outputs are in Appendix A.

4.1 Webinar Series

The research team hosted a webinar series on anaerobic digestion systems in collaboration with Water Research Foundation and the American Biogas Council, from February through April of 2016 (funding provided by this project and through the United States Department of Agriculture, National Institute of Food and Agriculture). The webinar series, entitled "Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact" included five webinars:

- Dairy Nutrient Recovery Technologies within an Anaerobic Digestion Bio-Refinery, Dr. Timothy Ewing.
- Anaerobic Digestion Bio-Refinery: Potential for Biochar Production and Utilization, Dr. Manuel Garcia-Perez.
- Agronomic Evaluation of Anaerobic Digestion System Recovered Fertilizers, Dr. Harold P. Collins.
- An Introduction to the Anaerobic Digestion System Enterprise Budget Calculator, Dr. Gregory Astill.
- Insights for Anaerobic Digestion from Dairy-CropSyst, a Decision Support Tool for Gaseous Emissions and Nutrient Management, Mr. Bryan Carlson.

A total of 341 people watched these webinars live, with most reporting moderate knowledge gain as a result of participating in the webinars (see Appendix B). The video recordings had received an additional 1,595 asynchronous views as of June 2018.

4.2 Extension Documents and Video

To support dairy, dairy-allied industry, and agency knowledge and decision making, we also developed an extension manual that provides an overview of the major nutrient recovery approaches now emerging or in use for recovery or removal of P, N, K, and other salts from dairy manure, particularly after anaerobic digestion (AD) (Frear et al. 2018). The review drew on a variety of sources relating to pilot and commercial demonstrations of nutrient recovery technologies, including the scientific literature, pilot reports, company literature, project feasibility studies, and interviews. For each of the more common technical approaches being used or considered by the dairy industry, the publication aimed to summarize important indicators, including approximate performance, capital and operating and maintenance (OPEX) expenses, co-product form and price, and potential impacts on manure management. While this is clearly a time-sensitive and changing snapshot, our goal was to gather existing information in a way that was accessible to non-academic stakeholders, to support their understanding of a rapidly changing field, and provide a starting point for additional investigation into technology approaches most likely to be of interest.

This publication is part of a series of three publications related to nutrient recovery on dairies, and part of a broader series on Anaerobic Digestion Systems:

- Yorgey, G.G., C.S. Frear, C.E. Kruger, and T.J. Zimmerman. 2014. "The rationale for recovery of phosphorus and nitrogen from dairy manure." Washington State University Extension Publication FS136E. Pullman, WA: Washington State University Extension Publishing.
- Frear, C.S., Ma, J., and G.G. Yorgey. 2018. "Approaches to Nutrient Recovery from Dairy Manure." Washington State University Extension Publication EM112E. Pullman, WA: Washington State University Extension Publishing.
- Hall, S., Benedict, C., Harrison, J., and Yorgey, G.G. In press. "Nutrient Recovery Products from Dairy Manure." Washington State University Extension Publication. Pullman, WA: Washington State University Extension Publishing.

We also developed and produced a peer-reviewed video (Hall and Yorgey 2017) that profiles two Washington State dairies – Edaleen Dairy and Royal Dairy – who have implemented new technologies that partition, and in some cases recover, some of the nitrogen and phosphorus in manure. The video discusses both the potential that these new tools have to improve manure management for dairies, and some of the challenges that remain. Between October 2017 and June 2018 (approximately eight months), the video was viewed 482 times.

4.3 AD Systems and Nutrient Recovery Field Days

Funding from this project also supported an anaerobic digestion and nutrient recovery field day in Lynden, WA in June 2016. Complementary funding that supported this event included Washington State University Biomass Research Funds, USDA's National Institute of Food and Agriculture, the Washington Department of Ecology's Waste to Fuels Technology Partnership, and USDA's Natural Resource Conservation Service [NRCS]). More than 80 participants attended, including dairymen and women, dairy-allied organizations and industry, and individuals from state and federal agencies. The morning included presentations on topics including: dairyman's perspective on AD and nutrient recovery, economic lessons learned, Renewable Natural Gas technologies, biochar and its integration with AD systems, fine solids separation, nutrient recovery approaches, water quality and application issues, and composition of nutrient recovery products (Figure 4-1). The afternoon introduced participants to a new, three-year effort looking at the application of dairy manure-derived fertilizers to red raspberries and blueberries (funded by USDA NRCS), an effort that aims to build on this project by focusing on addressing some of the barriers to market development for nutrient recovery products (Figure 4-2). This USDA NRCS-funded effort builds upon the efforts undertaken in this project and allow the team to support market development for nutrient recovery products, a key barrier to adoption of nutrient recovery technologies.

Figure 4-1. A Dairyman Shares His Experiences with Nutrient Recovery and Anaerobic Digestion with Field Day Attendees, June 2016.

Figure 4-2. Washington State University Researcher Chris Benedict Shares Information About Newly Installed Field Trials to Examine the Use of Nutrient Recovery Products in Raspberries (project funded by NRCS), June 2016.
Additional experiments (part of the same project) not pictured here examine the use of ammonium sulfate solution in blueberries.

Among the 33 evaluations that were turned in from the 2016 field day, 66% learned a lot about nutrient recovery, while an additional 30% learned a little. Meanwhile, 53% gained a lot of knowledge in anaerobic digestion systems, while an additional 36% gained a little knowledge. Based on experiences and knowledge gained at the field day 18% said they planned to make behavior changes and an additional 45% indicated that they were considering behavior changes. These changes include expanding potential collaborators, supporting AD and NR efforts, changing their investment behavior within the dairy industry, and incorporating these technologies into their digester facility.

Utilizing complementary funds, the project team also hosted a dairy field day in April 2018 at Edaleen Dairy, Lynden, WA, focusing specifically on nutrient recovery. Two systems with different technological approaches were available for attendees to view, neither of which had been available in 2016: a commercial-scale fine solids separation system utilizing dissolved air floatation (DAF) that was installed at Edaleen Dairy in 2017 (Figure 4-3), and a pilot-scale mobile struvite unit that is part of a project led by Dr. Joe Harrison of Washington State University (Figure 4-4). The 62 participants that attended the morning session included producers, NRCS, EPA, and state agency personnel, private consultants, technology providers, representatives from agricultural and environmental organizations, legislative staffers, and university researchers. Among the attendees, it was particularly notable that fourteen NRCS or conservation district employees actively involved in nutrient management planning in Washington State attended.

Figure 4-3. Dissolved Air Flotation System Installed at Edaleen Dairy for Fine Solids and Phosphorus Removal.

Figure 4-4. Attendees Viewing a Pilot-Scale Mobile Struvite System at Edaleen Dairy, April 2018.

Topics covered during the field day included an overview of the issues around nutrient cycling, how the DAF unit fits into the nutrient management picture at Edaleen dairy, struvite and DAF treatment processes. Products from both systems were available for attendees to view and interact with as well. Attendees were given three peer-reviewed extension documents relating to nutrient recovery (Yorgey et al. 2014, Frear et al. 2018, completed with Water Research Foundation support, and Hall et al. forthcoming). The lunch program featured the video on nutrient recovery completed with Water Research Foundation support, along with presentations from researchers from WSU who are working on projects related to nutrient recovery from dairy manure.

Most participants who completed evaluations at the 2018 field day felt that the field day did a “good” to “excellent” job contributing to their knowledge on the topic (average score of 3.9 on a five-point scale). When asked about the most valuable part of the field day, participants commonly mentioned seeing how the nutrient recovery technologies worked and networking with other attendees.

CHAPTER 5

Conclusion and Next Steps

The results obtained in this study point to the need for additional work to support the development and implementation of ammonia stripping as a viable nutrient recovery technology for dairies. However, it may be the case that ammonia stripping, with its focus on nitrogen removal, may be most likely to be adopted in poultry facilities than on dairies because of the susceptibility of anaerobic digestion of poultry litter to ammonia inhibition.

Poor financial performance is of particular concern given the economic constraints that the dairy industry has recently been facing. Net income for dairies in the Pacific Northwest has been negative two of the last five years (Shannon Neibergs, unpublished data). This represents the money available to pay debt obligations and provide owner returns. When net income is negative, investments in improving nutrient management through technology adoption are unlikely to occur. If they do, they will be funded by debt expansion, which may ultimately be detrimental to the viability of the dairy.

To achieve adoption on dairy farms under these constraints, three major efforts will need to be implemented. The first is improved performance and reliability of the technology, which was lower in continuous operation as compared to batch, and notably, quite variable. The second need is to reduce costs. Ongoing investigations into strategies such as in-situ ammonia stripping and absorption of ammonia using the carbon dioxide in biogas continue are one avenue through which such cost reductions may be achieved in the future.

Third, there is an ongoing need for both technology development and market development related to nutrient recovery products, as the development of viable markets will generate some revenues to help offset costs. On the technology side, there is ongoing work to further develop means to convert recovered nutrients and other co-products to preferred forms. Most nutrient recovery products, including both the fine solids and ammonium sulfate solution generated by the biorefinery system explored in this study, are not yet fully developed (Yorgey et al. 2014; Ma et al. 2013). Products may be heterogeneous, have inconsistent form, and may require further processing to dry, or make product handling and application manageable. Food pathogen risks are also a concern for some products, especially if application to food crops is being sought (Hall et al. in press; Yorgey et al. 2017). Further development of economical dewatering technologies and improvements in consistency of fertilizer form, function, and performance will allow nutrient recovery to generate a consistent product that can be easily applied with crop producers' existing equipment.

Markets development will take both a more consistent availability of products, as well as documented fertilizer efficacy in crops of interest. Some products may be appropriate in specialized situations, while others may be used more generally. For example, ammonium sulfate will acidify soils, and therefore may be particularly useful to maintain drip line irrigation systems and amend soil pH in applications such as blueberry production. In contrast, struvite may be more widely used as a phosphorus source, because of its dry, granular form.

There has also been some ongoing interest in whether nutrient trading could help close the financial gap and spur adoption. Under the most common form of nutrient crediting, an entity exceeding regulated nutrient discharge levels, normally a point source polluter such as a water treatment plant, could purchase credits from another entity instead of reducing their own nutrients. In this case, they would be purchasing credits from a non-point source polluter such as a dairy, who would use nutrient recovery or other means to reduce nutrient inputs below the levels required by them. However, work remains to be done before this is a widespread and viable solution across the U.S. Of relevance to nutrient recovery technologies, the water quality impacts of changes implemented by non-point sources can be difficult to understand, measure, and verify.

Credit values are a function of the measured water quality benefits (the pollution reductions tracked from the edge of the field into a waterbody and downstream to a point of concern), adjusted by baseline requirements and trading ratios (Willamette Partnership, World Resources Institute, and the National Network on Water Quality Trading 2015). The three most common methods for quantification are modeling, use of pre-determined pollution reduction rates (typically derived from measured data, literature values, or iterative modeling exercises), and direct monitoring – often with components operating in three physical locations, including edge-of-field, edge-of-stream, and instream attenuation (Willamette Partnership, World Resources Institute, and the National Network on Water Quality Trading 2015). Ultimately, uncertainty associated with quantification results in higher trading ratios, which lowers the amount of credit buyers receive for their estimated load reduction. Thus, higher uncertainty raises the costs for buyers, and makes it more likely that trading will not be economically feasible (Olander et al. 2014).

Despite the financial challenges, there is likely to be ongoing interest from dairies in nutrient recovery technologies, including both the fine solids separation and ammonia stripping technologies explored here, and other technological approaches. Environmental, regulatory, and legal pressures continue to grow with respect to nutrient management on dairies. Growing public concern about nutrient-related water and air quality issues led to the first legal action that applied federal solid and hazardous waste laws (Resource Conservation and Recovery Act [RCRA]), to manure (Bruderer 2015; Dumas 2015). In response to this case and to growing public pressure more generally, Washington's Department of Ecology has evaluated and issued a new CAFO Permit rule, and the Washington State Department of Agriculture has undertaken a review of the Dairy Nutrient Management Program.

As livestock facilities re-evaluate the risks associated with their current manure management practices in light of these evolving public and regulatory pressures, there is likely to be continued interest in nutrient recovery. As of 2018, in Washington State, two dairies had recently installed commercial-scale dissolved air flotation systems, one had a centrifuge and vermi-filtration trickling filter, and one had a centrifuge. In addition, a mobile struvite separation unit is being piloted in the state, and a commercial-scale distillation-based system is being planned, and the Washington Conservation Commission has invested nearly $3.8 million dollars in supporting experimentation with novel technologies to improve nutrient management on dairies (Bray 2017, WSCC 2018). As these installations proliferate, there will continue to be a need for objective, third-party information about performance and costs, to provide unbiased information that supports dairy decision making.

APPENDIX A

Publications Relating to the Funded Work

Peer-Reviewed Journal Publications Relating to the Funded Work

Anping, J., T. Zhang, Q.-B. Zhao, X. Li, S. Chen, and C.S. Frear. 2014. "Evaluation of an Integrated Ammonia Stripping, Recovery, and Biogas Scrubbing System for Use with Anaerobically Digested Dairy Manure." *Biosystems Engineering,* 119:117-126.

Ma, J., Q.-B. Zhao, L.L.M. Laurens, E.E. Jarvis, N.J. Nagle, S. Chen, and C.S. Frear. 2015. "Mechanism, Kinetics, and Microbiology of Inhibition Caused by Long-Chain Fatty Acids in Anaerobic Digestion of Algal Biomass." *Biotehnol Biofuels,* 8:141.

Peer-Reviewed Extension Publications Relating to the Funded Work

Frear, C.S., Ma, J., and G.G. Yorgey. 2018. "Approaches to Nutrient Recovery from Dairy Manure." Washington State University Extension Publication EM112E. Pullman, WA: Washington State University Extension Publishing.

Hall, S. and G.G. Yorgey. 2017. Video. "Recovering Nutrients from Manure – New Tools for Maintaining Air and Water Quality." Produced by CAHNRS Communications. Extension Publication PRV03. Pullman, WA: Washington State University Extension Publishing.

Webinar Series

Full series: Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University, in Partnership with the Water Research Foundation and the American Biogas Council. Individual webinars included:

- Ewing, T. 2016 "Dairy Nutrient Recovery Technologies within an Anaerobic Digestion Bio-Refinery." Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University. February 10, 2016.

- Garcia-Perez, M. "Anaerobic Digestion Bio-Refinery: Potential for Biochar Production and Utilization." Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University. February 24, 2016.

- Collins, H.P. 2016. "Agronomic Evaluation of Anaerobic Digestion System Recovered Fertilizers." Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University. March 23, 2016.

- Astill, G. 2016. "An Introduction to the Anaerobic Digestion System Enterprise Budget Calculator." Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and

Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University. April 6, 2016.

- Carlson, B. 2016. "Insights for Anaerobic Digestion from Dairy-CropSyst, a Decision Support Tool for Gaseous Emissions and Nutrient Management." Anaerobic Digestion Webinar Series: Emerging Technologies to Improve Environmental and Economic Impact. Hosted by the Center for Sustaining Agriculture and Natural Resources, Washington State University. April 20, 2016.

Other Outputs

Ewing, T.W., C.E. Kruger, and G.G. Yorgey. "From Dairy Farm to Bio-refinery: Developing Technologies to Produce Environmentally Friendly Fuels, Power, and Value-Added Products. USBI Biochar 2016, August 24, 2016, Corvallis, OR.

Ewing, T., G. Yorgey, and C. Kruger. 2016. Seminar. Anaerobic Digestion Systems. Mount Vernon Research and Extension Center Brownbag Series, Mount Vernon, WA. December 13, 2016.

Frear, C, Q. Zhao, and S. Dvorak. 2015. Presentation and Conference Proceedings. "Poultry Digestion: An Emerging Farm-Based Opportunity." Waste to Worth Conference. Seattle, WA. March 31-April 4, 2015.

Ma, J. and C. Frear. 2015. Presentation and Conference Proceedings. "A Primer on Available and Emerging N, P and Salt Recovery: Performance and Cost." Waste to Worth Conference. Seattle, WA. March 31-April 4, 2015.

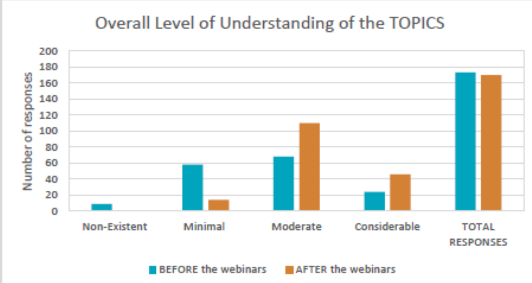
Yorgey, G., C. Frear, N. Kennedy, C. Kruger, J. Ma, and T. Zimmerman. Presentation and Conference Proceedings. "The Dairy Manure Biorefinery." Waste to Worth Conference. Seattle, WA. March 31-April 4, 2015.

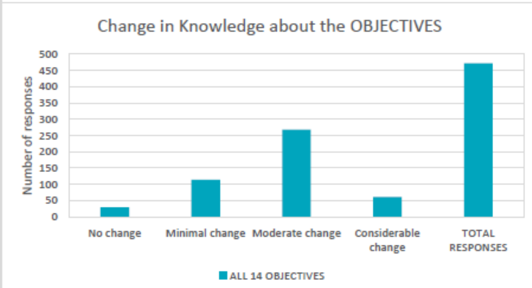
Yorgey, G., C. Frear, and C. Kruger. 2015. Presentation and Conference Proceedings. "Farm-Based Anaerobic Digestion Projects: Wastewater Disposal and Nutrient Considerations." Waste to Worth Conference. Seattle, WA. March 31-April 4, 2015.

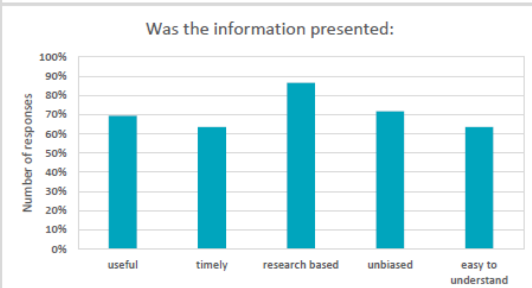
APPENDIX B

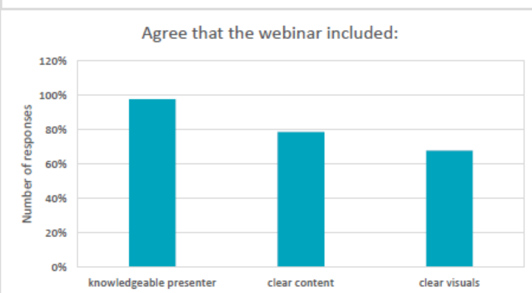
Summary of Webinar Series Evaluation Surveys

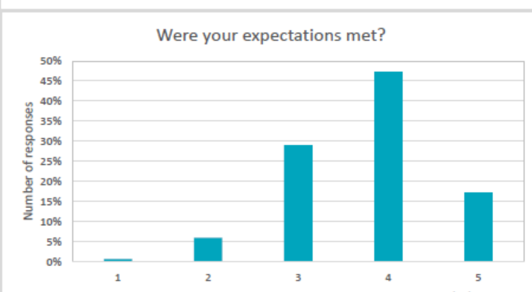
Data in graphs below is based on evaluation survey responses.











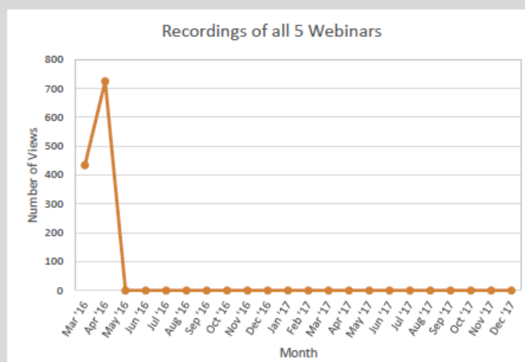
Washington State University (WSU) has an extensive research program focused on developing and evaluating technologies that enhance the economic viability of AD systems. Using a bio-refinery systems approach, researchers are working to maximize synergies between technologies, with support from the U.S. Department of Agriculture's National Institute for Food and Agriculture and from the Water Environment Research Foundation.

We presented a series of five webinars where WSU researchers and their collaborators shared their findings as they strive to quantify the climate, air, water, nutrient and economic impacts of integrating emerging, next-generation technologies within AD systems on U.S. dairies.

Data on attendees below is based on those who viewed at least 15 minutes of the webinar

Non profit	9
Grower/producer	7
Private industry	105
Government or tribal agency	102
University - extension faculty or staff	18
University - academic/research faculty or staff	50
University - student	17
Interested member of the public	10
Media/communications	2
Other	21
TOTAL ATTENDEES	**341**

United States	297
Idaho	*7*
Oregon	*7*
Washington	*7*
Pacific Nortwest States	*21*
Other States	276
Canada	21
Mexico	0
Central and South America	8
Asia	3
Europe	7
Oceania	1
Africa	4
TOTAL	**341**



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