An Integrated Nutrient Recovery, Class-A Fiber Production Process and H_2S Scrubbing System that Works in Series with Dairy Manure Anaerobic Digesters—Farm-Scale Demonstration on Two Washington State Dairies with Digesters

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PROJECT DELIVERABLES

1. Demonstrate the installation and operation of two integrated nutrient recovery units on two dairies with existing anaerobic digestion systems in WA: A flush dairy and a scrape dairy;
2. Measure and document the concentrations of nitrogen, phosphorus and pathogens in each of the waste streams from nutrient recovery processes. Additionally, measure and document the H_2S concentrations of the biogas before and after the H_2S scrubbing process;
3. Provide a report evaluating the economic viability of the integrated nutrient recovery units including the construction, operation and maintenance cost associated with the units, and the marketability of the products produced;
4. Provide a tour of the integrated nutrient recovery units near the end of the project for producers, researchers, USDA-NRCS and extension personnel to visit the units for a personal inspection;
5. Attend at least one NRCS CIG Showcase or comparable NRCS event during the period of the agreement;
6. Semi-annual performance progress reports and a final report;
7. Develop a fact sheet describing the new technology or approach. Publish an extension document, fact sheet, or NRCS Technical Note that can be presented to producers and engineers on the value and design criteria for the WSU nutrient recovery system/units.

FINAL REPORT TO USDA NRCS
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Background

While AD is well known for producing renewable energy and reducing odor, pathogens, and greenhouse gases (GHGs) in manure from livestock operations (US-EPA 2014; Frear et al., 2011), nutrient recovery (NR) technologies can play a role in reducing the release of excess nutrients to the environment (Yorgey et al., 2013; Ma et al., 2013). Recognizing these important environmental benefits, Washington State University (WSU) researchers and industry partners developed an integrated NR and biogas scrubbing technology for use on concentrated animal feeding operations (CAFOs). In 2010, upon award of this USDA NRCS CIG grant, WSU and its partners demonstrated this NR technology at farm-scale on two Washington State dairies with existing AD units. The goals of these demonstrations were to identify and solve hurdles at the commercial scale, make process enhancements, and validate system performance and techno-economic capabilities. With a one-year no-cost extension, all identified deliverables were met using the original budget. This report summarizes findings and evaluates the new technology's ability to meet 2010 NRCS-designated priorities in *promoting environmental enhancement/protection in conjunction with agricultural production*, specifically through:

- Innovative technologies/approaches to conserve or produce renewable energy while sustaining agricultural productivity;
- Demonstrating active methods which improve on the capture of nitrogen in manure management systems and provide the opportunity to recycle the manure nitrogen in lieu of synthetic fertilizers;
- Addressing climate change adaptation and mitigation for agriculture.

Following our original plan, NR system components were designed, constructed, and operated on 800 and 1,500 cow dairies with digesters in Lynden and Enumclaw, WA, respectively. Additional full and partial demonstrations were leveraged at a 1,500 wet cow equivalent (WCE) dairy with digester in Chilton, WI, and a 1.5 M egg laying operation with digester in Fort Recovery, OH.

Figure 1: Demonstration Sites

A—800-cow dairy, Lynden WA

B—1,500-cow dairy, Enumclaw WA

C—1,500-cow dairy, Chilton WI

D—1.5 M layer, Fort Recovery OH

The Technology

The Nutrient Recovery System

The system and its components are patented (Jiang et al., 2011; Zhao et al., 2011; Kennedy et al., 2013) and licensed through WSU to DVO Incorporated (Chilton, WI). Figure 2 is a schematic representation of one manifestation of the system, which can be sub-divided into four distinct unit operations: 1) AD, 2) primary fiber screening and treatment of fiber, 3) ammonia stripping, and 4) phosphorus-rich solids (P-solids) separation. Two versions of the core technology exist: a full system with all four operations *and* a reduced-cost version with unit operations 1, 2, and 4, aimed at recovering less nitrogen. Advantages rest in the relative simplicity of its unit operations and a reduced need for costly inputs, through integration between unit parts. In brief, the system works as follows:

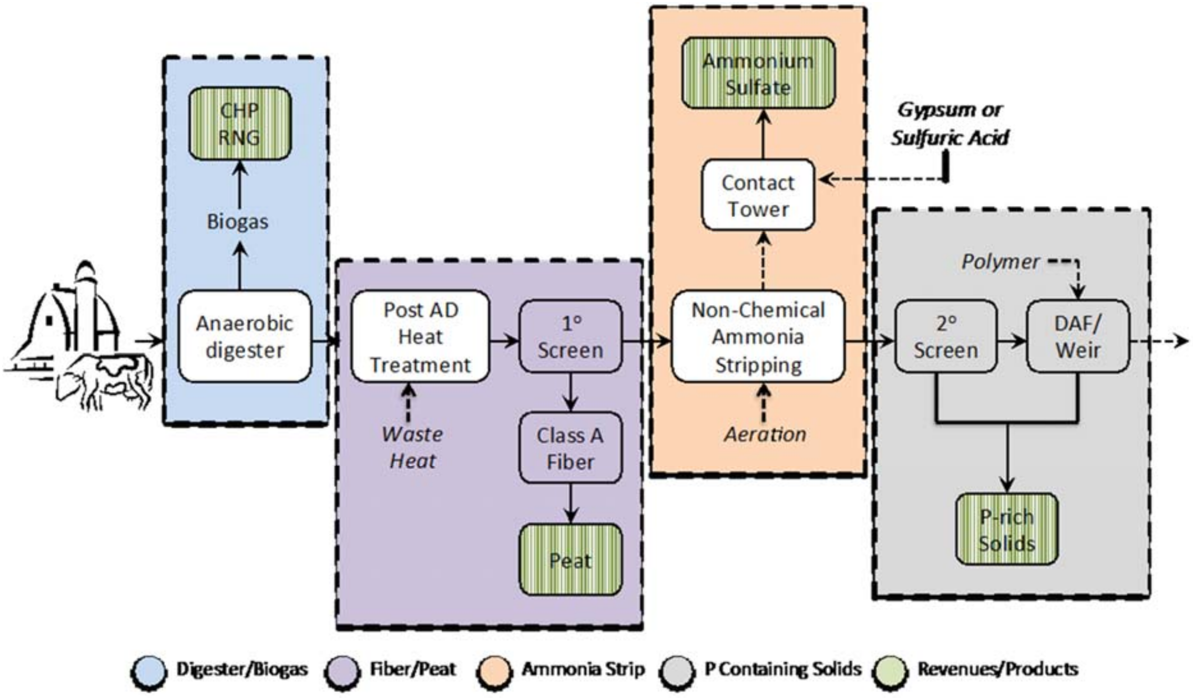


Figure 2: Schematic of NR system

Unit Operation 1 (AD):

- AD is carried out using existing commercialized technologies, although research has shown that use of a mixed plug-flow design as the main digester is noteworthy in regard to producing guaranteed time and temperature retention for both preferred pathogen treatment and elevation of effluent pH.

Unit Operation 2 (Primary fiber screening and treatment for high value peat replacement):

- Digested effluent is subjected to additional Class A time/temperature treatment for improved pathogen destruction and production of higher value fiber with more consistent electro-conductivity (EC) values. Source of heat is from combined heat and power (CHP) heat recovery and/or renewable natural gas (RNG) compression—although use of RNG supplies only limited heat recovery;

- Fiber is screened and may be optionally processed into high value peat replacement;

Unit Operation 3 (Ammonia stripping)

- Remaining effluent stream is sent through an aeration zone, where the combined attributes of higher temperature and higher pH allow for release of soluble ammonia to gaseous ammonia. The system requires no chemical inputs other than ambient air.
- A contact tower utilizes gypsum and/or concentrated acid to produce ammonium sulfate which can be either marketed as a 8% N and 10% S solution or as a solid (21% N and 24% S);

Unit Operation 4 (P-rich solids separation)

- Secondary screening is carried out using patented DVO Centriflow technology;
- This is followed by either a settling weir or in a preferred option, dissolved air flotation (DAF) processed with a low input of polymer. Both processes separate out a significant fraction of suspended solids, which contain a high proportion of the phosphorus (P) from the effluent. These processes are uniquely engineered to reduce chemical inputs.
- Remaining effluent is returned to neutral pH while assisting in biogas scrubbing (100% H_2S scrubbing and/or additional CO_2 scrubbing).
- An option also exists to utilize a portion of the treated effluent as dilution water in the front end of the AD process, reducing fresh water inputs and the total wastewater in need of land disposal.

Performance

Farm-scale demonstrations at the multiple sites have allowed for continued process improvements as well as a firm understanding of present and future performance capabilities. For comparability, values reported are for dairy manure-only projects. However, the system has been proven effective in dairy co-digestion as well as poultry digestion facilities.

- Both the full and scaled-back systems significantly reduce solids content in the digested effluent, particularly when using a polymer/DAF operation instead of the setting weir approach during the final stage treatment. When using the polymer/DAF, both systems consistently show *70-75% reduction in total solids (TS) and 93-97% reduction in total suspended solids (TSS).*
- Both the full and scaled-back systems produce considerable volumes of fibrous solids suitable either for animal bedding or higher-value peat moss replacement. A typical operation produces roughly *9-10 yards of fibrous solids cow^{-1} y^{-1} (~70-75% moisture content). Due to the AD and NR treatment, the fiber has low pathogen indicator counts, preferred EC values, and physical characteristics such as air holding capacity, water holding capacity, total porosity, and crude fiber* that allows for bulk sales to high-value distributors.
- Both the full and scaled-back systems significantly reduce P content in the digested effluent, consistently achieving *70-90% reduction in total phosphorus (TP)*, with the majority of the P being retained in P-rich solids emanating from the polymer/DAF process. The resulting product is produced wet (72% moisture content) but due to high nutrient content, will dewater quite readily under ambient storage conditions (~50% moisture content). With additional unit operations the solids can be dried/pelleted for

higher value sales (this value-added treatment is still in development and was not part of this demonstration project). Using dry values, the product is roughly *1.5% N, 3.0% P, and 0.25% K, with significant presence of additional micronutrients including calcium, magnesium, sulfur, and iron*. Approximately *0.5 dry tons cow^{-1} y^{-1} of secondary and DAF solids are produced*. Organic polymers are utilized in the DAF operation and while organic certification has not yet been officially applied for, it is hoped for that this product is organically certifiable.

- The scaled-back system has demonstrated that *25-35% of the total nitrogen (TN)* can be recovered from the AD effluent along with the P-rich solids. The recovered TN is primarily in organic form. The full-system is capable of removing a more significant portion of the N as it recovers ammonia-N. While system performance using *large-bubble aeration systems only achieved 40% recovery of ammonia-N, pilot-tested small-bubble aeration system can remove 70% of ammonia-N, leading to a 65-85% reduction of TN for this improved system*. At the higher ammonia-N recovery rate, systems can produce roughly *1/4 dry ton ammonium sulfate (AS) cow^{-1} y^{-1}*. The *dry AS has a nutrient value of 21% N and 24% sulfur (S). However, presently all systems produce a saturated solution that is roughly 38% AS by mass, the rest being water. This product has nutrient value of 8% N and 10% S*. Market penetration for the solution has been problematic due to concerns related to storage, transportation, concentration, and blending/application. Additional unit operations could crystallize the product for enhanced sales and marketing (this process is still in development and was not a part of this demonstration project). An additional item in development and not part of this project is the potential for substituting the use of concentrated sulfuric acid with mined or recycled gypsum to reduce costs.

This system does not focus on reducing potassium and total salts, due to the significant costs associated with these removal operations (membranes, reverse osmosis, etc.). However, there is still some recovery. Full-scale tests show that *25-30% of total potassium (TK) is recovered within the secondary solids (presumably due to adsorptive properties) while total salts removal is even higher, mainly ammonium, calcium, and magnesium*. Also, the full-system final effluent with pH 9-9.5 has been shown to be an effective agent for scrubbing of biogas while also returning the pH of the effluent to more neutral values (8.5-7.5). Full-scale demonstration at the leveraged Chilton site demonstrated *100% H_2S scrubbing of the raw biogas* when this effluent pH system was implemented. Ongoing tests of CO_2 scrubbing performance continue with some degree of promise but were not a focus of this demonstration project.

Table 1: Production and nutrient removal performance for NR system and its unit operations

	Unit Operations				Total System [c]
	AD	Fiber/Peat	Ammonia [a]	2° Solids/P [b]	
Production	110 ft^3 of biogas cow^{-1} day^{-1}	9-10 yards fiber cow^{-1} y^{-1}	1/4 dry ton AS cow^{-1} y^{-1}	1/2 dry tons solid cow^{-1} y^{-1}	---
N Removal (%)	---	15-20	40-50	10-15	65-85
P Removal (%)	---	15-20	---	60-70	75-90

[a] assumes use of small bubble aeration and higher 70% ammonia-N recovery

[b] assumes use/performance of the polymer/DAF unit as opposed to more simple settling weir unit

[c] variations result from different farms, systems, and sample sets—no statistical analysis

Table 1 summarizes recovery performance of the full system and its unit operations. As before, values are indicative of dairy manure-only systems. Figure 3 shows the products derived from the NR system: fiber/peat, ammonium sulfate, and fine solids enriched in P and other nutrients.

Figure 3: NR products (a) fiber/peat; (b) ammonium sulfate solution; (c) fine solids rich in P

Techno-economics

The NRCS demonstration and leveraged sites, with ongoing process improvements, have provided a greatly improved understanding of potential commercial design and costs. While many of the demonstration sites were built as add-on units to existing AD facilities, the ultimate commercial design is envisioned as an integrated fusion of AD with NR, with the two systems built simultaneously. For example, the post AD heat treatment and aeration system for ammonia-N removal is built directly into the mixed plug-flow digester, which leads directly to the DAF/P removal and biogas-cleaning units prior to ultimate storage in lagoons. This integrated design holds potential for reducing overall capital costs.

Table 2 is a techno-economic summary, as it would be presented for a potential first adopter at a commercial co-digestion dairy AD/NR project in Washington State. Note that it summarizes only the NR system (not including the fiber/peat, which is generally considered by project developers as its own stand-alone unit operation with known revenues). Design, engineering and cost projections are based on the emerging performance and cost evaluations from demonstration sites. This techno-economic summary for a hypothetical project involves 3,150 wet cow equivalents (WCE) of manure from a flush dairy operation, thickened in a clarify, with 30% volumetric addition of food processing waste, for a total volume of 167,000 gallons day^{-1} (the equivalent to a 5,200 scrape WCE flow) being fed to a mesophilic, mixed-plug flow digester. Total nutrient load to the digester is estimated at 1.5 and 0.2 tons of N and P day^{-1}, respectively. Biogas production, estimated at over 700 cubic feet minute^{-1}, will be cleaned to produce pipeline quality transportation fuel (renewable natural gas, RNG), with the main business plan focused on sales of the RNG and associated renewable identification numbers (RINs). Effluent from the digester will pass through the NR system, composed of fiber/peat separation, ammonia-N stripping for production of ammonium sulfate, and removal of fine solids/P through a polymer/DAF operation. High pH effluent recycle for H_2S scrubbing will assist in the biogas upgrade, though a dedicated water scrubber will do the majority of the CO_2 purification to RNG. Using the assumed performance capabilities in Table 1, the NR system would produce 86 cubic yards day^{-1} of fiber/peat, 3.1 tons of AS day^{-1}, and 6.5 dry tons of fine solids/P day^{-1}, using 2.1 tons concentrated acid day^{-1} and 140 lbs. polymer day^{-1}. The total efficiency of the NR system is estimated at 70% and 80% total N and P removal from influent wastewater, respectively. The NR system, particularly the ammonia-N stripping unit operation, requires considerable electrical input (aeration blowers, pumps, etc.) estimated at 195 Kwh/h as well as O&M (labor and parts), estimated at \$343 day^{-1}.

Table 2: Techno-economic evaluation for the equivalent of a 5,200 scrape WCE NR project [a]

Capital (167,000 gpd: 3,150 WCE plus 30% v/v substrates ~ 5,200 WCE)		**\$3.0 Million**	
Expenses	(\$/day)	**Revenue**	(\$/day)
Electricity (195 Kwh/h @ \$0.06/Kwh)	281	Ammonium Sulfate (3.1 tons @ \$250/ton)	775
Sulfuric Acid (\$200/ton)	420	P-Solids (6.5 tons @ \$80/dry ton)	520
DAF Dewatering (\$0.001/gallon treated)	167	Based on potential wholesale value of \$250/ton AS fine solids (Spring 2013) and \$80/ton for the P-rich solids with an assumed value of high nutrient compost (Spring 2013)	
O&M (labor, contingency parts)	343		
Heat (assume thermal available CHP)	---		
Storage (assume on-site storage)	---		
Transportation (assume near sales)	---		
Total	1,211	**Total**	1,295

[a] Part of an AD for RNG project, but techno-economics reported only for the NR and does not include fiber

As can be seen from Table 2, capital cost estimations for the identified project come in at roughly \$2.75 M, which translates to \$529 cow^{-1}. By comparison stand-alone AD projects have capital expenditures of 1,500-2,000 cow^{-1}. Thus NR, as presently designed, *results in 25-35% increase in total project capital costs—an additional burden to project economics*. Operating expenses amount to roughly \$1,211 day^{-1}, which on a per cow basis is \$85 cow^{-1} y^{-1}. However, this does not include expenses associated with processing of the fiber/peat material, long-term storage of the AS, potential purchase of heat (RNG projects supply less excess thermal energy than combined heat and power, CHP, operations), and transportation of products to markets. These factors could raise costs to *\$100-150 cow*$^{-1}$ *y*$^{-1}$*. For comparative purposes, stand-alone AD projects have estimated operating expenses of \$12-24 cow*$^{-1}$ *y*$^{-1}$*. Thus inclusion of NR raises operating expenses by a factor of six or seven—a notable increase that must be made up through revenues of co-products produced.*

Table 2 also identifies and summarizes potential revenues from the ammonium sulfate and the fine solids. These values have been developed from extensive meetings with regional suppliers of fertilizers and soil amendments. It is very important to note that markets for such material are in their infancy and susceptible to volatile market pricing, local nuances, wholesale contracts, transportation, and form/consistency/blending suitable for end-user needs. These challenges in estimating revenues make estimation of true market pricing difficult, project development complicated, and securement of financing problematic.

Given these difficulties, the best interpretation of Table 2 is that, *even under optimal identified revenue projections, the NR system, as presently designed, at best, only operates at break even, and more likely operates at an annual loss.* While this is not optimal, the project PI has completed a NR technology review, which places this studied NR system performance and costs in relation to other emerging NR technologies. The review indicates that the present system's techno-economic performance compares favorably to many of the other systems presently being demonstrated (Figure 4) (Ma et al, 2013).

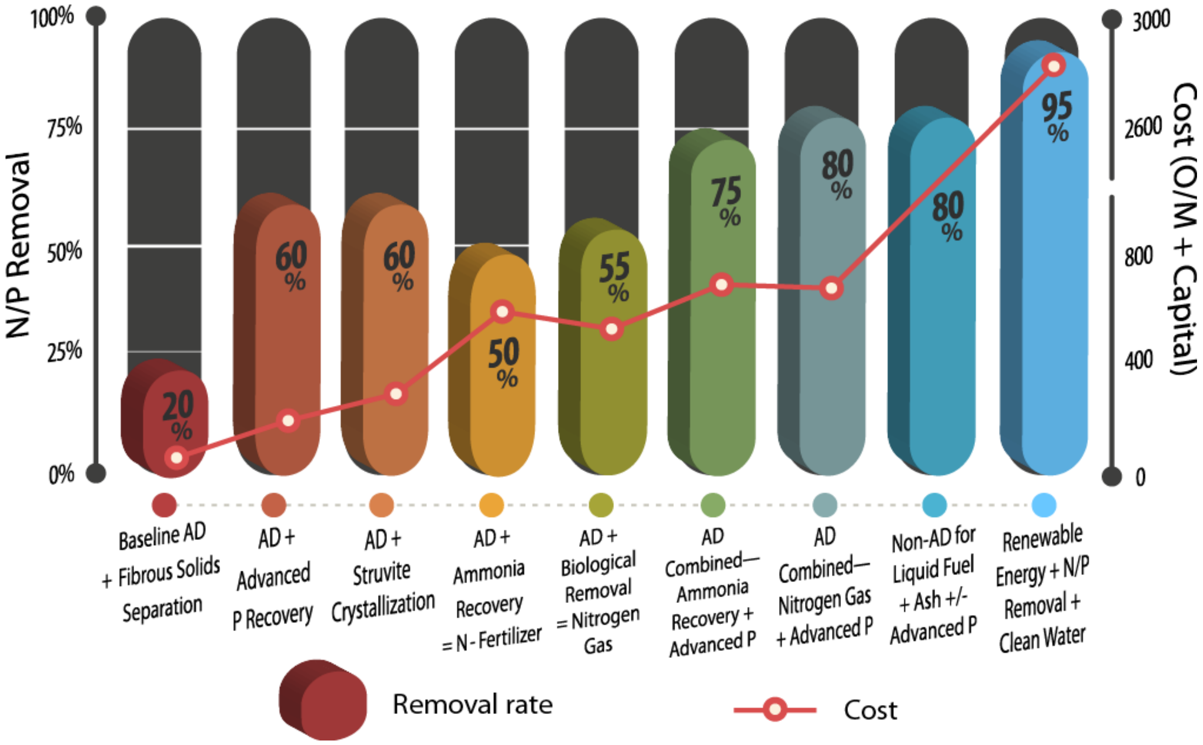


Figure 4: Comparison of various NR approaches in regard to combined N/P recovery performance and total operating/capital costs (Ma et al, 2013)

It is important to note that the above techno-economic analysis treats the NR as a separate unit operation. This means that several important considerations that may be decisive have not been included: larger project economics, offsets to present manure management/hauling costs, and potential revenues from eco-system service benefits such as nutrient trading credits and carbon credits from displacement of fossil fertilizer production. In the next section, identified process enhancements designed to lower the present operating and capital costs while also improving upon performance are discussed. While these improvements will be vital, corollary shifts in federal and state policy, perhaps spearheaded by USDA NRCS, will be important influencers of future adoption rates for NR technologies.

Process Enhancements

Four areas of process improvement have been identified and are presently undergoing R&D at the University and industrial demonstrations at farm sites. These four areas are aimed at improving performance and reducing costs, specifically through enhancing the ammonia recovery rate, reducing electrical/chemical/material inputs, and improving revenues for products through value-added and organic markets. All four of these enhancements are under active development and will undoubtedly alter the techno-economic evaluation. Additional funding is being sought to effectively demonstrate these new refinements.

- *Enhanced Ammonia Recovery*—All demonstration systems' ammonia-N stripping units were designed using large bubble aerators, which upon evaluation do not supply the necessary mass transfer to accomplish high stripping efficiency. This limits the existing systems to a consistent 40-50% ammonia-N recovery rate. Subsequent laboratory and pilot-scale testing has shown that commercially available small bubble aerators can achieve at least 70% ammonia-N recovery, the project's original target. Industrial partners are now evaluating the effect of conversion to the small bubble aerators on power consumption and capital costs. For purposes of the above techno-economic evaluation, it was assumed that conversion is cost-neutral (based on preliminary information regarding offsetting additional power consumption with reduced size/retention).

- *Replacement of Acid with Gypsum*—All demonstrations of the NR system are producing AS solution using sulfuric acid. Market development efforts have indicated that substitution of sulfuric acid with gypsum could be preferred as it could significantly reduce chemical costs (i.e. inexpensive recycled gypsum wall board) and also raise revenues through the possibility for organic certification for higher value sales. For purposes of the above techno-economic evaluation, use of sulfuric acid was assumed. Industry partners are presently designing modified gypsum contact towers for testing and demonstration.
- *Solid Fertilizer Product*—Evaluation of AS markets has shown that production of crystalline fines is preferable from the perspective of storage and transportation. Thus, in future manifestations, techno-economic analyses will need to incorporate additional operating, capital and thermal costs associated with crystallization. The higher costs will need to be contained, so they can be offset by increased sale price, gains in market penetration, and reduction in storage/transportation costs.
- *Drying of P-solids*—Lastly, higher-value sales of the fine P-rich solids could be achieved by undertaking additional drying/pelleting—requiring additional operating, capital and thermal inputs.

Conclusion

While the current capital and operating costs for the WSU/industry partner N and P recovery system is significant—representing nearly 1/3 additional capital costs and nearly 7x the operating costs over installation of a stand-alone AD operation—there is strong potential for consideration. These considerations reside in the environmental benefits gained, particularly in regard to meeting nutrient management goals and protecting air, water and climate. Performance has been demonstrated to be effective, particularly assuming that ongoing process enhancements will be achieved. Future manifestations of the NR system should be able to achieve 70% N and 80% P recovery from the initial dairy manure wastewater. Ultimate economic viability and adoption will depend not only continued process improvements, but also on development of more mature product markets and implementation of policies that can allow for increased revenue through items such as nutrient trading and carbon fertilizer credits. Total project business plans must also be considered in relation to stand-alone NR economics. While the present demonstration shows stand-alone NR (not including AD/biogas, fiber/peat and AD credits) to be at best cost-neutral and more likely cost-negative, incorporation of NR into the larger business plan could be viable, especially as process improvements are made and with inclusion of manure management cost offsets.

INTRODUCTION

Project Goals and Objectives

The overarching goal of this project was to design/fabricate/construct/operate two novel NR systems on Washington dairies so as to identify and solve hurdles at the commercial scale, make process enhancements, and validate system performance and techno-economic capabilities. As the project evolved, additional site locations and their data were leveraged to the project as described above. Specific project deliverables were to:

1. Demonstrate the installation and operation of two integrated nutrient recovery units on two dairies with existing anaerobic digestion systems in WA: A flush dairy and a scrape dairy;
2. Measure and document the concentrations of nitrogen, phosphorus and pathogens in each of the waste streams from nutrient recovery processes. Additionally, measure and document the H_2S concentrations of the biogas before and after the H_2S scrubbing process;
3. Provide a report evaluating the economic viability of the integrated nutrient recovery units including the construction, operation and maintenance cost associated with the units, and the marketability of the products produced;
4. Provide a tour of the integrated nutrient recovery units near the end of the project for producers, researchers, USDA-NRCS and extension personnel to visit the units for a personal inspection;
5. Attend at least one NRCS CIG Showcase or comparable NRCS event during the period of the agreement;
6. Semi-annual performance progress reports and a final report;
7. Develop a fact sheet describing the new technology or approach. Publish an extension document, fact sheet, or NRCS Technical Note that can be presented to producers and engineers on the value and design criteria for the WSU nutrient recovery system/units.

While WSU took the lead in grant management, data collection and report writing, completion of the project could not have been possible without extensive assistance from industrial and government partners. Industry partners were DVO Incorporated and Andgar Corporation. Not only were these two industrial partners co-assignees on patents and licensing partners, they were also responsible for continued engineering enhancements and marketing of the technology across the US and internationally. DVO was instrumental in much of the engineering design as well as data collection at the two leveraged sites. Andgar supplied construction management and operational control at the two main WA dairy sites.

Project Overview/Team

WSU was the lead institution on this project—supervising budgets, sub-contracts, matches, project leveraging, and project reporting. DVO Incorporated (Chilton, WI) and Andgar Corporation (Ferndale, WA) were licensing/patent as well as construction/operation partners within industry while Vander Haak Dairy/FPE Renewables (Lynden, WA) and Rainier Biogas (Enumclaw, WA) were the producer/digester partners. Subsequent leveraging of demonstrations occurred at Dallmann Dairy (Chilton, WI) and Wenning Poultry (Fort Recovery, OH).

- *DVO Incorporated*—The U.S. market leader for farm-based AD and environmental engineering, has been dedicated to providing reliable, proven agricultural and industrial solutions and services for over 22 years. DVO is known for its patented mixed plug-flow digester capable of high biogas production as reduced operating costs and is committed to developing next generation systems capable of multiple environmental benefits, including nutrient extraction and biogas cleaning.
- *Andgar Corporation*—Through its licensing arrangement and partnership with DVO, Andgar is an industry leader in cradle to grave development of AD projects on farms. Beginning with project design and continuing through permitting, fabrication, construction and operation, Andgar supplies full service to producers and project developers interested in AD development. Andgar provides O/M for the Vander Haak Dairy and FPE Renewables as well as expertise for WSU during multiple pilot/demonstration projects.
- *Vander Haak Dairy/FPE Renewables*—A scrape dairy with 800 WCE on 400 acres of owned and rented land. In 2004 Vander Haak Dairy constructed a 650 KW AD unit to improve his environmental and sustainable business approach. Today the dairy operates the AD portion of their business as FPE Renewables, utilizing active co-digestion of on-farm manures with off-farm food processing waste substrates for additional farm revenue. With the decision to practice co-digestion, FPE Renewables has been forced to adjust its nutrient management plan primarily through elevated land purchases and rentals to properly dispose of accumulated nutrients. The dairy and FPE Renewables have worked closely with WSU on numerous pilot/demonstration projects, opening their facilities as a R&D test bed.
- *Rainier Biogas*—The digester is sized for 50,000 gallons per day of dairy cow manure and pre-consumer food waste. The project is owned and operated by Rainier Biogas, LLC. The Rainier Biogas digester is a community digester that takes in manure from multiple dairies as well as pre-consumer food waste from multiple sources. The project was finished in 2013. The Rainer Biogas digester project has capacity to produce 1MW of renewable electricity. Because the Rainier Biogas project takes manure in from the multiple dairies and sends back digester effluent in return, as a result, Rainier Biogas has to carefully track and manage the amount of manure, and subsequently the amount of nutrients, that come and go to the dairies and work closely with them to maintain the proper balance. NR is aiding Rainier Biogas in maintaining that balance.
- *Dallmann Dairy*—The dairy is home to a 1,500 WCE dairy with mixed plug-flow digester. It’s nearby location to DVO Inc. corporate office makes its site an ideal marketing and test-bed tool for the company. A full NR system as well as H_2S/biogas scrubbing system has been installed at the dairy, serving as the primary site for collection data on H_2S scrubbing performance. Not an original part of the grant project, this site and its data was leveraged to the project.
- *Wenning Poultry*—A full AD/NR system has been installed at this 1.2 M egg laying operation in Ohio. The NR is required to reduce inhibitory levels of ammonia and suspended solids within effluent that is used as return/dilution water to the system so that 35-50% TS manure can be diluted to the desired 10% TS content. Approximately 10 tons of AS solution is produced per day at the site and sold to the local fertilizer distributor. This site has been the primary data collection site for AS production and sales. Not an original part of the grant project, this site and its data was leveraged to the project.

Funding Financials

Both of the industrial partners as well as WA dairies and state/federal partners aided in financial commitments to the project. Table 4 is a summary of the financials for the project, which were followed throughout the course of the project. The main NRCS CIG commitment of $750,000 was both matched (1:1; $750,000 of which 50% cash) and leveraged ($500,000). The leverage was supplied by the Washington State Department of Commerce using federal ARRA flow-through funds. Total project commitment was $2,000,000. Because of ARRA flow through funding, construction/operation costs at the two WA dairies were completed under Davis/Bacon salary regulations. Given the extensive project refinements that took place during the project and its one year extension, total project costs were clearly above the aforementioned $2M, with industrial partners, Andgar Corporation and DVO Incorporated, supplying all of the additional costs through cash and in-kind services—primarily through re-designs, retrofits, equipment replacements, operational maintenance, additional site leverages, sample collection/shipping, and sample analyses.

Table 4. Funding financials

	Cash	In-Kind
NRCS CIG	750,000	
WA Dept. Commerce/ARRA	500,000	
FPE Renewables (VDH Dairy)	149,000	80,000
Rainier Biogas	130,000	220,022
Andgar Corporation		74,395
WSU	96,583	
Total	$2,000,000	

BACKGROUND

Problem Being Addressed

Each dairy cow generates 15 pounds of P and 132 pounds of N annually in liquid and solid manure (ASAE, 2005). Manure is expensive to transport so dairy manure is generally applied to nearby fields, sometimes leading to excess applications of P and/or N. The ongoing trend of increased numbers of dairy cows per farm in the US (USDA-NASS, 2010) results in a concentration of manure, bedding and urine in small areas. This in turn increases the transport distances (and costs) required for appropriate land application of manure. Analysis of national data suggests that in 2000, roughly 75% of dairies with more than 300 animal units (AU) were spreading manure at rates in excess of crop N needs, and roughly 96% were spreading manure at rates in excess of crop P needs (Ribaudo et al., 2003). More recent data indicate that larger operations apply manure to cropland at rates that are more than three times higher than smaller farms, suggesting that excess nutrient applications are still an issue, particularly for large operations (MacDonald and McBride, 2009). This observation is also supported by a study of manure application to field corn (receiving crop for more than half of all applied manure), which found that the vast majority of dairies applied to fewer acres than would be needed to meet best management practices for nutrient management (USDA-ERS, 2011).

There are many factors that can contribute to nutrient loading at higher than recommended levels:

- Expense of transporting manure to distant fields. This is particularly true for liquid manure, but also applies to "dry" manure, which contains significant moisture (Henry and Seagraves, 1960; Ribaudo et al., 2003; Heathwaite et al., 2000).
- Reluctance to apply manure to food crops due to environmental and food safety concerns (Guan and Holley, 2003), largely limits the land base available for manure application to forage fields (USDA-ERS, 2009).
- Variability in the nutrient content and form of stored manure and the timing of nutrient availability to plants (especially for N) can lead producers to apply extra manure or supplement with inorganic fertilizer (Davis et al., 2002: Eghball et al., 2002; Power et al., 2001; Alva et al., 2005).
- The nitrogen-phosphorus-potassium (NPK) ratio of manure may not match the ratio needed by crops, necessitating additional inorganic fertilizer for proper nutrient balance (USDA-ERS, 2009).
- Broadcasting and timing of manure application may encourage nutrient loss and runoff (USDA-ERS, 2009).
- Crop producers tend to target nutrient application toward high-yield goals, rather than average yields (USDA-ERS, 2009).

Application of excess nutrients is of concern to producers, regulatory agencies, and communities. Excess P and N can reduce crop yields. It can also result in losses of P and N from soils to the environment, contributing to a number of significant water and air quality concerns:

- ***Phosphorus and Nitrogen Eutrophication.*** Both P and N can be lost through runoff or infiltration and leaching at manure storage locations and field application sites, as well as through soil erosion. Losses increase substantially as nutrient application exceeds plant needs

(Bock and Hergert, 1991; Schlegel et al., 1996). Once lost from agricultural systems, P and N can migrate to lakes, rivers, estuaries, and coastal oceans. Overabundant nutrients can then lead to excessive growth of algae and aquatic weeds and subsequent oxygen shortages (Carpenter et al. 1998), fish toxicity (Ward et al., 2005), habitat loss (NRC, 1993; Jeppesen et al., 1998) and decreased species diversity (Sutton et al., 1993).

- *Nitrate Pollution**.*** Infants under six months of age who ingest high levels of nitrates in the water supply can get blue baby syndrome, which can cause bluish skin, stupor, brain damage and in severe cases, death (Walton 1951).

- *Ammonia Volatilization.* An estimated 70% of total manure N is lost as ammonia during manure management and application on U.S. dairies and feedlots (CAST, 2002). Ammonia is highly reactive and contributes to the development of ultra-fine particulate matter (PM 2.5) in the atmosphere. PM 2.5 has detrimental effects on overall air quality and human and animal health (Erisman and Schaap, 2004; McCubbin et al., 2002; Archibeque et al., 2007).

- *Greenhouse Gas Emissions**.*** Dairy cattle create direct and indirect emissions of greenhouse gases throughout the production process, with over half generated by manure management (US-EPA, 2013). There is significant variation due to the type of manure management system, with higher methane emissions from liquid manure management systems. These liquid manure systems are increasingly used in dairy operations, particularly large ones (US-EPA, 2013), leading to recent increases in greenhouse gases associated with manure management. In total, manure management for dairy cattle in the U.S. contributed an estimated 32.4 MMT CO_2e in 2011, representing 46% of the estimated greenhouse gas emissions associated with manure management for all livestock and poultry, or 0.48% of gross greenhouse gas emissions in the US (US-EPA, 2013).

Dairies in many regions of the U.S. are facing increasing pressure due to growing public concern about these nutrient-related water and air quality issues. In some cases regulation of dairies has increased as a result of these public concerns. High levels of P in waterways and in cropland soils have been a concern for many years in the Chesapeake Bay and Lake Champlain in the Eastern U.S (US-EPA, 2010; LCBP, 2012), and more recently in the Magic Valley of Idaho (IDEQ, 1998; Leytem and Bjorneberg, 2009). Nitrate issues and excess N in water have also received increased attention and studies suggest that manure applications play a role in a number of areas including the Chesapeake Bay (US-EPA, 2010), Tulare Lake Basin and Salinas Valley of California (Viers et al., 2012), the Magic Valley of Idaho (Baldwin, 2006), the Yakima Valley of Washington (US-EPA, 2012a), and the Abbotsford-Sumas aquifer along the U.S. Canadian border (Mitchell et al., 2005). Air quality is a significant concern in the San Joaquin Valley, where Federal PM 2.5 standards are being exceeded (US-EPA, 2012b), and in the Yakima Valley, where meeting the air quality standards remains an ongoing concern (Pruitt, 2013).

Environmental and regulatory concerns, along with the high costs of current manure management practices, have made nutrient management a top concern of dairy producers in the US. In a recent survey, dairymen identified nutrient management as the lead concern that would cause them to adopt new manure management technologies (Bishop and Shumway, 2009).

While most discussion about nutrients and dairy manure focuses on the possibility for negative environmental consequences, these nutrients have important potential values. Within emerging AD/NR business plans, nutrients are converted to valuable products. If advanced technologies are used to separate, concentrate and sell nutrients to areas that are in need of nutrients, this strategy could assist dairies in meeting their nutrient management plans while also providing for additional products and revenue streams. The key is successful implementation of NR technologies.

Existing/Emerging NR Technologies and Approaches

Partnerships developed in part through this NRCS funding has allowed for development of a thorough review of existing/emerging NR technologies for application within the CAFO manure workplace. Within this section are highlights of that review sponsored by the Innovation Center for US Dairy (Ma et al, 2013).

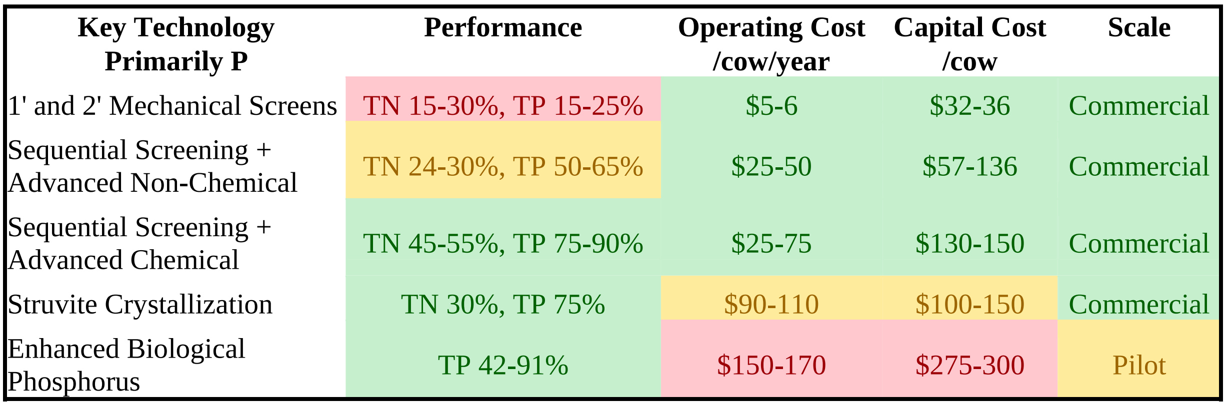
Phosphorus Recovery Technologies

Because of the form of P in dairy manure, particularly digested dairy manure, methods for solids and P removal are linked. Thus, increasing P removal efficiencies are achieved mainly by increasing separation of fine solids. As a result of this linkage, commercial applications are at this time focused on mechanical separation processes that use chemicals to flocculate very fine, colloidal solids that are associated with the majority of P. Given the existing business plans for AD, of capitalizing on high value sales of digested and separated fibrous solids, these systems are sequential in nature. Fiber (and its associated N/P content) is removed first, followed by removal of smaller solids with the majority of the P. This approach produces a stackable but quite wet product. Thus, drying and form modulation will be required before high value markets can be realized. This would add to the thermal and economic costs. Importantly, development of these processes should be designed with explicit consideration of organic certification, particularly as the product could supply a generally balanced fertilizer product with numerous macro and micronutrients. Organic certification may be important to developing product markets, as organic producers have access to more limited types of fertilizers, and therefore may be more willing to pay a price premium or purchase products in less-than ideal forms.

Two other P recovery approaches of note are struvite crystallization and advanced biological nutrient removal processes. Struvite is notable for its production of a preferred product that is already pelleted, mostly dry and quite balanced in fertilizer property. As a consequence, it is easily spread using existing fertilizer application methods. The costs for this process may be comparable to, or slightly higher than, the combined mechanical-chemical processes. Among biological P recovery processes, EPBR is well known in municipal wastewater processes, but is problematic for incorporation into an AD operation on farms. Algae systems, another biological approach, represent a relatively undeveloped concept but one that has potential due to its nutrient absorbance efficiencies. Refinement of the system and cost reductions in algae separation processes will be key to advancement of this concept.

Figure 5 summarizes the five main classes of approaches to P recovery. Estimated performance and costs ranges are color-coded red (low relative performance or high relative cost) yellow (medium performance or cost) or green (high performance, low cost). In general, as P removal improves, costs also increase. Also, while large pore size screening leads only to limited removal

(15-30%), methods that allow for recovery or absorption of small particle sizes achieve near-maximum recovery of P (75-90%).



Key Technology Primarily P	Performance	Operating Cost /cow/year	Capital Cost /cow	Scale
1' and 2' Mechanical Screens	TN 15-30%, TP 15-25%	\$5-6	\$32-36	Commercial
Sequential Screening + Advanced Non-Chemical	TN 24-30%, TP 50-65%	\$25-50	\$57-136	Commercial
Sequential Screening + Advanced Chemical	TN 45-55%, TP 75-90%	\$25-75	\$130-150	Commercial
Struvite Crystallization	TN 30%, TP 75%	\$90-110	\$100-150	Commercial
Enhanced Biological Phosphorus	TP 42-91%	\$150-170	\$275-300	Pilot

Figure 5: Summary of performance and cost estimates with partial list of concerns and scale tested for representative class of P recovery approaches

While various methods can be utilized for P recovery, it is clear from full-scale demonstrations that the following performance can be achieved:

45-55% N and 75-90% P removal at roughly a cost of \$25-75 cow^{-1} year^{-1} in operating costs and \$130-150 cow^{-1} for capital costs, while also separating a valued fibrous product.

Combined N/P Recovery Technologies

While combined N/P recovery technologies are not as developed as P recovery technologies, several of these strategies are being demonstrated or practiced at commercial scale. One important class, ammonia-N stripping, takes advantage of the fact that the AD process raises pH (though not as far as needed for N-stripping), provides excess thermal energy and increases the proportion of ammonia N. Various manifestations of ammonia-N stripping exist, with all approaches having made strides over the years in reducing chemical, electrical and thermal inputs, while maintaining effective N removal. Contact of the stripped free ammonia with acids allows for production of ammonia salt fertilizers, which could generate revenue to offset costs, though markets for these products are not yet developed.

Another class of approaches involves biological conversion of reactive forms of N within the manure (digested or undigested) to non-reactive N_2 gas. Specific processes within this class include nitrification-denitrification, partial nitrifications and Annamox. Current interest and deployment is active in larger municipal operations, but still limited within farm projects, although swine lagoons in particular have several demonstration projects. Figure 6 summarizes the current performance capabilities and cost structures of these two integrated systems.

Key Technology N & P Combined	Performance	Op Cost /cow/year	Capital Cost /cow	Scale
Integrated Ammonia Stripping	TN 65-85%, TP 85-90%	$100-190	$450-650	Commercial
Conversion to non Nr + Chemical P	TN 80-90%, TP 65-85%	$80-180	$425-575	Pilot

Figure 6: Performance and cost ranges for integrated ammonia N stripping and conversion to non-reactive N technologies

From a cost and performance perspective, the completed review shows that integrated systems that allow for recovery of value-added fibrous solids as well as effective removal of both P and N are feasible and now emerging within the commercial setting. Performance and costs for the integrated systems are in the following general range. Notably costs, both capital and operating are considerable. Ongoing work on both these classes of technologies may clarify whether further improvements in performance, reductions in costs, or development of NR product markets will facilitate their adoption on dairies in the coming years.

65-85% N and 75-90% P removal at roughly a cost of \$100-200 cow^{-1} year^{-1} in operating costs and \$400-600 cow^{-1} for capital costs, while also separating a valued fibrous product and in some cases N/P fertilizer products.

Salts Recovery Technology

Salts are an important environmental concern in many key dairy regions, particularly in California and other western states. To remove a large percentage of salts from the wastewater, AD integrated NR must involve RO membrane filtration, likely in combination with other membrane classes. Operation and capital costs are significantly higher than the cost increases identified for P and N recovery. While extremely costly and still in need of full-scale demonstration on farms, the outputs are considerable and not just from an environmental or regulatory viewpoint. Organically certifiable fertilizer products as well as relatively clean water are both produced from such systems, offering the potential for high value sales and important offsets. On the downside, energy requirements are so high that such projects potentially cease to be renewable energy projects but fertilizer/clean water projects, as a significant percentage of the produced renewable energy would be utilized within the processing, forcing project economics to rely on the sales and offsets from the NR process. Current limited data suggests that membrane systems could achieve performance and costs in the following general range. Despite the current high costs, the need for future process improvements, and the necessity for scaled demonstrations, clean-water approaches should be quite exciting to the dairy industry. They meet emerging salting concerns on valuable soils (Chang et al., 2005), while offering the potential for a future where dairies do not have to store or land-apply wastewater.

85-95% N and 85-95% P removal at roughly a cost of \$900-1,000 cow^{-1} year^{-1} in operating costs and \$1,500-1,800 cow^{-1} for capital costs, while also separating a valued fibrous product, concentrated nutrient/salt fertilizer and clean water.

Thermal Processes for Nutrient Recovery

Thermal processes offer intriguing business and sustainability capabilities. While historically focused on dry manures such as poultry litter, newer applications such as those described above use effective solids and P separation to successfully treat very dilute flush manures as well as a wide variety and even mixture of feedstock. Similar to the earlier discussed membrane technologies, thermal processes provide mechanisms to harness and collect salts within products that have value-added potential (ash, chars). Air quality concerns associated with thermal processes must be closely monitored, as a portion of the N can be released during processing. The performance and cost summaries are difficult to compare with other technologies, as these are not merely NR unit operations but combined thermal and NR systems. However, the included case study indicates that effective performance can be achieved at relatively modest operating costs and capital costs nearing or below AD, if additional liquid fuel components are not included. Nonetheless, further demonstration is required to solidify performance, economics and application to scale. Existing data suggests that performance and cost are within the following range. An intriguing option for both AD and thermal processes is the potential for moving beyond CHP systems and towards fuel production systems that make compressed natural gas (CNG), syngas to fuels, or other products. While they do increase complexity, these strategies are particularly appealing as received electrical prices continue to drop across the nation due in part to production of new found fossil-based natural gas (Coppedge et al., 2012). An additional area of exploration that is of potential technical importance but to date is still largely un-explored is the fusion of thermal and biological processes (e.g. pyrolysis/torrefaction and AD) within an integrated environment for process cost savings and production of multiple co-products (Garcia-Perez, 2012).

60-80% N and 80-90% P removal at roughly \$60-80 cow^{-1} year^{-1} in operating costs and \$1,200-1,400 cow^{-1} for capital costs for the entire system, while also producing renewable energy (additional costs to produce liquid fuel).

Summary

Figure 7 highlights nine classes of NR approaches, and their current documented achievements with regard to performance and cost. To the authors' knowledge, these classes represent some of the more common emerging approaches that have achieved some level of scale and commercialization, though additional approaches are being pursued. As can be seen from the figure, a variety of technological approaches are available, ranging from systems that remove limited fractions of nutrients at relatively low cost, to high performance systems capable of achieving near clean water at vastly increased costs. Note that these estimates of costs do not incorporate any assessment of the potential for cost recovery through sale of recovered nutrient products. Across the spectrum are three clear levels of performance and cost structure:

- Advanced solids and P recovery, typically using a polymer type approach.
- Solids and P recovery plus advanced N recovery.
- Solids and P recovery plus membrane treatment for salts recovery and clean water.

Between the first and second levels, total recovery of N and P goes from 50-60% to 70-80%, but with a three to four-fold increase in combined operating and capital costs. This cost increase implies that without cost decreases or improvements in N product markets, this technology is currently only applicable to areas with severe N or ammonia concerns. Accordingly, given current technologies, it is likely that incentives would need to be in place in order to induce adoption by dairy farms. Between the second and third levels, total recovery of combined N/P increases to 95%, with additional recovery of salts plus clean water, but with an additional four to five fold increase in operating and capital costs. If clean water and salt removal are not a priority, then an AD plus NR platform, via several different technical platforms is capable of:

A combined N/P removal of approximately 50-80% at operating costs of \$50-200 cow^{-1} year^{-1} and capital costs of \$150-600 cow^{-1}, while also separating a valued fibrous product and concentrated nutrient/salt fertilizer.

If compared to AD operating and capital costs of \$12-24 cow^{-1} year^{-1} and \$1,500-2,000 cow^{-1}, respectively (Andgar, 2013), these values represent a 3- to 11-fold increase in operating costs and 10-35% increase in capital costs for an integrated AD and NR system. Even at the lower end of the range, this increase in operating costs indicates that successful NR technologies most likely will require production of high-value products, emphasizing an industry need to solidify markets for these products.

Emerging NR technologies have been implemented at the commercial scale on several dairy farms in the US, and have proven capabilities at cost structures that may support more widespread adoption in the future. However, these technologies need to undergo additional development, both technical and product markets, before they can fully deliver on their promise. Current NR technologies range from those in the early stages of commercial adoption, to ideas that still need significant development, adaptation and scaled testing before they are ready for implementation across the industry.

As the NR sector develops, it will be important for industry to continue to keep abreast of, and support, these efforts. In particular, dedicated pilot or full-scale demonstrations will be important to testing how these technologies work in commercial farm settings. Ongoing development is also needed to reduce costs, enhance performance, and generate sustainable and salable nutrient products. In addition to focusing on improvements in existing promising NR technologies, it will be important for the industry to support the development of entirely new NR strategies. Many of the reviewed NR technologies were adapted from technologies designed for the municipal wastewater industry to treat either their very dilute wastewaters or their digested and pressed bio-solids. Dairy and other animal manures are quite different in form and structure than these materials, and thus there is a need for investigation of completely new approaches not previously considered or researched by the municipal wastewater industry.

Despite the remaining challenges, significant progress has been made in recent years in making these technologies a reality. With development, these technologies may become an essential tool for enhancing the economic and environmental sustainability of the dairy industry. This vision, though, will not only require researchers, producers, and entrepreneurs, but also support from government and the larger industry. Within this context, it is hoped that this review can help focus the current and future efforts of project developers, industry, and government agencies.

This information can also serve as a baseline to the dairy industry as manure management transitions from being an assumed liability to a resource capable of sustainable economics as well as environmental sustainability.

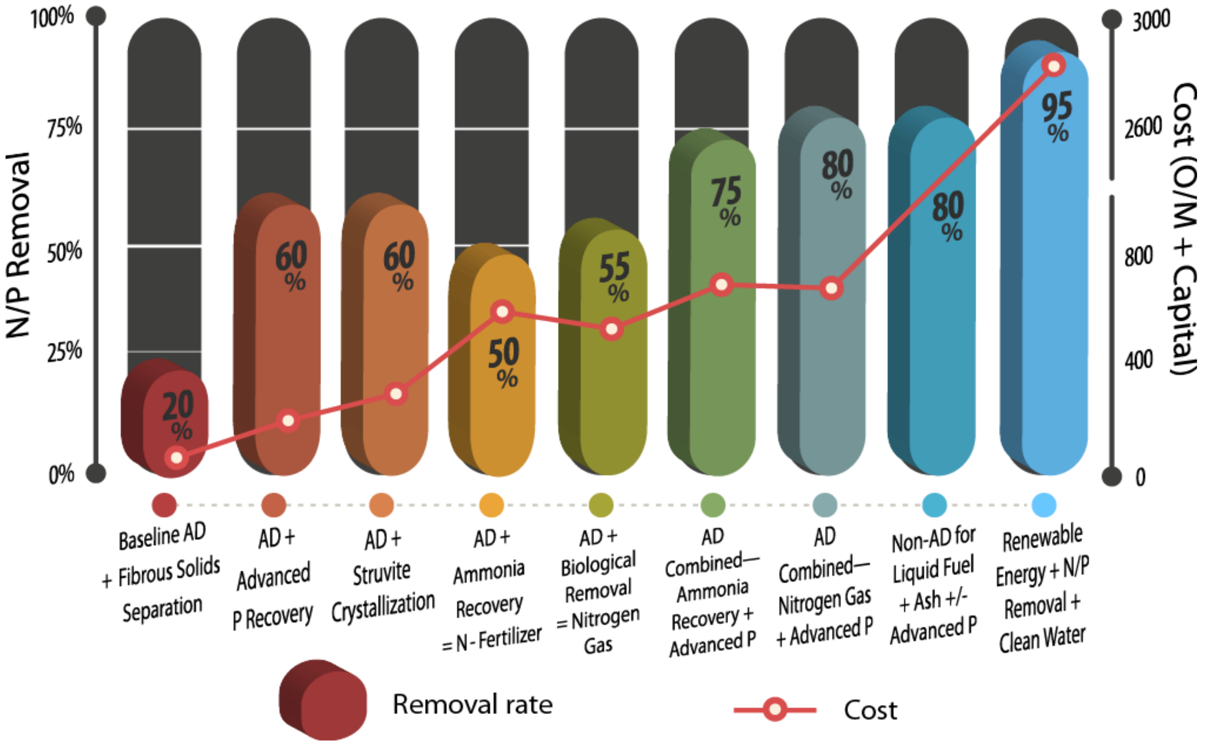


Figure 7: Nine general classes of NR approaches on dairies and their comparison in regard to performance *(left axis, bars)* and cost *(right axis, red dots; combined operating and capital).* Notice the break in cost axis scale, due to large cost of clean water systems (Ma et al, 2013).

Conclusion

It is the authors' belief that existing sales/adoption of AD will not only rely on pricing and valued uses of the biogas (CHP or RNG) but as well on its association with NR technology so as to meet multiple climate, air and water environmental needs. Hurdles delaying adoption of AD/NR systems are a matter of cost (capital but in particular, operating), end market sales of recovered bio-fertilizer products, and demonstration of viable processes so that funding authorities can find levels of technological risk acceptable. Completion of this NRCS CIG project has gone a long way to furthering this agenda and opening the door to additional work required to further meet the identified limitations. Similar actions are ongoing for other NR technologies, at times through NRCS funding as well. No single NR approach will suffice due to the varying manures, manure handling procedures, renewable energy business plans and local/regional environmental needs—as such ongoing demonstrations and improvements for a suite of NR technologies will be required, further placing importance on NRCS technology demonstration funding.

REVIEW OF METHODS

Innovative Aspects to the Project/Technology

The previous chapter highlighted the need for AD to incorporate active NR units into a more environmentally and potentially more economically viable systems approach to renewable energy and environmental sustainability. While numerous NR approaches, some linked to AD, exist and are under similar R&D—all are common in that they attempt to harness significant percentages of nutrients from the manure wastewater so as to reduce the environmental threats associated with application of that nutrient-rich wastewater to limited fields. The previous chapter also highlighted the need to develop NR technologies that can fit within a renewable energy platform at capital and operating costs that do not put undo burden on business plans and dairies. Methods for accomplishing this are to demonstrate technologies that have *high levels of removal efficiency, reduced complexity/costs, and an ability to provide saleable products in forms desired by the marketplace*. Below is a summary of the demonstrated technology with discussion as to its innovativeness in these areas highlighted in ***bold italics***.

The Technology

The Nutrient Recovery System

The system and its components are patented (Jiang et al., 2011; Zhao et al., 2011; Kennedy et al., 2013) and licensed through WSU to DVO Incorporated (Chilton, WI). Figure 8 is a schematic representation of one manifestation of the system, which can be sub-divided into four distinct unit operations: 1) AD, 2) primary fiber screening and treatment of fiber, 3) ammonia stripping, and 4) phosphorus-rich solids (P-solids) separation. Two versions of the core technology exist: a full system with all four operations *and* a reduced-cost version with unit operations 1, 2, and 4, aimed at recovering less nitrogen. In brief, the system works as follows:

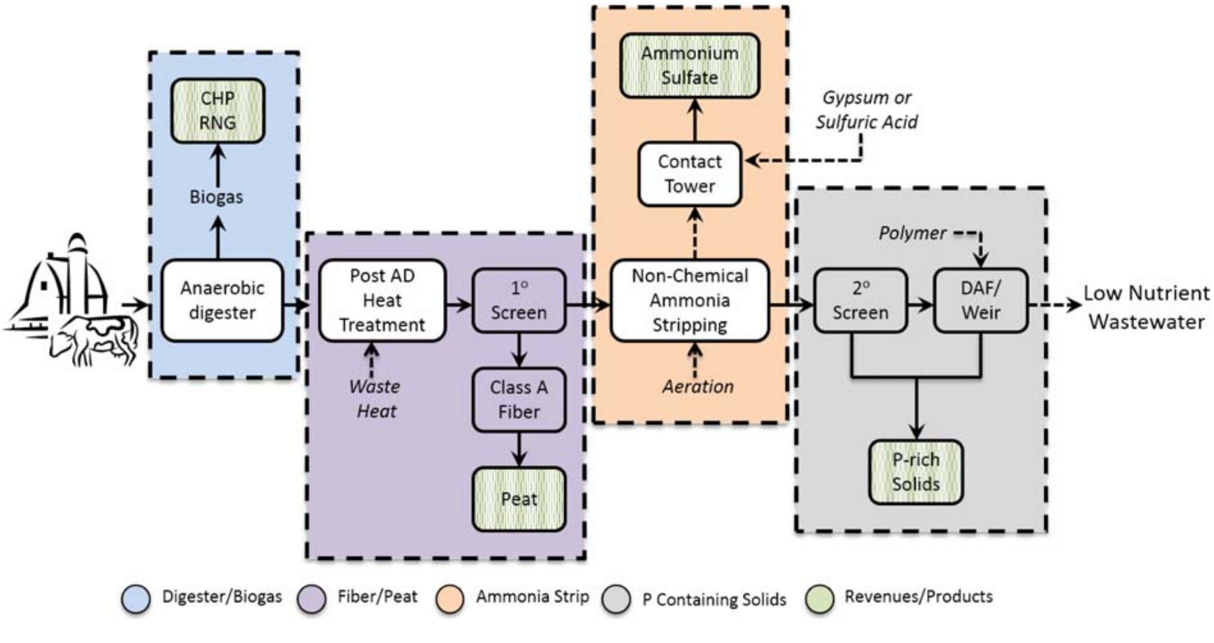


Figure 8: Schematic of NR system

Unit Operation 1 (AD):

- AD is carried out using existing commercialized technologies, although research has shown that use of a mixed plug-flow design as the main digester is noteworthy in regard to producing guaranteed time and temperature retention for both preferred pathogen treatment and elevation of effluent pH. ***Mixed plug-flow digesters, presumably due to their mixing pattern and/or guaranteed retention time, typically produce effluent with pH in the range of 8.0-8.2, which facilitates in achieving the desired pH range near 9.5 required for ammonia stripping.***

Unit Operation 2 (Primary fiber screening and treatment for high value peat replacement):

- Digested effluent is subjected to additional Class A time/temperature treatment for improved pathogen destruction and production of higher value fiber with more consistent electro-conductivity (EC) values. Source of heat is from combined heat and power (CHP) heat recovery and/or renewable natural gas (RNG) compression—although use of RNG supplies only limited heat recovery;
- Fiber is screened and may be optionally processed into high value peat replacement. ***The additional heat treatment while predictive of additional pathogen destruction is surprisingly important in facilitating the washing/release of soluble organics/salts from the fibrous surface, providing for a superior fiber product preferred in EC and physical parameters for peat replacement use.***

Unit Operation 3 (Ammonia stripping)

- Remaining effluent stream is sent through an aeration zone, where the combined attributes of higher temperature and higher pH allow for release of soluble ammonia to gaseous ammonia. ***The system requires no chemical inputs other than ambient air. The previous AD step, which accumulates carbon dioxide and carbonates into the AD effluent, allows for a mechanism to raise the pH to ammonia stripping needs through displacement/release of acidic carbon dioxide by the aforementioned aeration process.*** Previous studies have shown this effect but only to a limited extent, still requiring additional chemical treatment.
- A contact tower utilizes gypsum and/or concentrated acid to produce ammonium sulfate, which can be either marketed as a 8% N and 10% S solution or as a solid (21% N and 24% S). ***While such contact towers for use with acid and gypsum are known, unique engineering allows for superior ammonia capture at desired final pH ranges.***

Unit Operation 4 (P-rich solids separation)

- Secondary screening is carried out using patented DVO Centriflow technology. ***While advances in sequential screening using smaller mesh sizes and vibrating screen have allowed for enhanced capture of suspended solids, the centriflow technology allows for even greater capture of even smaller suspended particles, requiring only a fraction of the energy/moving parts of other devices such as decanting centrifuges. Importantly, use of this unit operation reduces the solids recovery burden on the downstream DAF operation, making its operation for feasible and robust.***
- This is followed by either a settling weir or in a preferred option, dissolved air flotation (DAF) processed with a low input of polymer. Both processes separate out a significant fraction of suspended solids, which contain a high proportion of the phosphorus (P) from the effluent. These processes are uniquely engineered to reduce chemical inputs. Data has

shown that the preceding steps in solids removal and ammonia/carbon dioxide removal are instrumental in reducing the amount of polymer dosing required. ***The hypotheses still in validation with laboratory data are that their combined removal allow for significant changes in charge distribution within the liquid and removal of supersaturated gases that interfere with natural flocculation.***

- Remaining effluent is returned to neutral pH while assisting in biogas scrubbing (100% H_2S scrubbing and/or additional CO_2 scrubbing). ***An inexpensive means for H_2S removal while concurrently returning the effluent to neutral pH was devised through a contact tower reacting raw biogas (with acidic impurities, CO_2 and H_2S) with higher pH effluent. The contact tower design/operation is unique in its ability to preferentially scrub H_2S within the presence of overwhelming concentrations of acidic CO_2.***
- An option also exists to utilize a portion of the treated effluent as dilution water in the front end of the AD process, reducing fresh water inputs and the total wastewater in need of land disposal. While use of return/dilution water is not a unique principal it is not a method commonly used within the AD industry, primarily because the effluent has traditionally been considered too inhibitory for its reuse. ***With incorporation of NR, these inhibitory agents are to a large extent removed, allowing for return of the effluent for dilution water, thus opening up the AD industry to high solids digestion of manure such as dry lots and poultry—all within a slurry AD environment that is kinetically advantageous for digestion.***

Demonstration and Data/Performance Timeline

Table 5 is a summary of the timeline that was completed for the project in regard to when demonstration unit constructions were complete, troubleshooting/operations were conducted, data collection and performance determinations were summarized, and deliverables completed.

Table 5: Summary of Construction, Operation/Troubleshooting, and Data Timelines

	FPE Renewables	Rainier Biogas	Wenning Poultry	Dallmann Dairy
Completed	F-11/S-12	W-12	F-12	S-13
Data/Performance	Spring 2013 through Fall 2013			
Deliverables	Spring 2013 through Fall 2013			

e.g. S-11 refers to spring 2011 and split dates refer to completion dates for original and retrofit constructions

The first demonstration system constructed for the project was the FPE system in Lynden and was designed to treat the full farm flow of 50,000 gallons day^{-1}. The system was a retrofit to an existing digester, using the digester effluent pits to complete post-AD heat treatment before sending the effluent for fiber separation and then aeration for ammonia stripping. After stripping, the effluent was then sent through a settling weir for removal/recovery of suspended solids/P, with no H_2S treatment before final storage in a lagoon (Figure 9). This system was completed and open for operation as of fall 2011. Considerable hurdles were experienced in regard to heat exchanger operation/efficiency, foaming within the aeration basin, noise control with the aeration blowers, operation of the acid contact tower, production of a quality product with high ammonia removal efficiencies, and operation/data collection within settling weir. From fall 2011 through to spring 2012, operation/troubleshooting was undertaken, systematically attempting to solve many of the troubles and deficiencies. In spring 2012, several redesigns were completed based on lessons learned, so as to allow for a period of more refined data collection and performance determinations. This system was used extensively for troubleshooting many of the unit operations with performance data regarding aeration/ammonia stripping efficiency, ammonia sulfate production performance, settling weir/P removal, and costs coming from analyses from its data. H_2S removal unit operations were at this time still being studied at lab/pilot scale and not installed at this site. Subsequent full-scale demonstration of the H_2S scrubbing system was completed at the Dallmann Dairy.

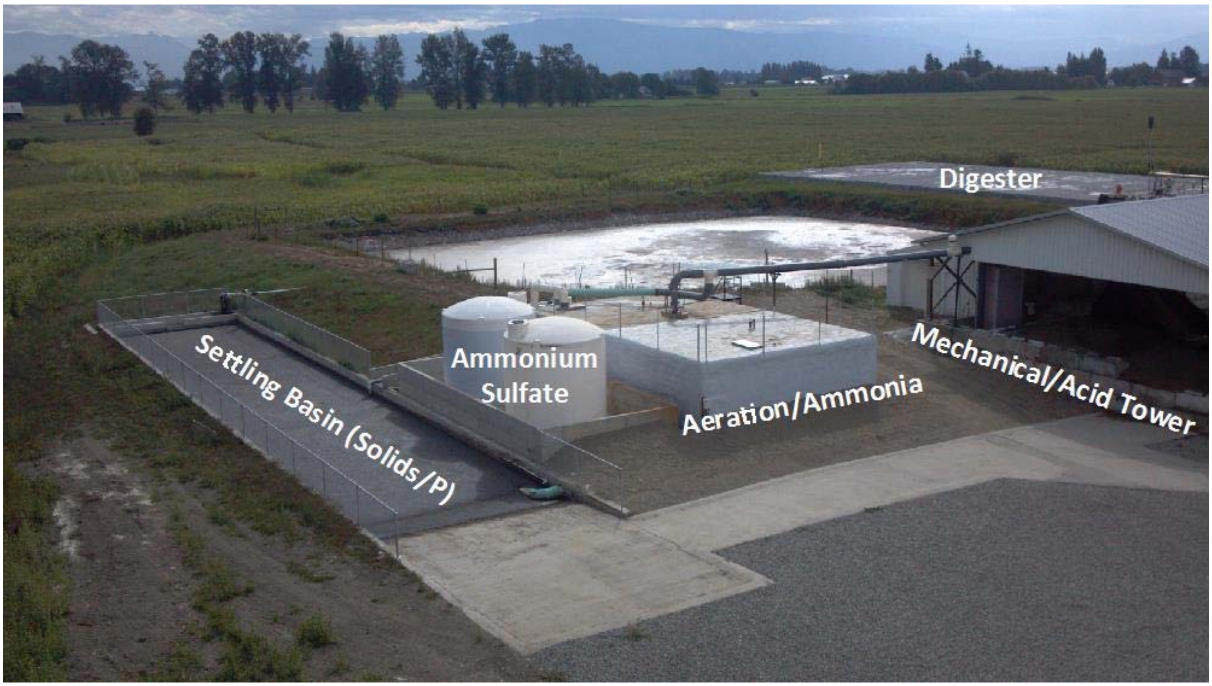


Figure 9: FPE Renewables System (50,000 gallons day^{-1})

Nearly concurrent to the FPE system was completion of a NR system at Wenning Poultry (150,000 gallons day^{-1}), which was used as leverage to this project (Figure 10). This facility had a more preferred U-shaped plug-flow aeration basin with more efficient heat exchanger/gas-mixing systems aimed at supplying improved post-AD heat treatment and aeration/mixing. In addition, the system had underground feed/supply lines for acid/AS delivery, additional foam reduction protocols, and a centrifuge for solids/P (later a DAF/polymer system) recovery. Importantly, treated effluent is used as dilution water to the system. This system also supplied plenty of troubleshooting experience but in regard to data collection was a primary factor in regard to reporting performance analysis for aeration/ammonia stripping, ammonium sulfate production, marketing/sales of ammonium sulfate, and performance of the DAF/P solids. Considerable international interest and touring of this facility continues to this day due to the higher ammonia concentrations and therefore higher fertilizer production rates as well as the need for suitable AD technologies for poultry manure. For this reason, initial commercial sales of the NR system(s) being developed via this NRCS project are most likely to be within this poultry sector.

Figure 10: Wenning Poultry (150,000 gallons day^{-1})—(1) poultry solids collection; (2) mixing with return/dilution water, (3) anaerobic digestion (CHP); (4) ammonia stripping; (5) ammonia sulfate production; (6) DAF/P solids separation; and (7) H_2S removal from biogas

Lessons learned from both the FPE Renewables and Wenning Poultry facilities were utilized for design of the Rainier Biogas facility in Enumclaw WA (85,000 gallons day^{-1}). Construction was completed and operation ensued as of winter 2012 (Figure 11). This system utilized a modified settling weir system for solids/P recovery as well as an integrated aeration/ammonia stripping unit within the anaerobic digester (this system was not a retrofit and instead was built at the same time as the digester). Data collected from this facility was used primarily to validate new enhancements in regard to foam control and to provide performance data in regard to costs and settling weir performance.

A full NR system was lastly constructed at Dallmann Dairy next to DVO Inc., corporate headquarters (67,000 gallons day^{-1}) in Spring 2013. Completion of this system was primarily so that DVO could use the site as a nearby test bed and demonstration/tour facility. For purposes of this project, data was collected primarily in regard to validation of the full-scale H_2S scrubbing system and concurrent effluent pH control system (Figure 12). This facility is now actively used for on-going studies involving CO_2 scrubbing within the NR platform as well as pilot studies in gypsum use and crystallization of ammonium sulfate product.

Figure 11: Rainier Biogas (85,000 gallons day^{-1})

Figure 12: Dallmann Dairy H_2S scrubbing unit (67,000 gallons day^{-1})

During monitoring and troubleshooting within all of these facilities, certain functions performed as expected while others had less than expected performance with at times unexpected concerns. While some of these concerns have been resolved through subsequent troubleshooting/redesigns, to date a list of hoped for improvements and enhancements to unit operations and total system still exist and are being worked on. A reporting of these will be summarized in the later *Findings* section of the report.

DISCUSSION OF QUALITY ASSURANCE

Sampling/Analysis

The protocol undertaken in all aspects of the project and at all site locations was to first construct the process or technology at the various sites and troubleshoot. This troubleshooting was accomplished by a combination of operating without sampling, focusing on mechanical/material flow concerns, and then at later dates doing intermittent sampling to get approximate understanding of performance, potential concerns and possible positive/negative responses to changes. After the period of troubleshooting and once the majority of fixes had been accomplished allowing for a relative steady state and consistent operation, then more serious sampling and analysis was completed.

At times during this troubleshooting period, laboratory/pilot data was simultaneously performed to ascertain technical solutions. These laboratory/pilot tests were done under more rigorous experimental design with data and conclusions being utilized to implement technical responses to the main commercial demonstration unit.

During the periods of more serious sampling/analysis, the usual protocol was to sample at various places along the flow each day (hour if necessary) and do so for extended period of time, say a week so as to get an average performance somewhat removed from external errors such as precipitation, changes in feed, etc. General areas of testing were as follows:

- Monitoring of effect of temperature, pH, inorganic carbon, ammonia (TAN), hydraulic retention time before and after the ammonia stripping process so as to determine process efficiencies and removal rates. Less frequently, samples were tested for chemical oxygen demand (COD), volatile fatty acids (VFA), total solids (TS), and fecal coliform (FC) to determine if any biological aerobic activity was occurring, the degree which solids were settling or volatiles being blown off, and level of pathogen reduction treatment was accomplishing.
- Monitoring of reductions in total nitrogen (N), total phosphorus (P), and TS at various places along the process so as to get sequential removal efficiencies, particularly in regard to use of mechanical screens, centriflows, settling weirs and DAF units.
- Determination of moisture content, solids and nutrient content of the various products emerging from the study, namely ammonium sulfate solution, fibrous solids, centriflow solids, and settling weir/DAF solids.
- Determination of biogas content (CH_4, CO_2, H_2S) prior to and post treatment with high pH effluent for determination of efficiency of removal of H_2S during the scrubbing process.
- Summarization of known analyses with flow rates and capital/operating costs (supplied by industry partners constructing and operating facilities) for overall techno-economic and performance evaluation.

Sample custody at commercial demonstration sites was accomplished via sampling by operational technicians who then stored samples for the collection time period in 4°C refrigerators until packaging in sealed containers shipped with ice packs to the WSU Biological Systems Engineering Analytical Laboratory. Upon receipt by the laboratory, technicians stored samples under 4^{o}C until analysis. All analytical methods for the parameters listed below were conducted according to their referenced standard method (APHA, 2005) and were analyzed as duplicates or triplicates and reported as mean values. Wherever possible internal and external quality controls were used to assure proper operation of protocol and analytical machinery. TS (2540B) and volatile solids (VS, 2540E) utilized standard ovens and furnaces using the particular standard method identified in parentheses. COD was analyzed with a Hach 45600 COD Analyzer (Loveland, Colorado, USA; 5220D). Alkalinity, pH, and Ripley ratio values were analyzed using a Mettler Toledo T50A Automatic Titrater (Schwerzenbach, Switzerland; 2320B). Total Kieldahl nitrogen (TKN), and total ammonia nitrogen (TAN) were analyzed using a Tecator 2300 Kjeltec Analyzer (Eden Prairie, MN, USA; 4500-NorgB; 4500NH3BC). TP was digested and analyzed using an O-I-Analytical FS3000 Flow Injected Analyzer (College Station, TX, USA; 4500PB; 4500PE). Potassium was analyzed using a Varian Spectra AA220 (Palo Alto, CA, USA; 3111B). VFA including acetate, propionate, and butyrate were analyzed using a Dionex DX- 500 IC (Sunnyvale, CA, USA) using a method as detailed in Hu and Chen (2007). Biogas composition, including CH_4, CO_2, and H_2S were analyzed using a Varian GC CP-3800 (Palo Alto, CA) using a method as detailed in Wen et al. (2007). Fecal coliform (FC) counts were determined using method 07.01 as described in TMECC (2002).

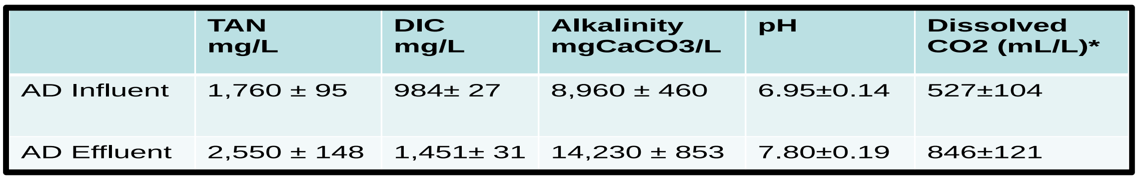
FINDINGS

Findings for the project will be summarized by unit operation as earlier depicted in Figure 8, with a final overall conclusion and recommendations section included as a separate chapter heading.

Anaerobic Digestion

Due to the licensing arrangement with DVO Incorporated, all digesters associated with the nutrient recovery units were in series with DVO patented mixed plug-flow digesters. Previous analyses of the performance potential of DVO digesters have been published (Frear et al, 2011; US-EPA 2005) but were not be the focus of this study. It is important, however, to state two emerging but not fully conclusive aspects about the digestion process as it relates to the nutrient recovery process. First, it appears that the release of CO_2 from the effluent through the novel ammonia stripping process is limited by the initial pH and concentration of dissolved CO_2 and inorganic carbon within the effluent. Put another way, the higher the effluent pH, the less pH rise that has to be accomplished through the aeration stripping process and the more CO_2 and inorganic carbon, the greater the pH rise potential (Table 6).

Table 6: Changes in chemical parameters during anaerobic digestion



	TAN mg/L	DIC mg/L	Alkalinity mgCaCO3/L	pH	Dissolved CO2 (mL/L)*
AD Influent	1,760 ± 95	984± 27	8,960 ± 460	6.95±0.14	527±104
AD Effluent	2,550 ± 148	1,451± 31	14,230 ± 853	7.80±0.19	846±121

TAN (total ammonia), DIC (dissolved inorganic carbon), standard deviation from n=3 replicates

It has also been qualitatively noticed that both of these parameters are at their highest when digestion occurs to its most complete extent. Put another way, certain digester designs, organic loading rates and co-digestion feeds do not allow for effective digestion producing effluent with lower than desired pH, DIC, dissolved CO_2, and TAN, all which impact ultimate release of CO_2, rise of pH and release of free ammonia (Table 7). Adding to this concern is that incomplete digestion also releases un-digested organic carbon into the effluent, particularly with hard to anaerobically digest feeds such as fats, oils and greases (FOG). This is important, as there is evidence that the physical aeration process does to some extent result in some growth of aerobic organisms (< BOD/pH post aeration, data not shown), which metabolize this organic carbon and produce more CO_2, thus negating the purpose of the aeration stripping process and reducing overall efficiency

Table 7: Effect of digested effluent quality on aeration pH and TAN removal

	FPE Renewables Manure + large v/v substrates (FOG)	Dallmann Dairy Manure +small v/v substrates
Influent pH	7.0	7.1
Effluent pH	7.8	8.3
Air Stripping pH	9.0	9.3
TAN Removal (%)	40	50

Continuous flow aeration experiment using same micro-aerators, aeration rates, and temperatures for both treatments

Fibrous and Secondary Solids Removal

After digestion, the typical ensuing unit operation is to mechanically remove the fibrous solids for subsequent use as animal bedding or soil/peat amendment, followed again by secondary solids removal to lower the TS and total suspended solids (TSS) concentrations prior to downstream processing. Conceivably, aeration stripping could occur with solids still contained within the effluent so as to remove more ammonia that might be attached to the solid particles as well as produce fibrous solids removed in ammonia odor. Experimental observation has qualitatively shown that such a process adversely affects the quality of the fibrous solids, producing solids that are somewhat decomposed and deteriorated in water/air holding capacity properties. Presumably this is a result of exposure to time, temperature, pH and ammonia soaking conditions not unlike those typically used in lignocellulosic material pretreatment for ethanol production via *soaking aqueous ammonia* methodology (SAA) (Gao et al, 2012). In addition, qualitative evidence also points toward a hypothesis that presence of these solids during the aeration stripping process negatively impacts mass transfer of the CO_2 and NH_3 release (data not shown). It is for these reasons that the applied technical approach is to remove fibrous and secondary solids prior to aeration stripping.

Removal efficiencies for the sequential mechanical treatment for primary fibrous solids and secondary finer solids using a centriflow are given in Tables 8 and 9. As can be seen from Table 8, the primary screening operation removes roughly 33% of total solids and in regard to nutrients, 9, 17, and 3% N, P and K, respectively—although results may vary from site to site depending upon type of primary screens and material digested. The final fibrous solids product is available for direct sales without any additional pre-treatment at a moisture content of roughly 75% and having a dry value NPK of 2.5:0.6:0.5, again with allowance for variations upon site and feed to digester.

Table 8: FPE Renewables mass balance and primary fibrous solids removal efficiencies

	TS (%)	TN (%)	TP (%)	K (%)
Flows	17.73 ± 1.10 m^3 fiber day^{-1} and 122.02 ± 12.21 m^3 manure day^{-1}			
Fiber Density (wet)	400.48 kg m^{-3} and 1000 kg m^{-3}			
Fiber (wet %)	23.80 ± 0.8	0.59 ± 0.06	0.13 ± 0.02	0.12 ± 0.015
Manure (wet %)	4.2 ± 0.04	0.38 ± 0.05	0.044 ± 0.01	0.23 ± 0.04
Reductions (%)	32.98	9.03	17.20	3.04
F-Solids (dry %)	23.80	2.5	0.6	0.5

Mean and standard deviations calculated from n = 3 replicates

As can be seen from Table 9, the centriflow removal efficiencies were nearly 15, 5, 4, and 0% for TS, TN, TP and K, respectively. The final product without any pretreatment is quite moist like the fiber with a moisture content of 75% and an NPK value near that of fiber at 2.4:0.5:0.7.

Table 9: FPE Renewables centriflow secondary solids removal efficiencies

	TS (%)	TN (%)	TP (%)	K (%)
Influent	2.77 ± 0.24	0.218 ± 0.019	426 ± 15	---
Effluent	2.37 ± 0.22	0.207 ± 0.008	410 ± 10	---
Reductions (%)	14.44	5.05	3.76	ND
C-Solids (Dry %)	23.79	2.4	0.5	0.7

Total removal from the post digester primary and secondary screenings than is on the order of 45, 15, 20, and 5% for TS, TN, TP, and K from the original influent to the digester. Note though that typical digester TS reduction are on the order of 35-50% depending upon design and feed, so total TS removal for digester plus screenings is considerable and on the order of 70-80%. As noted in earlier discussions, this unit operation can be accomplished for relatively low capital and operating costs, while also producing potentially valuable solids products, however some value added pretreatment (drying, pelletizing, pH control, etc.) might be required. While the above results and technical approaches to primary and secondary solids removal are for the most part non-distinct from present normal practice, a few key points are important to keep in mind. First, while numerous attempts have been made to provide reliable secondary solids screening, many approaches have resulted in poor removal and/or non-reliable operation. The centriflow tested here holds promise for providing a relatively simple and cost effect means to recover secondary solids so, as will be discussed later, that downstream treatment can operate more effectively. Second, the fibrous product under this process has been exposed to an additional heat treatment which early evidence shows might allow for a superior soil amendment product due the additional time/temperature treatment and related pathogen kill.

Aerated Stripping for Ammonia Removal

After the AD and fibrous/secondary solids separation, the remaining effluent, elevated in temperature, is sent to an aeration basin so that micro-aerators, working in concert with heat exchangers (maintenance of elevated temperature, ~50°C) and gas-recirculation agitators (maintain a rolling action to facilitate rotational mixing during plug-flow action), can strip the effluent of CO_2, raise the pH, and subsequently strip ammonium to the free or gaseous form. As noted before, the novelty of this unit operation rests in the attempt to raise the effluent pH to near 9.5-10 and accomplish a high degree of ammonia removal through only the aeration action—requiring no input of alkali chemicals. While previous laboratory and small-scale batch studies confirmed the concept, it was via this full-scale demonstration project that the concept was evaluated at scale and under continuous conditions.

Full-scale batch/continuous trials

Upon completion of the full-scale system, using design criteria developed during early testing, initial batch studies were conducted. During this batch testing, numerous physical and mechanical hurdles were overcome, most relating to temperature control, operation of micro-aerators and blowers, noise control, and foaming. Over time most of these concerns were addressed through modifications to design and mechanical systems. Typical results of the batch capabilities are detailed in Figure 13. Analysis of the data shows that while earlier laboratory proof-of-concept work showed removal capabilities to be 70-80% over a 15-20 hour period achieving a pH of near 10, at the full-scale trials, only 60% removal was obtained, achieving only a pH of 9.6 and requiring at least 24 hours. A primary explanation for this was that during design, considerations regarding equipment available and costs, required installation of an aeration system operating at approximately 0.25 L L^{-1} min^{-1}, whereas early laboratory/pilot trials occurred at closer to 0.3-0.4 L L^{-1} min^{-1}. In addition, during winter the full-scale system was only able to achieve 45-48°C as opposed the desired 50-55°C. As the initial aeration basin was designed for a hydraulic retention time (HRT) of 15 hours and Figure 13 clearly shows an upward TAN removal curve with time, it was decided to retrofit and expand the basin size to be around 30 hours in hopes of achieving the targeted 70% removal efficiency.

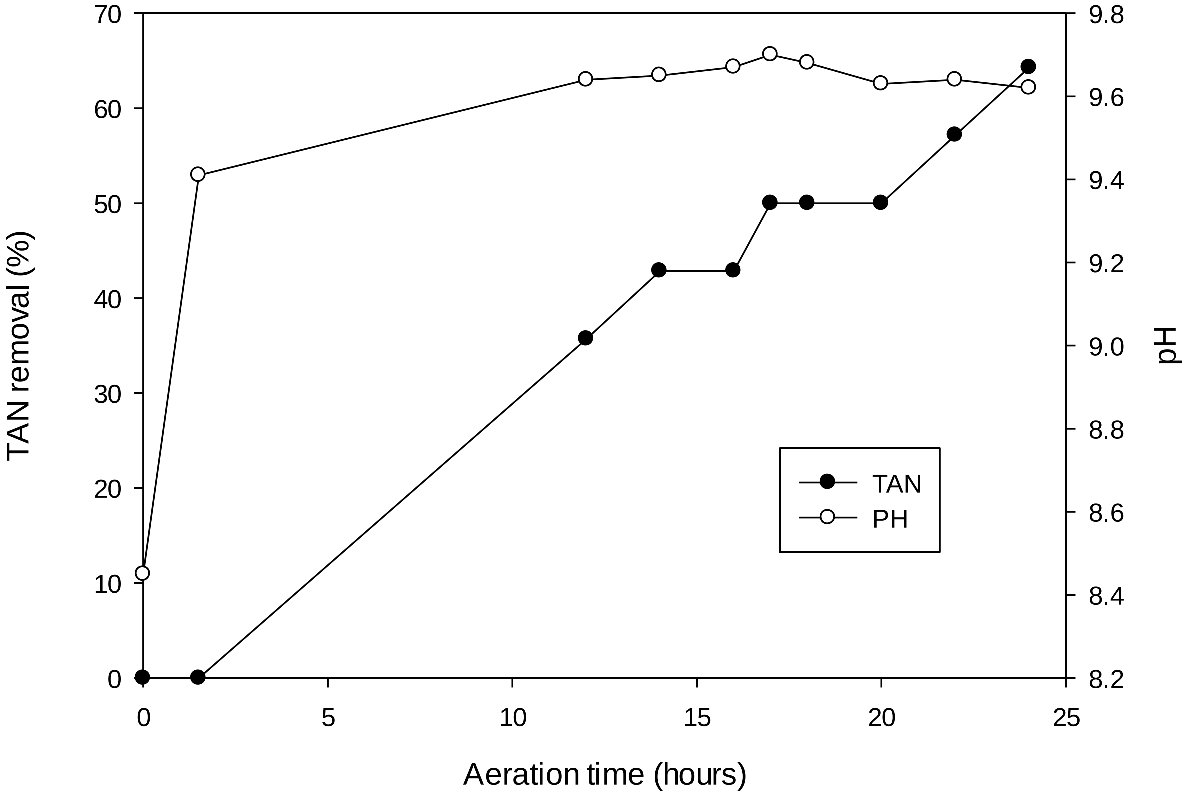


Figure 13: Batch results from FPE Renewables (0.25 L L^{-1} min^{-1}, 48°C)

Subsequent operation under continuous flow with the expanded HRT (using a new set of micro-aerators as the previous sock design were prone to tearing and failure) is summarized in Table 10. As can be seen from the table, results were unexpectedly worse than seen during batch performance with the smaller HRT.

Table 10: Continuous flow FPE Renewables performance (24-30 hours HRT)

	Flow Rate (gday^{-1})	Temp (°C)	pH	AS (gday^{-1})	Acid (gday^{-1})
Fall 2013	54,000±14,100	56.7±1.5	8.9±0.1	265±38	45.0±8.9
Performance	35-40% TAN removal				

Calculations based on acid added and AS produced with means similar but not exact (35.3% vs. 41.4%), TAN changes difficult to use for performance purposes as during aeration volume changes by 15-20%

Hypotheses for this poor performance, which were echoed at the other leveraged and project sites (~35-40% TAN removal except for poultry facility which was 45-50% TAN removal), were particular unknown concerns due to continuous operation (specifically partial CO_2 pressure inhibition in single headspace) and/or poor performance of the new micro-aerators. Subsequent laboratory tests were made using the same manure and similar operating conditions and these results are presented in Figure 14.

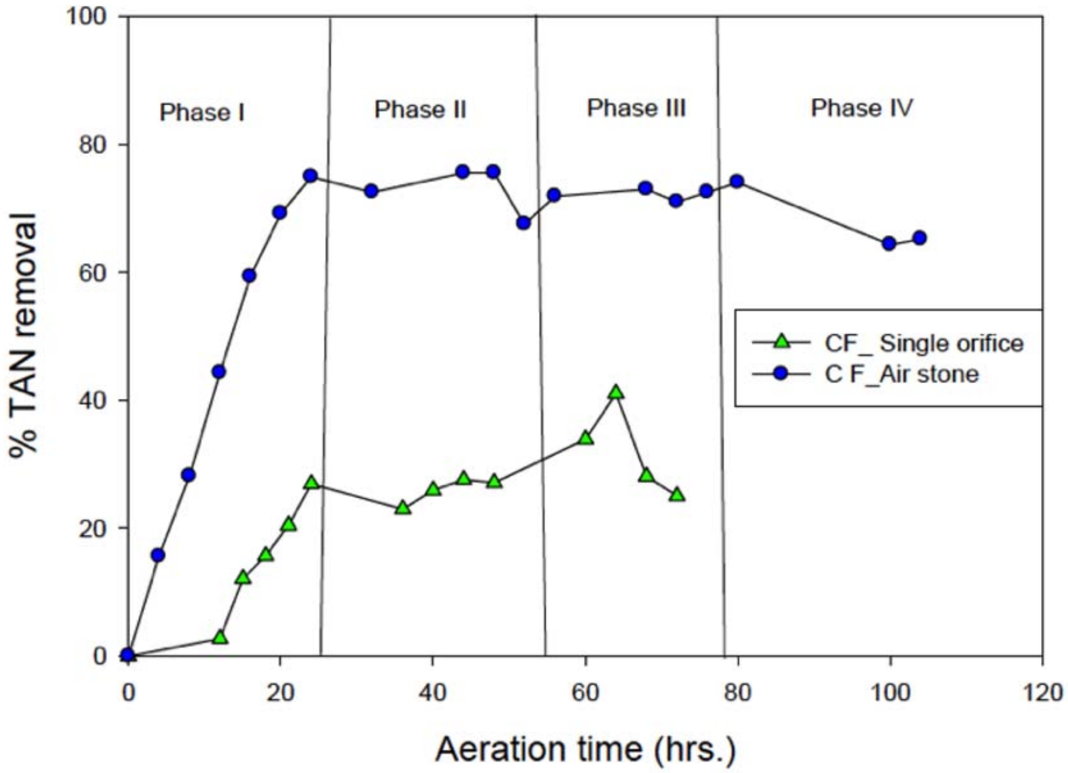


Figure 14: Laboratory tests of continuous flow of FPE effluent at using both micro and large bubble diffusers (Phase I is batch, Phase II-IV is continuous)

Figure 14 reflects two separate continuous flow experiments using FPE Renewables effluent, each one exposed to similar aeration stripping conditions as the commercial demonstration site, with the exception that one treatment used air stones with much finer bubbles and the other treatment used an orifice that mimicked the bubble size of the disc diffusers in the retrofitted FPE Renewables aeration pit. As can be seen from the data, the laboratory results with the single orifice are well in line with the results seen in commercial demonstration testing, while much more TAN removal, and of an order desired, was accomplished with the small bubble diffuser approach. This test as well as other observations/data (data not reported) leads project developers to conclude that the *major limiting factor leading to poor TAN removal performance is the size of the bubbles produced by the micro-diffusers presently installed at the commercial facilities.* Presently, testing is ongoing in regard to modifying design, operating parameters to switch to the use of small bubble micro-diffusers, with determination of performance and techno-economic data/impacts a major goal upon completion of this testing. *Project developers are cautiously optimistic that an engineering solution can be found whereby new small bubble diffusers are utilized to achieve anticipated 70% TAN removal but at little to no additional capital/operational costs, however as of this date and end of project, this has not been confirmed.* Until such design modifications can be confirmed/installed, all present demonstration units continue to use the larger bubble diffusers, yielding TAN removal efficiencies on the order of 35-40% for dairy/co-digestion and 45-55% for poultry.

Acid contact tower/Ammonium Sulfate production

After stripping of the ammonia from the manure, the ammonia containing gas stream is sent to a novel two-stage acid contact tower for production of ammonium sulfate solution at a saturated concentration while also controlling pH to desired levels. A few modifications to the tower were required during troubleshooting testing, particularly in regard to: redesign of particular tubing/pumps utilized to better meet environmental demands, redesign of the spray distributor with mist control to supply better chemical contact while avoiding backwash, and inclusion of a water spray for periodic cleaning and control of concentration to avoid crystallization. With these modifications in place the acid tower system performed excellently, with no detectable release of unreacted ammonia from the exhaust stack (data not shown) and consistent production of high concentration, saturated ammonium sulfate solution of a clear color and appropriate pH for market and sales. Table 11 is a summary of analysis of the ammonium sulfate solution that is consistently being produced at FPE Renewables and other sites.

Table 11: Ammonium Sulfate solution properties and quality

	AS Concentration (%)	pH/color	N/S (%)
FPE Renewables	38.4	6.0/clear	7.2/8.3
Dallmann Dairy			
Rainier Biogas			
Wenning Poultry			

AS refers to ammonium sulfate solution

For easy analysis and marketing/sales, a simple hand-held bubble hydrometer is used to determine specific gravity for a tank of product to be sold. Using a provided calculation table, the measured specific gravity can be accurately converted to both AS concentration as well as N/S concentrations knowing the stoichiometric elemental ratio within AS.

Settling Weir/DAF units for P recovery and reduction in TSS

After ammonia stripping, the de-gassed and higher pH effluent with low TAN levels is more ideal for separation of suspended solids, the majority of which are extremely small particles associated with the majority of the contained phosphorus (P) (Zhao et al, 2012) that manifests itself in digested manures primarily as colloidal size calcium/magnesium phosphate salts (Gungor and Karthikeyan, 2008). At FPE Renewables and Rainier Biogas, the concept was to use a more low-tech solution involving settling weirs that would periodically be drained and cleared of settled solids and allowed to air dry. Concurrently at Wenning Poultry and Dallmann Dairy evaluations were made on a higher-tech dissolved air flotation (DAF) approach that would use polymer to flocculate, float and skim the solids off of the top through a dewatering auger.

Settling weir

Table 12 is a summary of performance and pertinent information from the operation of the settling weir at FPE Renewables. Sampling and determination of performance were difficult for a variety of reasons: solids settled so quickly that they accumulated at end of pump house pit prior to the settling weir, manure within settling weir was still degassing and served to some degree as a DAF unit producing a floating crust, weir filled with solids very quickly causing poor settling performance as time passed, and draining/collection resulted in some loss of solids as they were so small and easily re-suspended. An additional concern is the very wet nature of the collected product requiring considerable time and space to dewater so as to stack and potentially sell. For all of these reason, as well as the excellent performance of the DAF unit described below, it is believed that a DAF operation is the best option moving forward.

Table 12: Settling weir performance and information

	TS (%)			VS (%)			P (ppm)		
	In	Out	R%	In	Out	R%	In	Out	R%
Performance	2.47±0.3	2.14±0.4	13.3	1.59±0.2	1.29±0.3	18.9	358±28	166±46	53.6
Solid (dry %)	20%C; 1.5%N, 1.5%P, 0.2%K, 1.5%S, 5%Ca, 1.5%Mg, 1%Fe								

Mean and standard deviation calculated on n=7, taken during a week of steady operation and no precipitation. Samples collected and allowed to dewater for a week, producing a product with a TS of 21%.

DAF

As noted, the concept behind the DAF is to use a more high tech approach alongside small additions of polymer to produce large flocs that can be continuously separated and dewatered, also allowing for a greater recovery of TS and TP in a more preferable market form. Table 13 is a summary of DAF information taken at various sites during commercial testing.

Table 13: DAF removal performance and solid properties

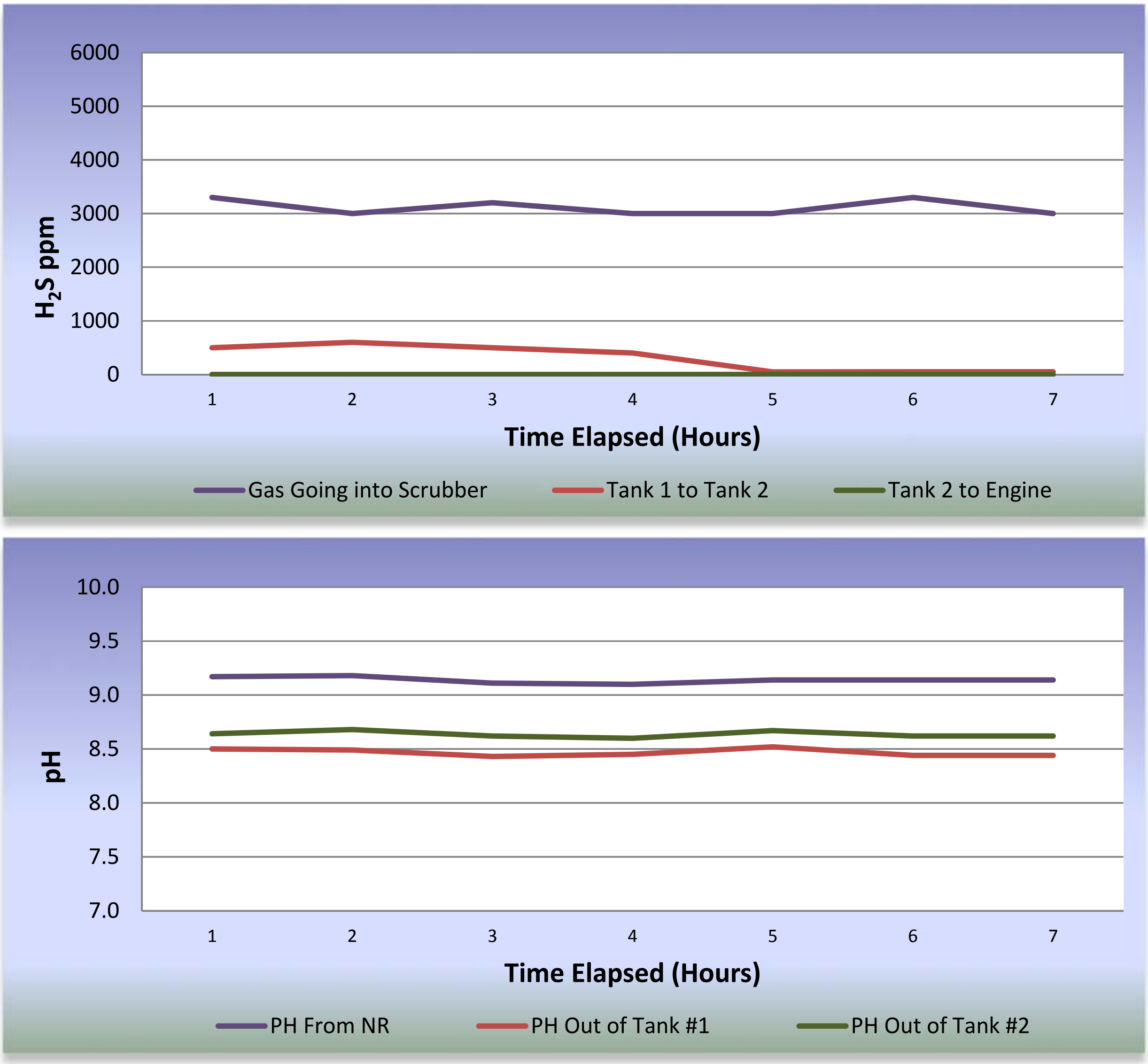
	TS (%)		TSS (%)		N (%)		P (ppm)		K (%)		FC (cf/g)	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Dallmann Dairy	4.2	1.5	4.4	0.31	0.22	0.17	500	89	0.14	0.10	ND	ND
	64.3%		93.0%		22.7%		82.2%		28.6%		---	
	Dewatering Not Applied—8.0% TS, 6%N, 1.5% P, 1%K, dry values											
Wenning Poultry	6.3	2.5	3.3	0.22	0.53	0.36	3100	320	0.53	0.42	ND	ND
	60.3%		93.3%		32.1%		89.7%		20.8%		---	
	19.6% TS, 80.4% moisture, 5% N, 7% P, 1.5% K dry values											

Trials after ammonia air stripping, fecal coliform (FC) levels were non-detectable, presumably through combination of AD, post-heat treatment, pH elevation, exposure to free ammonia, and DAF separation. Multiple day runs with composite samples but only n=1 replicates for nutrient analysis.

Analysis of Table 13 shows a very impressive performance from the DAF process, yielding significant reductions on the order of 60-65%, 92-94%, 25-35%, 80-90%, 20-30% for TS, TSS, N, P, and K, respectively while producing liquids and solids that are non-detectible in fecal coliform indicator pathogens. Additionally, solid products produced when dewatered with an attached dewatering screw press are capable of producing products with a TS of around 20% and high nutrient fertilizer value of macronutrients but also micronutrients such as sulfur, magnesium, calcium, iron and manganese (data not shown). Additional drying/pelletization will be preferred for value added sales. In addition, thanks in part, to the earlier degassing from the ammonia stripping operation, less polymer and no chemical flocculent is needed to induce these effective removal efficiencies. Use of polymer has been determined to be at a cost of roughly \$0.002 gallon^{-1} treated, which is quite low when compared to other manure polymer/flocculent processes on the market (Kemira, 2011).

H_2S scrubbing and effluent pH normalization

Originally project designs were to directly install commercial demonstration units responsible for contacting DAF effluent with raw AD biogas so that H2S could be scrubbed from the biogas while also returning the pH of the DAF effluent from approximately low 9-high 8 to near neutral. However, it was determined that a little bit of extra proof-of-concept laboratory work was required, thus delaying actual commercial demonstration until later in the project. Laboratory work was complete during the first two years, yielding a more refined process that was summarized in a MS thesis/manuscript (Kennedy et al, submitted) as well as a new patent filing (Kennedy et al, 2013). Full-scale demonstration occurred at the leveraged Dallmann facility and summary results are reported in Figures 15-16.



Figures 15-16: H_2S scrubbing efficiency and pH return for raw biogas/NR effluent contact within patent-pending two-tower system

From the figures it can be seen that the two-tank scrubbing system was able to scrub raw biogas with a H_2S concentration of roughly 3,000 ppm to approximately zero and maintain that ND level forward in time during continuous operation. Meanwhile the pH was stabilized from mid 9 to closer to 8.4, a more preferable pH to release effluent to the environment. Optimization of the process continues with studies at Dallmann dairy, mainly to facilitate both H_2S as well as CO_2 scrubbing. In addition, evaluations continue in regard to recycling this H_2S containing liquid back through the air stripping process for recovery of the H_2S within the ammonium sulfate product, as opposed to leaving it in the effluent to be applied to the fields.

Techno-economic evaluation

Table 14 is a techno-economic summary, as it would be presented for a potential first adopter at a commercial co-digestion dairy AD/NR project in Washington State. Note that it summarizes only the NR system (not including the fiber/peat, which is generally considered by project developers as its own stand-alone unit operation with known revenues). Design, engineering and cost projections are based on the emerging performance and cost evaluations from demonstration sites. This techno-economic summary for a hypothetical project involves 3,150 wet cow equivalent (WCE) of manure from a flush dairy operation, thickened in a clarify, with 30% volumetric addition of food processing waste, for a total volume of 167,000 gallons day^{-1} (the equivalent to a 5,200 scrape WCE flow) being fed to a mesophilic, mixed-plug flow digester. Total nutrient load to the digester is estimated at 1.5 and 0.2 tons of N and P day^{-1}, respectively. Biogas production, estimated at over 700 cubic feet minute^{-1}, will be cleaned to produce pipeline quality transportation fuel (renewable natural gas, RNG), with the main business plan focused on sales of the RNG and associated renewable identification numbers (RINs). Effluent from the digester will pass through the NR system, composed of fiber/peat separation, ammonia-N stripping for production of ammonium sulfate, and removal of fine solids/P through a polymer/DAF operation. High pH effluent recycle for H_2S scrubbing will assist in the biogas upgrade, though a dedicated water scrubber will do the majority of the CO_2 purification to RNG. Using the assumed performance capabilities in Table 1, the NR system would produce 86 cubic yards day^{-1} of fiber/peat, 3.1 tons of AS day^{-1}, and 6.5 dry tons of fine solids/P day^{-1}, using 2.1 tons concentrated acid day^{-1} and 140 lbs. polymer day^{-1}. The total efficiency of the NR system is estimated at 70% and 80% total N and P removal from influent wastewater, respectively. The NR system, particularly the ammonia-N stripping unit operation, requires considerable electrical input (aeration blowers, pumps, etc.) estimated at 195 Kwh/h as well as O&M (labor and parts), estimated at $343 day^{-1}.

Table 14: Techno-economic evaluation for the equivalent of a 5,200 scrape WCE NR project [a]

Capital (167,000 gpd: 3,150 WCE plus 30% v/v substrates ~ 5,200 WCE)		**$3.0 Million**	
Expenses	($/day)	**Revenue**	($/day)
Electricity (195 Kwh/h @ $0.06/Kwh)	281	Ammonium Sulfate (3.1 tons @ $250/ton)	775
Sulfuric Acid ($200/ton)	420	P-Solids (6.5 tons @ $80/dry ton)	520
DAF Dewatering ($0.001/gallon treated)	167	Based on potential wholesale value of $250/ton AS fine solids (Spring 2013) and $80/ton for the P-rich solids with an assumed value of high nutrient compost (Spring 2013)	
O&M (labor, contingency parts)	343		
Heat (assume thermal available CHP)	---		
Storage (assume on-site storage)	---		
Transportation (assume near sales)	---		
Total	1,211	**Total**	1,295

[a] Part of an AD for RNG project, but techno-economics reported only for the NR and does not include fiber. Note that improved ammonia recovery efficiency from 40% to 70% using planned small-bubble micro-aerators at a similar cost to existing system is assumed. Techno-economic evaluation is on-going process prone to fluctuations in determined capital, operating and revenue parameters

As can be seen from Table 14, capital cost estimations for the identified project come in at roughly $2.75 M, which translates to $529 cow^{-1}. By comparison stand-alone AD projects have capital expenditures at 1,500-2,000 cow^{-1}. Thus NR, as presently designed, *results in 25-35% increase in total project capital costs—an additional burden to project economics*. Operating expenses amount to roughly \$1,211 day^{-1}, which on a per cow basis is \$85 cow^{-1} y^{-1}. However, this does not include expenses associated with processing of the fiber/peat material, long-term storage of the AS, potential purchase of heat (RNG projects supply less excess thermal energy than combined heat and power, CHP, operations), and transportation of products to markets. These factors could raise costs to *\$100-150 cow^{-1} y^{-1}. For comparative purposes, stand-alone AD projects have estimated operating expenses of \$12-24 cow^{-1} y^{-1}. Thus inclusion of NR raises operating expenses by a factor of six or seven—a notable increase that must be made up through revenues of co-products produced.*

Table 14 also identifies and summarizes potential revenues from the ammonium sulfate and the fine solids. These values have been developed from extensive meetings with regional suppliers of fertilizers and soil amendments. It is very important to note that markets for such material are in their infancy and susceptible to volatile market pricing, local nuances, wholesale contracts, transportation, and form/consistency/blending suitable for end-user needs. These challenges in estimating revenues make estimation of true market pricing difficult, project development complicated, and securement of financing problematic.

Given these difficulties, the best interpretation of Table 14 is that, *even under optimal identified revenue projections, the NR system, as presently designed, at best, only operates at break even, and more likely operates at an annual loss.* While this is not optimal, the project PI has completed a NR technology review, which places this studied NR system performance and costs in relation to other emerging NR technologies. The review indicates that the present system's techno-economic performance compares favorably to many of the other systems presently being demonstrated (Figure 4) (Ma et al, 2013).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations as for much of this report will be organized by the unit operation within the overall technical approach.

Anaerobic Digester

Testing has shown that operation of an AD unit allows for important physical and chemical changes to the effluent that works synergistically within this novel nutrient recovery approach. The air stripping process for ammonia capture is affected by the quality of the effluent leaving the digester with co-digestion substrates such as FOG. They can adversely affecting ultimate ability to produce high quality effluent capable of supplying enough inorganic carbon to be stripped out for required pH elevation and subsequent free ammonia release. Thus, it is important that in this AD/NR operation, suitable and effective digestion occurs and that management of appropriate feeds, retention times, mixing, temperature, etc. within the digester be maintained.

Fiber/Peat/Secondary solids separation

The present system involves the post-AD heat treatment of the effluent (using recovered waste heat) to allow for increased time/temperature treatment and further reduction in indicator pathogens, followed by primary screening of fibrous solids and secondary screening of fine solids using a new centriflow concept. Preliminary data shows that, when using this system in conjunction with a mixed plug-flow digester, a preferred fibrous product (quality, pathogen count, reduced soluble organics, more optimal electro-conductivity) can be produced while also economically separating out a significant fraction of secondary solids at relatively low moisture content. This performance allows for both enhanced downstream treatment with the air stripping and DAF unit operations and improved marketability of the produced solid products (although some additional treatment for both the fibrous and secondary solids is required to meet higher value markets).

Non-chemical air stripping for free ammonia recovery

Present systems are only able to recover 35-55% of the effluent ammonia, which is lower than the desired and targeted 70% removal range. On a positive, both smaller and demonstration scale studies from this project have shown the viability of using no external chemicals and only air stripping of a suitably digested and high inorganic carbon content effluent as a means to strip free ammonia for nitrogen recovery. The reason for this weak performance has been determined, leading to the belief that the systems could be redesigned to operate with commercially available smaller bubble micro-aerators, so as to generate greater mass transfer and more efficient and faster free ammonia release. Attempts are ongoing to redesign this operation so to demonstrate this improved removal efficiency and to what cost extent the modification will incur.

Acid/ammonia contact tower for production of bio-based ammonium fertilizer

Demonstration at all funded and leveraged projects are showing very effective contact tower performance—with all sites reporting near 100% capture of the free ammonia, producing a clear, saturated and concentrated ammonium sulfate solution of pH suitable for use on fields. A typical product being produced is at approximately 38% ammonium sulfate concentration, yielding a bio-based fertilizer with 8%N and 9%S. The cost of acid is a major operating cost parameter both in its purchase and its handling. As such ongoing research/pilot efforts are attempting to replace the use of sulfuric acid with mined or waste gypsum, potentially producing a similar product but at either reduced costs or with organic certification. Another area of active research is in the desire to produce a crystalline product as opposed to the ammonium sulfate solution, due to present concerns in regard to cost of storage and transportation.

Settling Weir/DAF for suspended solids and phosphorus extraction

While the settling weir was effective at settling out considerable solids and nearly 50% of total phosphorus, the difficulties in operating the weir, collecting the incredibly fine solids, and dewatering, when placed in conjunction with excellent performance of the DAF unit, makes its use perhaps non-viable. Instead, an emphasis is placed on future units utilizing the DAF units, capable of superior performance in regard to constituent removal—realizing 60-65%, 92-94%, 25-35%, 80-90%, 20-30% efficiency for TS, TSS, N, P, and K, respectively. Importantly its operation as well as positioning within the sequence of unit operations allows for a reduced input of polymer, only requiring about \$0.002 gallon^{-1} in polymer cost. Additional work, as with the fibrous and secondary solids, is required in regard to better dewatering and ultimate drying/pelletization for high value sales.

H_2S scrubbing and effluent pH normalization

Operational data for the H_2S scrubbing system demonstrates excellent results, scrubbing raw biogas with as high as 3,000 ppm concentrations of H_2S to zero values under continuous flow operation. This is all at quite low costs, only requiring some pressurization of the biogas and some liquid pumping. Ongoing tests are attempting to remove CO_2 as well while also trying to isolate the captured H_2S within the produced ammonium sulfate.

Overall performance summary with emphasis on quantified data

Farm-scale demonstrations at the multiple sites have allowed for continued process improvements as well as a firm understanding of present and future performance capabilities. For comparability, values reported are for dairy manure-only projects. However, the system has been proven effective in dairy co-digestion as well as poultry digestion facilities.

- Both the full and scaled-back systems significantly reduce solids content in the digested effluent, particularly when using a polymer/DAF operation instead of the setting weir approach during the final stage treatment. When using the polymer/DAF, both systems consistently show *70-75% reduction in total solids (TS) and 93-97% reduction in total suspended solids (TSS).*

- Both the full and scaled-back systems produce considerable volumes of fibrous solids suitable either for animal bedding or higher-value peat moss replacement. A typical operation produces roughly *9-10 yards of fibrous solids cow^{-1} y^{-1} (~70-75% moisture content). Due to the AD and NR treatment, the fiber has low pathogen indicator counts, preferred EC values, and physical characteristics such as air holding capacity, water holding capacity, total porosity, and crude fiber* that allows for bulk sales to high-value distributors.

- Both the full and scaled-back systems significantly reduce P content in the digested effluent, consistently achieving *70-90% reduction in total phosphorus (TP)*, with the majority of the P being retained in P-rich solids emanating from the polymer/DAF process. The resulting product is produced wet (72% moisture content) but due to high nutrient content, will dewater quite readily under ambient storage conditions (~50% moisture content). With additional unit operations the solids can be dried/pelleted for higher value sales (this value-added treatment is still in development and was not part of this demonstration project). Using dry values, the product is roughly *1.5% N, 3.0% P, and 0.25% K, with significant presence of additional micronutrients including calcium, magnesium, sulfur, and iron*. Approximately *0.5 dry tons cow^{-1} y^{-1} of secondary and DAF solids are produced*. Organic polymers are utilized in the DAF operation and while organic certification has not yet been officially applied for, it is hoped for that this product is organically certifiable.

- The scaled-back system has demonstrated that *25-35% of the total nitrogen (TN)* can be recovered from the AD effluent along with the P-rich solids. The recovered TN is primarily in organic form. The full-system is capable of removing a more significant portion of the N as it recovers ammonia-N. While system performance using *large-bubble aeration systems only achieved 40% recovery of ammonia-N, pilot-tested small-bubble aeration system can remove 70% of ammonia-N, leading to a 65-85% reduction of TN for this improved system*. At the higher ammonia-N recovery rate, systems can produce roughly *1/4 dry ton ammonium sulfate (AS) cow^{-1} y^{-1}*. The *dry AS has a nutrient value of 21% N and 24% sulfur (S). However, presently all systems produce a saturated solution that is roughly 38% AS by mass, the rest being water. This product has nutrient value of 8% N and 10% S*. Market penetration for the solution has been problematic due to concerns related to storage, transportation, concentration, and blending/application. Additional unit operations could crystallize the product for enhanced sales and marketing (this process is still in development and was not a part of this demonstration project). An additional item in development and not part of this project is the potential for substituting the present use of concentrated sulfuric acid with mined or recycled gypsum. This has the potential to reduce costs and make the product organically certifiable.

This system does not focus on reducing potassium and total salts, due to the significant costs associated with these removal operations (membranes, reverse osmosis, etc.). However, there is still some recovery. Full-scale tests show that *25-30% of total potassium (TK) is recovered within the secondary solids (presumably due to adsorptive properties) while total salts removal is even higher, mainly ammonium, calcium, and magnesium*. Also, the full-system final effluent with pH 9-9.5 has been shown to be an effective agent for scrubbing of biogas while also returning the pH of the effluent to more neutral values (8.5-7.5). Full-scale demonstration at the leveraged Chilton site demonstrated *100% H_2S scrubbing of the raw biogas* when this effluent pH system was implemented. Ongoing tests of CO_2 scrubbing performance continue with some degree of promise but were not a focus of this demonstration project.

Table 15 summarizes recovery performance of the full system and its unit operations. As before, values are indicative of dairy manure-only systems. Figure 17 shows the products derived from the NR system: fiber/peat, ammonium sulfate, and fine solids enriched in P and other nutrients.

Table 15: Production and nutrient removal performance for NR system and its unit operations

	Unit Operations				Total System [c]
	AD	Fiber/Peat	Ammonia [a]	2^{o} Solids/P [b]	
Production	110 ft^3 of biogas cow^{-1} day^{-1}	9-10 yards fiber cow^{-1} y^{-1}	1/4 dry ton AS cow^{-1} y^{-1}	1/2 dry tons solid cow^{-1} y^{-1}	---
N Removal (%)	---	15-20	40-50	10-15	65-85
P Removal (%)	---	12-18	---	60-70	72-88

[a] assumes use of small bubble aeration and higher 70% ammonia-N recovery

[b] assumes use/performance of the polymer/DAF unit as opposed to more simple settling weir unit

[c] variations result from different farms, systems, and sample sets—no statistical analysis

Figure 17: NR products (a) fiber/peat; (b) ammonium sulfate solution; (c) fine solids rich in P

Process Enhancements

Four areas of process improvement have been identified and are presently undergoing R&D at the University and industrial demonstrations at farm sites. These four areas are aimed at improving performance and reducing costs, specifically through enhancing the ammonia recovery rate, reducing electrical/chemical/material inputs, and improving revenues for products through value-added and organic markets. All four of these enhancements are under active development and will undoubtedly alter the techno-economic evaluation. Additional funding is being sought to effectively demonstrate these new refinements.

- *Enhanced Ammonia Recovery*—All demonstration systems' ammonia-N stripping units were designed using large bubble aerators, which upon evaluation do not supply the necessary mass transfer to accomplish high stripping efficiency. This limits the existing systems to a consistent 40-50% ammonia-N recovery rate. Subsequent laboratory and pilot-scale testing has shown that commercially available small bubble aerators can achieve at least 70% ammonia-N recovery, the project's original target. Industrial partners are now evaluating the effect of conversion to the small bubble aerators on power consumption and capital costs. For purposes of the above techno-economic evaluation, it was assumed that conversion is cost-neutral (based on preliminary information regarding offsetting additional power consumption with reduced size/retention).
- *Replacement of Acid with Gypsum*—All demonstrations of the NR system are producing AS solution using sulfuric acid. Market development efforts have indicated that substitution of sulfuric acid with gypsum could be preferred as it could significantly reduce chemical costs (i.e. inexpensive recycled gypsum wall board) and also raise revenues through the possibility for organic certification for higher value sales. For purposes of the above techno-economic evaluation, use of sulfuric acid was assumed.

Industry partners are presently designing modified gypsum contact towers for testing and demonstration.

- *Solid Fertilizer Product*—Evaluation of AS markets has shown that production of crystalline fines is preferable from the perspective of storage and transportation. Thus, in future manifestations, techno-economic analyses will need to incorporate additional operating, capital and thermal costs associated with crystallization. The higher costs will need to be contained, so they can be offset by increased sale price, gains in market penetration, and reduction in storage/transportation costs.
- *Drying of P-solids*—Lastly, higher-value sales of the fine P-rich solids could be achieved by undertaking additional drying/pelleting—requiring additional operating, capital and thermal inputs.

Conclusion

While the current capital and operating costs for the WSU/industry partner N and P recovery system is significant—representing nearly 1/3 additional capital costs and nearly 7x the operating costs over installation of a stand-alone AD operation—there is strong potential for consideration. These considerations reside in the environmental benefits gained, particularly in regard to meeting nutrient management goals and protecting air, water and climate. Performance has been demonstrated to be effective, particularly assuming that ongoing process enhancements will be achieved. Future manifestations of the NR system should be able to achieve 70% N and 80% P recovery from the initial dairy manure wastewater. Ultimate economic viability and adoption will depend not only continued process improvements, but also on development of more mature product markets and implementation of policies that can allow for increased revenue through items such as nutrient trading and carbon fertilizer credits. Total project business plans must also be considered in relation to stand-alone NR economics. While the present demonstration shows stand-alone NR (not including AD/biogas, fiber/peat and AD credits) to be at best cost-neutral and more likely cost-negative, incorporation of NR into the larger business plan could be viable, especially as process improvements are made and with inclusion of manure management cost offsets.

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APPENDICES

Several extension activities were completed as a result of this project with a summary of these activities (some of which are deliverables) listed below.

Field Day (July 10, 2013, Lynden WA)
This field day presented anaerobic digestion centered within a system of complementary technologies to transform organic waste from an environmental concern into an environmental, economic, and social solution—specifically centering on the work being done on nutrient recovery. WSU researchers and their partners presented developments in commercializing anaerobic digestion (AD) system on dairy farms in the Pacific Northwest. Featured efforts included the development of technology for extracting nutrients from manure, use of manure-derived soil amendment, mitigating atmospheric emissions and water quality concerns, producing renewable energy, and more. There were 115 people in attendance, including representatives from NRCS, USDA, EPA, Canada, WA state agencies, industry representatives, government agencies, agronomy/fertilizer, compost industry, tribe, concerned citizens, and students.

Video
A 7-minute video was made detailing, for a general public audience, the ways in which anaerobic digestion can be much more of a system, with future enterprises undoubtedly being connected with nutrient recovery, pyrolysis, clean water and renewable natural gas units. The video can be accessed at http://csanr.wsu.edu/waste-management or http://www.youtube.com/watch?v=Ei49Z4oeUtY.

Conference presentations
During the course of the project numerous conference presentations and/or webinars were made to producers, government officials, industry representatives and concerned citizens, including in particular recent joint NRCS and EPA Region 10 meetings. The presentations were either exclusively or partially related to the nutrient recovery work being conducted or in regard to AD systems and the need for nutrient recovery in general.

- USDA Capturing Valuable Nutrients from Manure Part II, Webinar Series, December 13, 2013
- EPA Region 10 AFO/CAFO Workshop, Portland OR, December 3, 2013
- Washington Organics Recycling Conference, Vancouver WA, November 20, 2013
- **USDA NRCS/EPA Region 10 Nutrient Recovery Conference, Portland OR, November 19, 2013**
- Center for Dairy Innovation Markets Webinar (2013) Chicago IL, October 29, 2013
- Washington Clean Technology Alliance Ag Tech Conference, Seattle WA, July 31, 2013
- EPA Region 10 Nutrient Recovery Conference, Seattle WA, July 30, 2013
- WSU NIFA Anaerobic Digestion Systems Field Day, Lynden WA, July 10, 2013
- ASABE National Conference, Kansas City, MO, July 22-25, 2013
- EPA Agstar National Convention, Indianapolis IN, June 10-12, 2013
- California Dairy Summit, Modesto, CA May 10, 2013
- Biocycle National Conference, San Diego, CA, April 8-11, 2013
- Center for Dairy Innovation Markets Webinar, Chicago IL, April 11, 2013
- WSU ANR Extension Meeting Invited Speaker, Ellensburg WA, February 14, 2013
- The PNW Fertilizer Association Annual Conference, Pasco, WA, December 12, 2012
- Washington State Future Energy Conference, Seattle WA November 13, 2012
- AiCHE National Conference, National Conference, Pittsburgh PA October 28-31, 2012
- Algal Biomass Organization, ABO National Meeting, Denver CO September 22, 2012
- Biocycle National Conference, Pacific Coast Biocycle, Portland, OR April 16-18, 2012
- State of Oregon, Oregon AD Summit, Portland, OR April 26, 2012
- US EPA Directorship, Technology Markets Summit, Washington DC May 11-12, 2012
- US EPA National AgStar Program, 7th National Conference, Syracuse NY March 27-29, 2012
- US China Anaerobic Digestion Conference, Beijing, China October 29-30, 2011
- Washington State Future Energy Conference, Seattle WA October 18, 2011
- Qualco Farm Field Day, Monroe WA July, 19, 2011
- USDA National Research Initiative Air Quality Program National Meeting, Washington DC, June 8, 2011
- US EPA National AgStar Program, 6th National Conference, Boise ID May 11-12, 2011
- WA Dairy Federation Annual Meeting, Everett, WA November 2-3, 2010.
- WA Biomass Symposium and Conference, Seattle, WA November 8-10, 2010.
- USDA NIFA NRI Air Quality Program, Air Quality Program PI Meeting, Amarillo, TX August 23-24, 2010.
- US EPA National AgStar Program, 5th National Conference, Green Bay WI April 27-28, 2010.

Factsheets and Articles

Several key factsheets beyond the promised deliverables were also made in conjunction with this grant. These are listed below and can be accessed at the WSU CSANR website previously named in the video section.

Gallinato, S., Kruger, C. and Frear, C. (In preparation) Economic feasibility of post-digester nutrient recovery using struvite crystallization and the WSU AIRTRAP approach. WSU

Extension Factsheet, Pullman, WA.

Yorgey, G., Frear, C., Kruger, C., and Zimmerman, T. (Accepted). The rationale for recovery of phosphorus and nitrogen from dairy manure. WSU Extension Factsheet, Pullman, WA.

Kruger, C.E., Frear, C., and Galinato, S.P. (Submitted). Economic feasibility of anaerobic digester in Washington. WSU Extension Factsheet, Pullman, WA.

Kennedy N., Yorgey, G., Frear, C., and Kruger, C. (2013). Economics of Dairy Digesters in Washington State. 2013, Biocycle, October 2013.

Ma, J., Kennedy, N., Yorgey, G., Frear, C. (2013). Review of emerging nutrient recovery technologies for farm-based anaerobic digesters and other renewable energy systems, Report to the Innovation Center for US Dairy, November 6, 2013.

Frear C., Kennedy N., Zhao Q., Liu J., Zhao B., Ma, J., Yu, L., Bule, M., Chen, S., Gao, A., Garcia-Perez M., Smith M., Suliman W., Pang C., Kantor S., Yorgey G., and Kruger C. (2013). Anaerobic digestion-related research and development summary for WSU ARC/WSDA Appendix A Funds, 2011-2013. Washington State Department of Agriculture, Olympia, WA.

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Frear, C., Kruger, C., Garcia-Perez, M., Chen, S., (2011) Washington State Appendix A: Anaerobic digestion final report, Report to Washington State Department of Agriculture.

Yorgey, G., Kruger, C., Steward, K., Frear, C., Mena, N. (2011) Anaerobic co-digestion on dairies in Washington State: The solid waste handling-permit exemption. Washington State University Extension Fact Sheet FS-040E, Washington State University, Pullman WA.

Two extension documents were a part of the deliverable of the project. The first was a factsheet describing the main attributes/capabilities of the system, which in this case is set up as a quick guide brochure. This document is enclosed below. The project team working on commercialization of the technology will continue to refine the product as advancements are made and when demonstration moves out to actual marketing. The second document, also enclosed is the first chapter (WSU Advertising now in later stages of finishing conversion of the word document to official magazine format) of a two-chapter combination placing the argument for manure management/AD/nutrient recovery as well as both the general principles/approaches behind nutrient recovery and specifics of the WSU AIR-TRAP system to the general public. The second chapter is under preparation but is a shortened, public audience version of the aforementioned nutrient recovery technology review completed for the Innovation Center for US Dairy as listed in the above extension documents.

TECHNOLOGY REVIEW CRITERIA

While considerable discussion with NRCS agents occurred during the AD Systems Field Day, with much of that centering on moving the lessons learned towards technology review criteria and standards/handbook development, it is believed that the project team should concentrate on the identified system enhancements prior to focusing on this effort. The project team believes that if this list of desired project enhancements can be realized, that then the technology will move out of technology demonstration and into active marketing and sales. It is at this point that we would like to work with NRCS on development of these criteria and standards.

Who we are...

DVO, Inc. is a worldwide leader in farm-based anaerobic digestion technology and has long recognized the need for auxiliary technology to accompany base digester units for enhanced protection of air/water concerns that are threatening concentrated animal feeding operations and its soils and waterways.

Environmental Concerns Mitigated:

- Phosphorus and nitrogen eutrophication
- Nitrate leaching
- PM-2.5 ammonia release
- Pathogen release

Continued creativity in supplying ***multiple*** value-added revenue streams beyond methane production is also of great importance to DVO, Inc.

DVO Inc. and Washington State University are now designing, engineering, and marketing a patented nutrient recovery technology for use alongside DVO's patented mixed plug-flow digester.

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Nutrient Recovery Technologies

Sustainable Solutions for Nutrient Management

Our Technology

DVO, Inc. markets two versions of its core nutrient recovery technology:

1. Full system for recovery of all key components: **nitrogen**, **phosphorus**, **suspended solids** and **fiber** (shown below)
2. Scaled-back unit (P-focused system) aimed at recovering **less nitrogen**, with all other components at relatively the same efficiency as the full system but at a reduced cost

Advantages of the DVO system result from the relatively simple configuration and an effort to reduce costly inputs through integration with the AD unit and other by-products produced throughout.

Commercial scale nutrient recovery process at Vander Haak Dairy in Lynden, WA

The **full system** works as follows:

- Digested effluent is subjected to Class A time/temperature treatment for improved pathogen destruction and production of higher value **fiber** with more consistent EC values
- Fiber is screened and processed into **high value peat** replacement
- Remaining effluent stream is sent through an aeration zone, where the combined attributes of higher temperature and higher pH allow for release of soluble **ammonia** to gaseous **ammonia**. The system requires no chemical inputs other than ambient air.
- A contact tower utilizes acid/gypsum to produce **ammonium sulfate**, which can be marketed either as a 8% N and 10% S organically certified solution or as a 21% N and 24% S organically certified solid
- Secondary screening and dissolved air flotation (DAF) processes separate out a significant fraction of suspended solids, which contains a significant proportion of the **phosphorus** from the effluent
- Remaining effluent is returned to neutral pH while assisting in **biogas scrubbing** (100% H_2S removal and partial CO_2 removal)

An option exists that utilizes a portion of the treated effluent as **dilution water** at the front end of the AD process—thereby **reducing fresh water** inputs as well as **reducing total wastewater production** requiring land disposal

Capabilities:

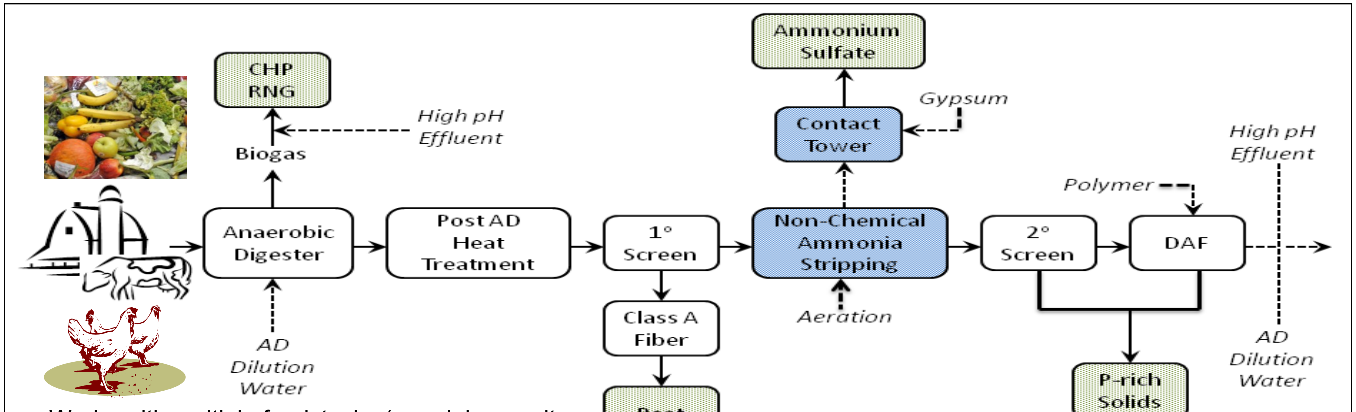
70–75% reduction in total solids (TS) and **93–97%** reduction in total suspended solids (TSS)

80–90% reduction in total phosphorus (TP)

The P-focused system has achieved **30–50%** total nitrogen (TN) removal, which can be recovered from the AD effluent. The full-system is capable of removing **70%** of ammonia-N, leading to a **65–75%** reduction of TN.

Full-scale tests show that **25–40%** of total potassium (TK) is recovered within the solids while total salts removal is even higher given the additional removal of ammonium, calcium, and magnesium

The DVO system is the **first commercial scale** nutrient recovery system in the U.S. and is currently operating at three dairies and one poultry farm.



Works with multiple feedstocks (e.g. dairy, poultry, food waste)

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The Rationale for Recovery of Phosphorus and Nitrogen from Dairy Manure

This factsheet explains the rationale for implementing emerging phosphorus and nitrogen nutrient recovery technologies on dairies, with particular focus on the Western U.S. Although dairy operations are emphasized, lessons learned are readily applicable to feedlot, swine, and poultry operations as well as other industrial and municipal organic solids and waste waters. The specific technology requirements will vary depending on the qualities of the waste streams being processed.

Manure Management and Environmental Issues in the United States

Each dairy cow annually generates liquid and solid manure that contains 15 lbs. phosphorus, 66 lbs. ammonia (a form of nitrogen), and 132 lbs. total nitrogen (ASAE 2005). Manure is expensive to transport so dairy manure is generally applied to nearby fields, sometimes leading to excess applications of phosphorus and/or nitrogen. The ongoing trend of increased numbers of dairy cows per farm in the U.S. (USDA-NASS, 2010) results in a concentration of manure, bedding and urine. This in turn increases the transport distances (and costs) required for appropriate land application of manure. In 2000 only 1% of large dairies (those with more than 1000 animal units) were applying phosphorus at agronomic rates, while only 23% were applying nitrogen at agronomic rates (Ribaudo et al. 2003). More recent data indicate that larger operations apply manure to cropland at rates that are more than three times higher than smaller farms, suggesting that excess nutrient applications are still an issue, particularly for large operations (MacDonald and McBride 2009).[1] This observation is also supported by a recent study of manure application to field corn (the receiving crop for more than half of all applied manure), which found that the vast majority of dairies applied to fewer acres than would be needed to meet best management practices for nutrient management (USDA ERS 2011).

Losses of phosphorus and nitrogen to the environment during manure management can contribute to a number of significant water and air quality concerns:

- **Phosphorus and Nitrogen Eutrophication.** Both phosphorus and nitrogen can be lost through runoff or infiltration and leaching at manure storage locations and field application sites, as well as through soil erosion. Losses increase substantially as nutrient application exceeds plant needs (Bock and Hergert 1991; Schlegel et al. 1996). Once lost from agricultural systems, phosphorus and nitrogen can migrate to lakes, rivers, estuaries, and coastal oceans. Overabundant nutrients can then lead to excessive growth of algae and aquatic weeds and subsequent oxygen shortages (Carpenter et al. 1998), fish toxicity (Ward et al. 2005), habitat loss (NRC 1993; Jeppesen et al. 1998) and decreased species diversity (Sutton et al. 1993).
- **Nitrate Pollution.** Infants under six months of age who ingest high levels of nitrates in the water supply can get blue baby syndrome, which can cause bluish skin, stupor, brain damage and in severe cases, death (US-EPA 1991).
- **Ammonia Volatilization.** An estimated 70% of total manure nitrogen is lost as ammonia during manure management and application on U.S. dairies and feedlots (CAST 2002).

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[1] Manure application intensities were calculated by reducing estimated inventories of animal units by the share of manure removed from the farm, and then dividing the adjusted inventories by the amount of acres receiving manure. Farms with 2,000 or more animal units had a manure application intensity of 4.8, while those with less than 300 animal units had a manure application intensity of 1.4 (MacDonald and McBride 2009).

Ammonia is highly reactive and contributes to the development of ultra-fine particulate matter (PM 2.5) in the atmosphere. PM 2.5 has detrimental effects on overall air quality and human and animal health (Erisman and Schaap 2004; McCubbin et al. 2002; Archibeque et al. 2007).

Greenhouse gas emissions are also a concern of current manure management practices. Dairy cattle create direct and indirect emissions of greenhouse gases throughout the production process, with over half generated by manure management (US-EPA 2013a).[2] There is significant variation due to the type of manure management system, with higher methane emissions from liquid manure management systems. These liquid manure systems are increasingly used in dairy operations (US-EPA 2013a), leading to recent increases in greenhouse gases associated with manure management. In total, manure management for dairy cattle in the U.S. contributed an estimated 46% of the greenhouse gas emissions associated with manure management for all livestock and poultry in 2011, or 0.48% of gross greenhouse gas emissions in the United States (US-EPA 2013a).[5]

Factors Contributing to Nutrient Overloading

Because P and N losses increase rapidly when these nutrients are land-applied in excess of plant needs, one strategy for minimizing losses of P and N to the environment is to ensure that manure applications do not provide more nutrients than can be taken up by the crops being grown on the

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[2] Emissions are commonly expressed using carbon dioxide equivalents (CO_2e), which indicates, for a given mixture and amount of greenhouse gas, the concentration of carbon dioxide that would cause the same global warming potential, when measured over a specified timescale (normally 100 years) Average emissions for dairy cows in the U.S. were estimated at 6.2 metric tonnes (MT) CO_2e/head/yr in 2011, with 3.2 MT CO_2e/head/yr specifically from manure management (US-EPA 2013a). These figures do not include N_2O emissions associated with grazing, nor indirect CO_2 emissions from fertilizer synthesis, diesel use, and transportation. 1 MT = 1 megagram (Mg) = 10^6 gram (g).

[5] This was an estimated 32.4 million metric tons[5] CO_2e. Carbon dioxide equivalents are explained in the previous footnote. 1 million metric tons = 1 Tg = 10^{12} g

land. However, there are many factors that can contribute to nutrient loading at higher than recommended levels despite the potential for negative environmental impacts:

- Expense of transporting manure to distant fields. This is particularly true for liquid manure, but also applies to “dry” manure, which contains significant moisture (Henry and Seagraves 1960; Ribaudo et al. 2003; Heathwaite et al. 2000);
- Reluctance to apply manure to food crops due to environmental and food safety concerns (Guan and Holley 2003), largely limiting the land base available for manure application to forage fields (USDA ERS 2009);
- Variability in the nutrient form and content of stored manure and the timing of nutrient availability to plants (especially for nitrogen) can lead producers to apply extra manure and/or supplement with inorganic fertilizer (Davis et al. 2002: Eghball et al. 2002; Power et al. 2001; Alva et al. 2005);
- The NPK ratio of manure may not match the ratio needed by crops, necessitating additional inorganic fertilizer for proper nutrient balance (Frear et al. 2012; USDA ERS 2009);
- Broadcasting application of manure, a widely used method, may encourage nutrient loss and runoff (USDA ERS 2009).
- Crop producers’ tendency to target nutrient application toward high-yield goals, rather than average yields (USDA ERS 2009), may result in over-application during years when conditions are average or below-average.

Water and Air Quality Issues in Dairy Regions of the Western U.S

Dairies in many regions of the Western U.S. are facing increasing pressure from growing public concern about nutrient-related water and air quality issues. In some cases regulation of dairies has increased as a result of these public concerns. High levels of phosphorus in the middle Snake River and in cropland soils are a concern in the Magic Valley of Idaho (IDEQ 1998; Leytem and Bjorneberg 2009). Nitrate issues and excess nitrogen in water have received increased attention and studies suggest that manure applications play a role in a number of areas including the Tulare Lake Basin and Salinas Valley of California (Viers et al. 2012), the Magic Valley of Idaho (Baldwin 2006), the Yakima Valley of Washington (US EPA 2012a), and the Abbotsford-Sumas aquifer along the U.S. Canadian border in Washington (Mitchell et al. 2005). Nitrogen eutrophication of surface water is an important concern in the Yakima Valley, particularly because the Middle Columbia River bull trout and the Middle Columbia steelhead (both listed under the Endangered Species Act) spawn or rear in this watershed. Air quality is a significant concern in the San Joaquin Valley, where air pollution exceeds the Federal standards for ultra-fine particulate matter (US EPA 2012b), and in the Yakima Valley, where meeting air quality standards remains an ongoing concern (Pruitt 2013).

Manure: Liability or Resource?

While most discussion of dairy manure focuses on negative environmental consequences, the nutrients and carbon in manure have important potential values. Many crop producers who use manure use less commercial fertilizer, and thus are impacted less from spikes in fertilizer prices (USDA ERS 2009). However, nutrients in manure are only valuable when there is a nearby market for those nutrients - and meanwhile, dairy producers have to utilize manure in a way that complies with stringent storage and application regulations that often specify loading rates and timing. This generates highly localized markets for manure with crop producers in some areas paying for manure while crop producers in other areas require dairies to pay them for accepting the manure. Manure management is thus a major consideration for dairy producers, with high potential costs in areas where there are few crop producers willing to accept manure (USDA ERS 2009).

Recovering, Concentrating, and Partitioning Nutrients from Manures

As a result of the increasing costs of nutrient management for dairy manure, increasing attention is being paid to the development of commercially viable nutrient recovery technologies. Although no technologies are widely commercialized at present, several nitrogen and phosphorus recovery technologies have recently emerged that have the potential to improve nutrient management on dairies. Some of these technologies are most appropriately used on specific forms of untreated dairy manure (e.g. scrape, flush), while others are more appropriate to be combined with anaerobic digestion (AD) as part of an AD system (Figure 1). Specific approaches also vary in that some recover both P and N (Figure 2), while others focus on only one nutrient (Figure 3).

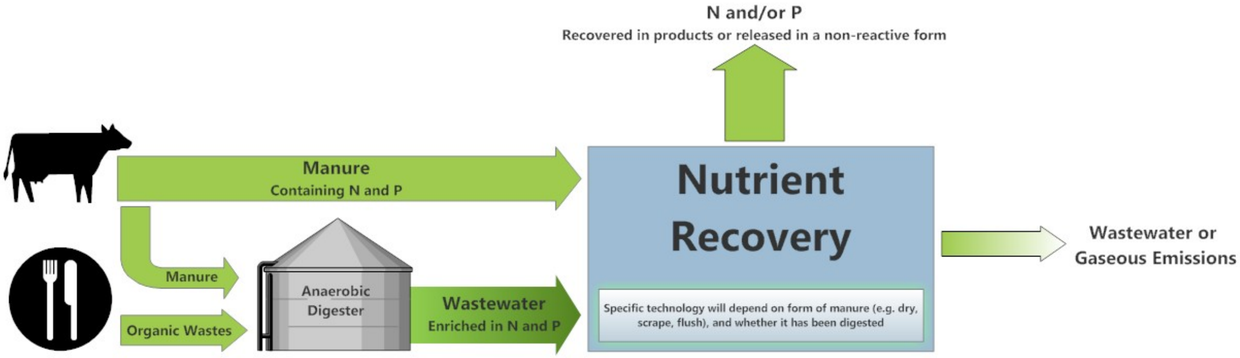

Figure 1. Generalized schematic of P and N nutrient recovery process. Figure credit: Nick Kennedy.

Figure 2. Commercial-scale P and N nutrient recovery facility integrated with dairy anaerobic digester, Lynden, WA (AD facility is not shown in photo).

Figure 3. Commercial-scale recovery of P solids, integrated with dairy anaerobic digester in Bio-Town, IN (AD facility is not shown in photo).

Each of these technologies has costs associated with installing, operating, and managing the system. The most promising of these technologies successfully minimize expenses or generate concentrated nutrient products that can be sold to offset costs. Because manure management is *already* a primary concern for dairy producers, a process that recovers nutrients and lessens the environmental and regulatory issues described above is likely to be appealing, even if the profits are not overwhelming.

Benefits and Challenges to Nutrient Recovery

Nutrient recovery has the potential to transform dairy nutrient management by reducing the amount of P and N in liquid and solid wastes. Some nutrient recovery processes "dispose" of these nutrients in a non-reactive form. For example, biological N recovery can transform ammonia or organic nitrogen into non-reactive nitrogen gas that can be released to the atmosphere without negative environmental impact. However, most nutrient recovery technologies produce concentrated nutrient products that can be more economically transported than manure. Such products include bio-ammonium sulfate solution (8:0:0:10(S)), phosphorus-rich solids (2:3:1 + micronutrients, dry weight) and phosphorus containing struvite crystals (6:29:0:10(Mg)) (Figure 4). In some cases, the nutrient recovery processes generate a product, which is more stable, homogenous and predictable than manure. This can make the products more appealing to crop producers, who can store them, better control application rates, and in some cases control application method (Figure 5). Blending of nutrient recovery products, with or without inorganic fertilizers, has the potential to produce products with desired NPK balances. Lastly, processing time for these nutrient products and (in some cases) exposure to high temperatures can diminish real and perceived environmental and food safety risks that lead some crop growers to avoid manures. Some nutrient recovery products, such as struvite and ammonium sulfate, are pathogen-inert chemicals.

Figure 4. Nutrient recovery products including (left to right) bio-ammonium sulfate solution, phosphorus-rich solids and phosphorus containing struvite crystals.

Figure 5. Preparing to apply bio-ammonium sulfate solution to fields.

However, in practice, most nutrient recovery products are not yet fully developed. Products from various technological processes are often heterogeneous, have inconsistent form, and may require further processing to dry or make product handling and application manageable (compare wet phosphorus solids in Figure 6 with the dry, homogenous struvite crystals in Figure 4, right). Products with diminished (but not eliminated) pathogen risks may still be unappealing to food crop producers. Further development of economical dewatering technologies and consistency of fertilizer form, function, and performance are needed. This will allow nutrient recovery to generate a consistent product that can be easily applied with crop producers' existing equipment.

Figure 6. Phosphorus-solids without drying or pelletizing.

In addition, markets for these products have not yet matured due to limited availability and unproven fertilizer efficacy. Additional research is needed to demonstrate these products' ability to meet specific growers' needs. Some products may be most appropriate in specialized situations, while others may be used more generally. For example, an ammonium sulfate solution will acidify soils, and therefore may be particularly useful to amend soil pH and maintain drip line irrigation systems in applications such as blueberry production. In contrast, struvite may be more widely used as a P source, because of its dry, granular form. Together, these steps could lead to market development and increased revenues adequate to provide cost-recovery for implementation of nutrient recovery processes.

In addition to the nutrient products, almost all P and N nutrient recovery processes leave a wastewater (Figure 1). If this wastewater is reduced in P or N, it may be less likely to exceed required nutrient regulations on nearby soils. However because it has less P and/or N, the NPK ratios are quite different than manure, with much higher ratios of potassium and other salts. Thus, it will be essential that cropland receiving the low-nutrient wastewater be effectively monitored for salt content. Changes in crop selection and rotation on dairy forage fields may be necessary to accommodate the distinctive characteristics of the nutrient-diluted wastewater.

The Role of Nutrient Recovery in Achieving Environmental Quality

Regulation has played an important role in nutrient management and undoubtedly will continue to do so. However, there are limits to the effectiveness of a purely regulatory approach. As Aillery and colleagues (2005) have pointed out, tighter regulation to protect water quality from nitrogen in manure applied to cropland has the potential to induce changes to manure management that reduce losses of N-nitrate by trading them for losses of N-ammonia (currently unregulated), with negative impacts to air quality. Implementing regulatory strategies for nutrient management without viable technology options to concentrate and export nitrogen from dairies will likely encourage further examples of this type of shifting.

Implementing nutrient recovery technology may become a cost-effective approach to improving nutrient management at a watershed level, through the replacement of imported chemical nutrients by crop farms with manure-derived nutrients already in the watershed. However, it is important to note that nutrients can still be lost from nutrient recovery products or from nutrient-diluted wastewater, especially if these are applied with improper application rates or timing. Nutrient recovery technologies need to be part of a comprehensive strategy at the watershed level to address issues of nutrient balance, equitable distribution of costs and benefits, and improved nutrient application timing and methodology.

Anaerobic Digestion and Nutrient Recovery

On its own, AD is not a nutrient recovery technology. The AD process creates an anaerobic environment (without oxygen) in which naturally occurring microorganisms convert complex organic materials in manure and other wet organic byproducts such as food processing wastes to biogas, a source of renewable energy (US-EPA 2006). The process also reduces greenhouse gas (GHG) emissions, decreases odors, stabilizes waste, and decreases pathogen counts (Martin and Roos 2007; US-EPA 2004; US-EPA 2005; US-EPA 2008). Although the process changes the form of nitrogen and phosphorus in manure, it does not appreciably decrease the total amount of nutrients, most of which are concentrated in the liquid effluent that is a product of the AD process (Frear et al. 2012).

An increasing number of dairies that practice AD have begun to import and co-digest food wastes along with manure in order to enhance biogas production and/or AD project profitability. However, this practice often exacerbates the existing nutrient management concern by increasing the import of nutrients to the dairy. In a study of co-digestion, Frear et al. (2012) showed that supplementing manure with 16% organic wastes by volume at a dairy in Washington State increased phosphorus and nitrogen 13 and 57%, respectively (Figure 7).[6]

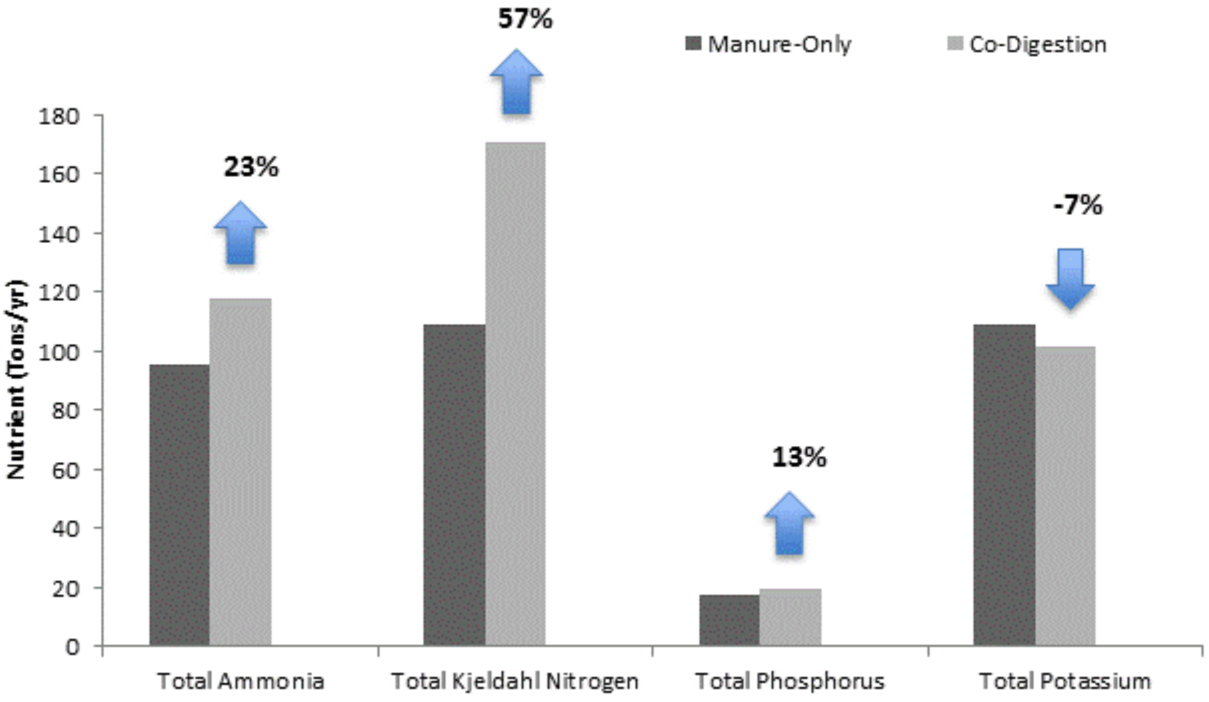

Figure 7. Modeled nutrient impacts of co-digestion with 16% organic wastes on a dairy in northwest Washington (Yorgey et al. 2011).

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[6] Co-digestion also produced a 110% increase in biogas and a tripling of gross revenues from anaerobic digestion, with 72% of all gross revenues directly attributable to outside organics digestion.

Anaerobic digestion creates unique opportunities for nutrient recovery (Figure 1). In addition to transforming nutrients from organic to inorganic forms, the AD process can assist in nutrient recovery by providing important process inputs such as heat, electricity and processing infrastructure. It also alters the effluent's ammonia and solids concentration, temperature and form of phosphorus (Frear et al. 2012). In return, the nutrient recovery process can assist the AD process by generating a combined system that can lessen dairy producers' nutrient concerns—something AD alone simply cannot do. Furthermore, potential income from the sale of recovered nutrients contributes to the economic feasibility of an AD project. Coppedge et al. (2012) showed that income from nutrient and fiber products can represent a substantial portion of a digester's gross revenue.

Nutrient recovery technologies also have the potential to stimulate adoption rates for AD. Adoption rates have been slow, with just over 150 digesters in operation on dairy farms in the U.S. as of May 2013, representing only 4% of dairy cows (US-EPA, 2013b; USDA ERS 2013). This number would need to increase considerably to meet the joint U.S. - dairy industry goal for the dairy industry to reduce its climate impact by 25% by the year 2020 (Innovation Center for U.S. Dairy 2011). Integrated nutrient recovery technologies have the potential to address one of producers' top concerns related to AD adoption, and thus may be more appealing than stand-alone AD technologies.

A combined AD-nutrient recovery system has greater capital and operating costs, but also (depending on the system) the potential to generate greater revenues and profits. This "add-on" nutrient recovery technology reflects an ongoing trend to use AD technologies as a "platform" for other technologies that work synergistically to provide operational and economic benefits. Refined natural gas is probably the most developed of these add-on technologies, and has been particularly important for improving project economics in regions with low electricity prices.

Conclusion

Current manure management strategies may not be adequate to meet the environmental challenges facing the dairy industry today. Technologies that recover, concentrate, and partition nutrients may contribute to a solution to these problems, in combination with improved regulatory structures, markets, and enhanced wastewater and fertilizer application management. Many of these nutrient recovery solutions work in concert with AD technologies, which provide additional benefits in the form of renewable energy and GHG emissions reductions.

These emerging nutrient recovery technologies are still under development, with particular effort being made to reduce costs and produce products that are easy to transport, store, and apply at chosen rates with chosen application methods. Pathogen risk reductions are also receiving ongoing attention. Together, these efforts aim to produce an economically viable option for nutrient management that makes sound business sense for dairy producers.

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