

# COMMERCIAL DEMONSTRATION OF NUTRIENT RECOVERY OF AMMONIUM SULFATE AND PHOSPHORUS RICH FINES FROM AD EFFLUENT

S. Dvorak, PE<sup>1</sup> and C. Frear, PHD<sup>2</sup>

<sup>1</sup>DVO Incorporated, Chilton WI

<sup>2</sup>Center for Sustaining Agriculture and Natural Resources, Washington State University

## INTRODUCTION

### Background

Anaerobic digestion (AD) is a treatment approach that mineralizes complex organic carbon into inorganic carbon in the form of biogas, diminishing odors/pathogens and stabilizing waste (US-EPA, 2008). Biogas can be used as a renewable energy, while AD also allows for reductions in methane (CH<sub>4</sub>) and overall greenhouse gas (GHG) release (US-EPA, 2011). As a result, there has been increasing interest in AD on animal feeding operations (AFOs) and on dairy farms in particular, with now over 150 dairy digesters in the U.S., providing an installed generating capacity of 38 MW, and GHG emission reductions of 1.1 MMT of CO<sub>2</sub>e/year (US-EPA, 2010). Presently, digesters serve less than 6 and 7% of potential dairy farms and cows, respectively (US-EPA, 2010). Barriers to adoption include intensive capital costs (~\$2,000/cow for 500-2,000 cow installation (Andgar, 2011)) and historically low received electrical prices, which combined, can produce low returns on investment (Bishop and Shumway, 2009). AD adoption is additionally hampered, as AD units are unable to resolve existing farm nutrient loading concerns (N and P are not gasified or reduced in liquid concentration during digestion).

Liquid manure is expensive to transport (Heathwaite et al., 2000) so manure is generally land applied to nearby fields. Long-term manure application on these lands has resulted in excess nitrogen (N) and phosphorus (P) accumulation; 36% and 55% of AFO dairies are in a state of N and P overload, respectively (USDA-APHIS, 2004). This has led to issues regarding ultimate fate of nutrients on these soils, in particular their ability to contribute to nitrate leaching, eutrophication, ammonia toxicity, and nitrite carcinogenesis (US-EPA, 1996). From an air quality perspective, AD with its partial conversion of organic N to ammonia, only potentially exacerbates existing concerns related to farm-based ammonia emissions; elevating levels of PM 2.5 (Archibeque et al, 2007). As a result, AFO and dairy owners identify nutrient issues as one of their most important concerns, one with potentially negative economic impacts (Bishop and Shumway, 2009). Meanwhile, much of the world's cropped farmland is nutrient-deficient, requiring fossil fuel based inorganic fertilizers: (1) whose production results in negative impacts to the climate (fossil fuel fertilizer results in 1.2% of global GHG emissions (IPCC, 2007)); (2) that have increased in price significantly during the last decade (USDA ERS, 2011); and (3) which in the case of P have finite worldwide resources (Cordell et al, 2009).

With an eye on improving overall economics, AD project developers are intensifying efforts to generate additional revenue through use and/or production of co-products. One approach that has been successful on many dairies is to accept off-farm organics and practice co-digestion, generating tipping fees for received material and producing additional biogas (Frear et al., 2012). Frear et al. (2012) showed that biogas production could be doubled and total revenues tripled by incorporating off-farm organics at a rate of 20% of the volumetric manure flow. When off-farm organics are from local sources, considerable GHG mitigation can occur via their diversion from long-distance hauls to CH<sub>4</sub>-releasing landfills (Murphy and McKeogh, 2004). However, co-digestion alone is insufficient to enhance adoption rates and GHG mitigation on AFOs, as co-digestion exacerbates nutrient loading concerns. Frear et al. (2012) showed that even limited co-digestion caused 60 and 10% increases in on-farm N and P, in one case study. It is imperative then from the perspective of AD adoption as well as environmental stewardship to incorporate nutrient recovery alongside AD, if technology improvements and new economic markets can warrant such a business approach

## Review of Nutrient Recovery Approaches

### *Phosphorus*

Studies have demonstrated that more than 80% of P in dairy AD effluent is insoluble, presenting itself as suspended colloidal particles that are difficult, especially economically, to remove through approaches that assume either its soluble nature or ability to easily be settled/separated (Gungor and Karthikeyan, 2008a; Pastor *et al.*, 2010). Several other studies on P extraction show that the particulates are predominantly Ca-P and/or Mg-P (Chapuis-Lardy *et al.*, 2004; Gungor and Karthikeyan, 2005a; Zhang *et al.*, 2008) that result from the high Ca:P molar ratio (1.66-2.43) of a dairy cow's diet (Gungor and Karthikeyan, 2008b). Biological P removal needs readily biodegradable carbon (Tchobanogolous, 2003), which is not available after effective AD treatment. Struvite crystallization, often touted as a viable mechanism for simultaneous ammonia and P removal is significantly hampered by this chemical structure, as crystallization requires the presence of free phosphate, which in this case is only available through costly acid/chemical pre-treatment (Zhang *et al.*, 2008). Chemical and polymer coagulation can significantly increase the size of these particles and therefore induce settling, reaching P removal efficiencies as high as 80%, however their operating costs, based on high chemical inputs, raise concerns on economic viability (Frear *et al.*, 2012). Conversely, simple gravity settling or use of screens and/or decanting centrifuges, while representing technical solutions with vastly reduced operating costs, are, due to the small size of the particles, only partly successful (10-50% TP removal) at removing P and simply do not meet the intense reduction efficiencies needed by dairy CAFOs for attainment of their nutrient management plans.

### *Nitrogen*

N recovery, whether from animal manure or from animal-manure AD effluent, poses a few problems. As such, to date, few N removal/recovery technologies have been applied at a commercial scale on operating AFOs, with or without AD. In the U.S. barriers include farm economics and the high solids concentration within manure

wastewaters, which preclude the use of the technologies commonly used in industrial and municipal wastewater settings. Thus, any existing or new technology developed for farm use must be able to simplify the recovery operation and minimize costs while also economically managing the solids. As discussed in the previous chapter, solids removal is intimately linked with P recovery. Therefore, N recovery should be combined with P recovery, allowing for mitigation of two nutrient concerns in one combined technology. Lastly, from both an economic and sustainability standpoint, recovered products must have a valued market so that farmers can offset capital and operating expenditures.

Biological ammonia removal technologies exist, however, the high concentration of ammonia and solids in the animal manure AD effluent make it difficult for biological treatment. Although conventional nitrification and denitrification can be applied to animal wastewater for N removal without AD (Choi et al., 2005; Tilche et al., 2001; Vanotti, 2005), it becomes problematic to work with AD effluent because of insufficient biodegradable carbon. A recently developed process, “anammox” does not need biodegradable carbon for N removal (Mulder et al., 1995), but anammox bacteria’s slow growth rate (Strous et al., 1999) makes it easily out-competed by other organisms, leading to poor kinetics and performance alongside process instability. Other researchers (Bolan et al., 2004; Bonmatí and Flotats, 2003; Guo et al., 2008; Liao et al., 1995; Vanotti, 2005) have opted for physical-chemical processes for N removal, including ion exchange and ammonia stripping. Ion exchange can be excluded for AD applications because it requires low solids concentrations (< 1%), which are unattainable even with effective prior solids/P removal technology implementation. However, ammonia stripping has some potential, as shown through studies on landfill leachate (Cheung et al., 1997), digester supernatant of a municipal wastewater treatment plant (Katehis et al., 1998), and digester supernatant from slaughterhouse waste (Siegrist et al., 2005). It tolerates a certain level of solids, has low energy requirements and involves relatively simple and low capital cost equipment. Ammonia stripping has already been successfully applied to municipal wastewater AD supernatant landfill leachate, and industrial wastewater at commercial scale (Janus and vanderRoest, 1997; Meyer and Wilderer, 2004; Thorndahl, 1993). It was also successfully tested under laboratory conditions for swine manure wastewater (Bonmatí and Flotats, 2003; Liao et al., 1995) and digested dilute dairy manure supernatant (Zeng et al., 2005; Zeng et al., 2006). In addition, ammonia stripping can be easily integrated with acid absorption to recover ammonia as N fertilizer. Although ammonia stripping has proven to be technically feasible for digested dairy manure, its economic feasibility has not been studied, nor has it been studied at scale utilizing concentrated scrape manure.

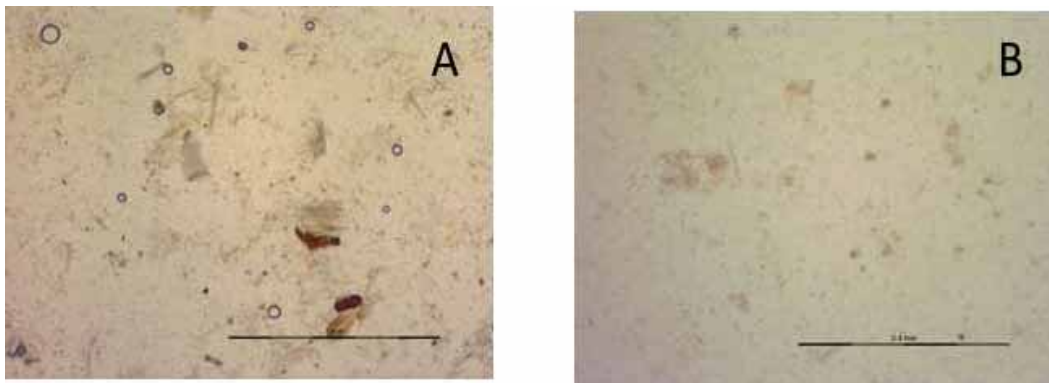
Although a strong potential candidate for economical recovery of N from dairy farms, ammonia stripping is not without its concerns. First, effective performance is highly dependent on temperature (US-EPA, 2000); however, the mesophilic (35°C) or thermophilic temperatures (55°C) of AD effluent can be used to overcome this concern. More problematic is the fact that, in order to strip ammonia from a wastewater, ammonia in its ionic form, must first become liberated as free ammonia. The ionic/free ammonia equilibrium is dependent upon pH with increases in pH (9.5-11) favoring the free ammonia form. AD effluent with its high alkalinity requires extensive input of chemicals

to raise the pH, thereby adding high chemical and economic costs to the process. Additionally, the traditional tower approaches used by the stripping industry are susceptible to clogging by the manure solids.

### NOVEL NUTRIENT RECOVERY APPROACH

In an attempt to look at the NR problem from a new angle, the project team developed a working hypothesis that settling of the aforementioned suspended P-solids was less a problem of charge and need of coagulants and polymers, but more a problem of super-saturated gases which interfere with the natural flocculation and settling process. During AD significant amounts of CO<sub>2</sub> produced during the biological process can become dissolved and/or super-saturated within the effluent.

Figure 1: Microscope images of AD manure effluent with (a) micro-bubbles of gas present and evolving and (b) without gas present after aeration treatment



This is particularly true of CO<sub>2</sub>, which is stored within the liquid effluent as aqueous CO<sub>2</sub>, bicarbonates and carbonates. Upon release from the digester, changes in temperature, pressure, pH, air and agitation can lead to a release of these super-saturated gases (Battistoni et al., 1997; Cecchi et al., 1994). As the CO<sub>2</sub> partial pressure in air is much lower than that inside a digester, a hypothesis was proposed that aeration would remove the super-saturated CO<sub>2</sub> and enhance P removal. Figure 1a shows an image of micro-bubbles within liquid AD effluent, showing that these bubbles occur in numbers high enough to disrupt attractive forces with the buoyant forces and micro-turbulence they induce. As per the hypothesis, during aeration, supersaturated CO<sub>2</sub> released from liquid to gas phase (Figure 1b). In addition, analysis of chemical equilibriums shows that as aeration releases the gaseous CO<sub>2</sub>, reactions move towards the right, generating more OH<sup>-</sup> and raising the pH of the solution, especially with elevated solution temperature (Figure 2; Figure 3a). Subsequent testing of this high temperature aeration process verified that the stripping of the CO<sub>2</sub> and corresponding elevation in pH also allowed for enhanced ammonia stripping and P-settling without chemical addition (Figure 3bc; Figure 4). Thus, aeration treatment not only leads to the desired P-settling but also N removal through the stripping and assumed recovery of the ammonia—yielding an integrated NR process with vastly reduced chemical inputs.

Figure 2: Chemical equilibrium associated with aeration process

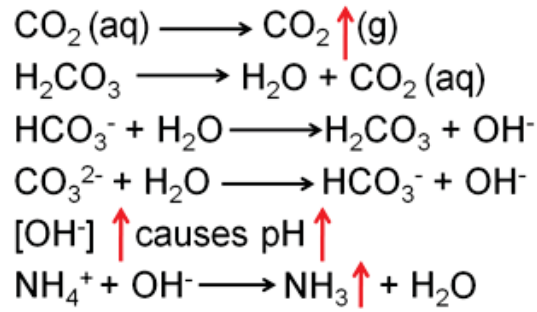


Figure 3: Effect of aeration/temperature on (a) pH, (b) NH<sub>3</sub> removal, and (c) TP removal

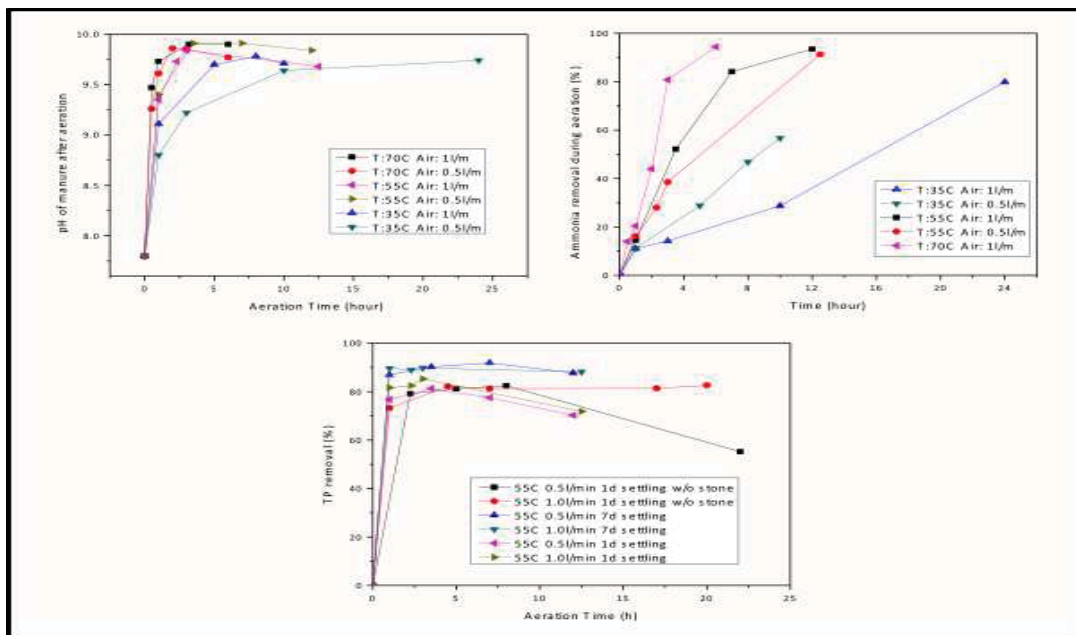
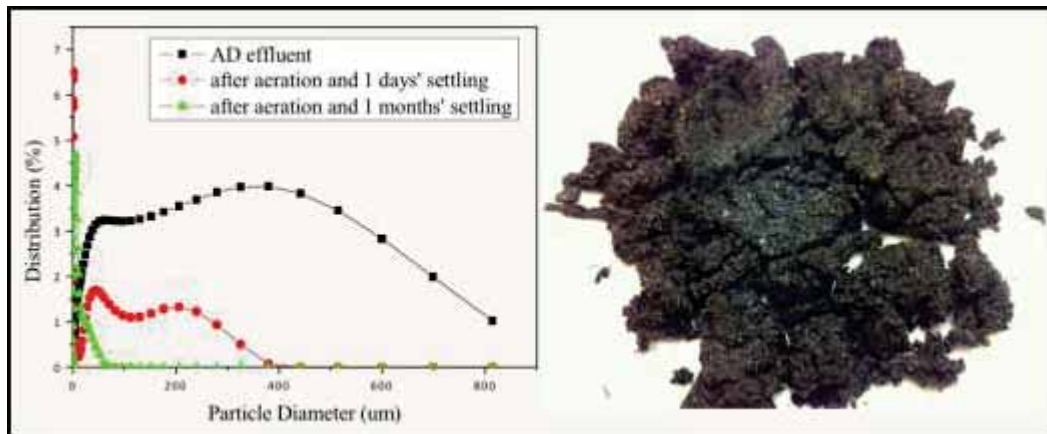


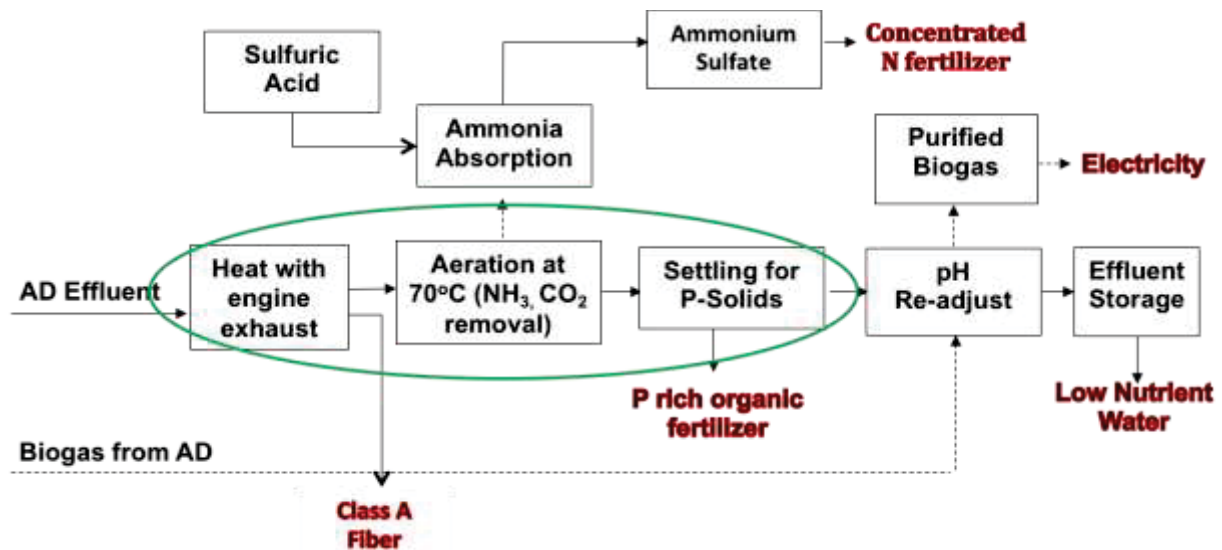
Figure 4: (a) Ability for aeration/settling to more effectively settle solids and P as compared to no aeration; (b) settled P-solids removed from settling weirs





Evolving from the base research discussed above is a novel system approach to both ammonia and P-solids recovery from digested effluent (Figure 5). Waste engine heat from the AD engine/generator sets is used to raise the temperature to 55-70°C for the necessary time duration to meet EPA Class A solids standards, thereby producing a more valuable and highly controlled pathogen-reduced fiber for bedding or off-farm sales as well as the necessary temperature to induce efficient aeration and degassing of super-saturated CO<sub>2</sub> and release of free ammonia. After aeration, the treated effluent is sent to a quiescent zone to allow for settling and removal of P-solids in a weir system. Stripped ammonia is then sent to an acid contact tower to convert the gaseous ammonia to ammonium sulfate solution (~35% concentration). An additional step still under development and evaluation is using the final effluent, still with a relatively high pH, as a media for scrubbing of biogas impurities, particularly H<sub>2</sub>S.

Figure 5: Second iteration, patented, and commercial approach to economic recovery of nutrients from an AD associated NR system



#### PILOT TESTING AND ECONOMIC ASSUMPTIONS

Batch trials using 5,000-gallon systems were completed at dairies in Wisconsin and Indiana (Figure 6) while evaluation of aeration and settling performance was evaluated at a dairy in Idaho. During the pilot-operation, the following unit operations and conditions were followed (inputs are in *italics* and products are in **bold**):

- 100°F AD effluent from an existing commercial AD unit was heated to 160°F using an *extended engine exhaust heat recovery system* to further heat treat the effluent and its fibrous solids to Class A pathogen standards.
- The **Class-A fibrous solids** were removed through mechanical screen separation using an inclined screen with screw press, while the remaining liquid with suspended solids was sent to an aeration zone for further treatment at operating temperatures of approximately 140°F.

- *Aeration* occurred in a dedicated plug-flow tank with a variable 10-20 hour retention time. Aeration was accomplished through the use of micro-aerators placed at the bottom of the tank to supply various degrees of aeration flow per gallon of treated effluent. Air was heated to temperature using *engine exhaust heat* sent through an air-to-air heat exchanger. As described before, the aeration allowed for the stripping of super-saturated CO<sub>2</sub> gas. High temperature enhanced the process, allowing for a more rapid release of the CO<sub>2</sub> and two important results. First the pH is increased and second gases, which interfere with natural settling were removed.
- The increase in pH (>9.5) allowed for a portion of dissolved ammonia to shift its equilibrium towards free, gaseous ammonia and enter the air stream leaving the chamber which was then piped to a dedicated two-stage acid tower where controlled amounts of *sulfuric acid* made contact with the ammonia in the air and produced dissolved **ammonia sulfate salt bio-fertilizer**. The two-tower approach was conceived so that a neutral pH product with consistent maximum concentration (~35% by weight) could be achieved.
- After return of the effluent to a quiet, settling zone, **phosphorous-rich solids** were then gravity settled and collected using dewatering weirs.

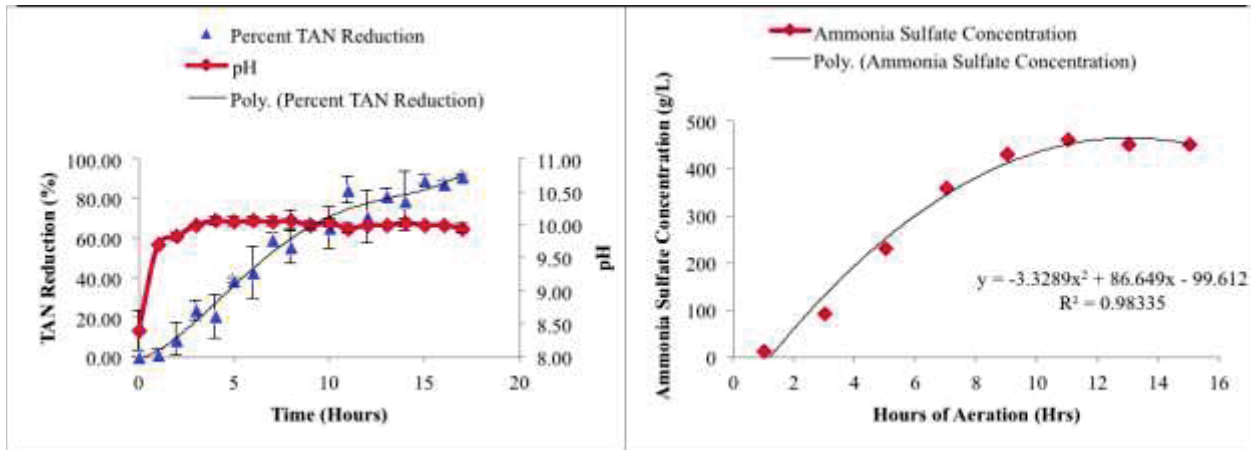
Figure 6: Batch testing of (a) aeration system and (b) two-tower acid contact system



Results of the testing at optimal aeration flow rates (micro-aerators, 20 gallons/cfm, and 55°C) are as described in Figure 7. While laboratory tests showed more ready stripping of ammonia, pilot-tests showed the need for considerably longer retention times, most likely due to lower operating temperatures (limited availability of waste heat energy and losses of heat due to mechanical separation of fibrous solids) and lower mass-transfer due to mixing limitations at larger scale (foaming). Results did determine a feasible temperature and aeration rate that minimized energy inputs and controlled foaming while still stripping ammonia in a reasonable retention time. At the aforementioned optimized parameters, nearly 80% of TAN was stripped during a 15-hour operation due to a consistent capability to raise the pH at or near 10.0. The two

tower acid contact system, once equilibrium at maximum solubility was attained, produced a consistent 35% by mass ammonia sulfate solution with pH at neutral.

Figure 7: Performance capabilities of ammonia stripping and ammonia sulfate production systems at optimized conditions during testing



The ability of aeration to settle P-solids was evaluated using only limited aeration (~40 gallons/cfm and temperature (20-35°C) and results are summarized in Table 1. As can be seen from the figure, limited aeration and temperature can keep capital and operating costs down while also retaining most of the ammonia and removing significant percentages of P from the effluent. No aeration resulted in a baseline of 40% P removal using the sequence of primary, secondary screening followed by extended weir settling while addition of 6 and 24 hours aeration resulted in 65 and 80% removal, respectively. Notably then, the system can be operated as a P-recovery system alone or as a combined system with more enhanced aeration and temperature yielding even higher P removal efficiencies.

### COMMERCIAL DEMONSTRATION—DAIRY WITH CO-DIGESTION

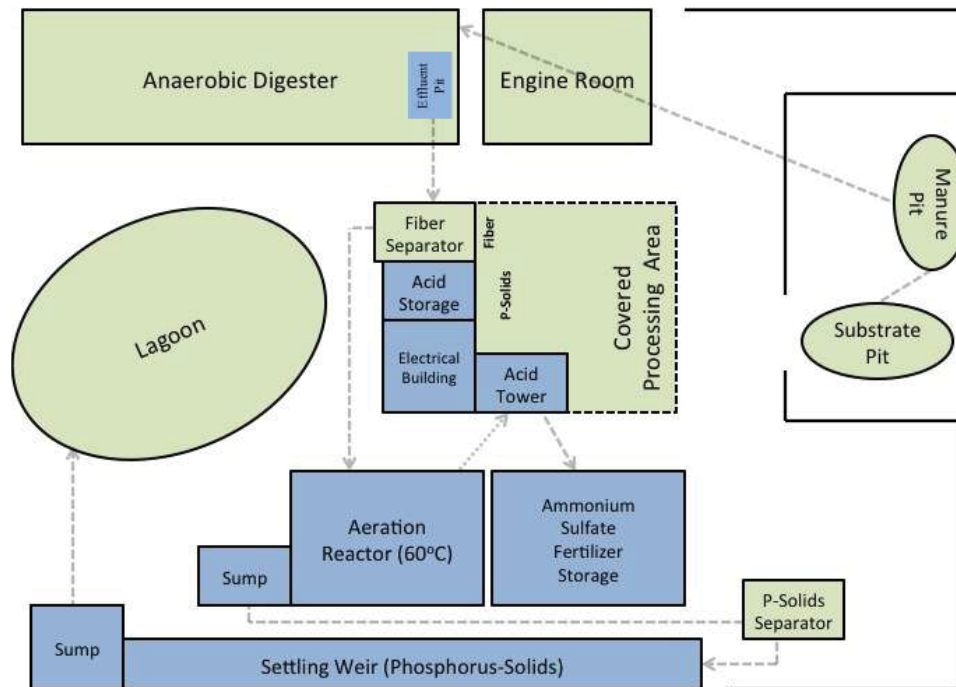
After pilot evaluations were completed, design and funding were completed for demonstration of a continuous flow system at commercial scale on a Washington dairy practicing co-digestion with their dairy manure using a DVO mixed plug-flow digester. The flow rate for this farm and digester is 40,000 gallons/day. Funding for the capital construction, evaluation and performance report are provided by USDA NRCS CIG and DOE ARRA grant funds with industry and producer match. Figure 8 is a schematic for the overall design of the system while Figure 9 is an overhead image of the actual completed construction.



Table 1: Limited aeration and temperature settling of P-solids

	TS (%)	VS (%)	TKN (g/L)	TAN (G/L)	TP (mg/L)
<b>Effluent Pit Only Aeration Experiment</b>					
Manure Effluent w/Fiber	5.15	3.28	4.03	2.61	564.53
Six hours of aeration at 35C and 40 gal/cfm	4.32	2.65	4.23	2.58	613.48
Post fiber separation	4.33	2.45	3.78	2.63	593.90
1 day settling	2.51	1.38	3.18	2.46	231.69
2 days settling	2.43	1.32	3.18	2.42	199.06
3 days settling	2.41	1.29	3.18	2.38	199.06
<b>Beginning to End Reduction (%)</b>	<b>53.20</b>	<b>60.67</b>	<b>21.09</b>	<b>8.81</b>	<b>64.74</b>
<b>Effluent Pit + Extra Aeration Experiment</b>					
Manure Effluent w/Fiber	5.15	3.28	4.03	2.61	564.53
Six hours of aeration at 40 gal/cfm	5.37	3.41	4.09	2.65	587.38
Post fiber separation	4.47	2.49	3.87	2.64	600.43
Add 18 hrs aeration at 20C and 40 gal/cfm	4.37	2.48	3.71	2.48	580.85
1 day settling	2.27	1.21	3.01	2.23	133.79
2 days settling	2.24	1.17	2.94	2.23	124.00
3 days settling	2.19	1.14	2.92	2.22	114.21
<b>Beginning to End Reduction (%)</b>	<b>57.48</b>	<b>65.24</b>	<b>27.54</b>	<b>14.94</b>	<b>79.77</b>

Figure 8: Schematic of NR system at co-digestion dairy (Green is existing AD systems while blue is new NR systems)



From Figure 8 you can see that as earlier described during description of the NR approach, manure and substrates leave their respective pits for entry to the digester. Digester effluent leaves the gas-tight vessel through a weir wall and enters an effluent pit that was retrofitted with heat exchangers to elevate the temperature of the manure for subsequent aeration and Class-A treatment. The effluent is then sent to a primary

screen separator and dewatering auger for production of fiber product while the remaining effluent is sent to the aeration pit for micro-aeration and subsequent removal of CO<sub>2</sub>, rise of pH and stripping of ammonia gas. The aeration pit is designed to be a plug-flow reactor capable of aeration (micro-aerators) and temperature (~50-60C) equivalent to pilot studies using an HRT of 17 hours. Aerated effluent with foam exits the aeration reactor and enters a sump house where continuous de-foaming is accomplished using recycled effluent and spray-bars. Resulting gases exit the sump house through a hood and ducting system for entry into an acid tower. Acid is continuously pumped into the acid chamber for contact with ammonia via control of automated pH meters. Resulting ammonium sulfate solution overflows and is sent to storage tanks while treated exhaust is run through an air-to-air heat exchanger to warm input air to the aeration reactor. Effluent leaving the sump house is sent to a 2-day settling weir for settling of P-solids. An additional micro-screen is operated in a continuous loop allowing for large solids at the bottom of the weir to be removed and dewatered while small solids (primary P containing solids) that are not captured by the micro-screen return to the settled bottom of the weir for periodic removal and natural dewatering. Finally, effluent leaving the weir is sent to a large lagoon for storage until field application is allowed.

Figure 9: Image of completed system



Figure 10 is a collage of system products. Four products are produced by the system with moisture level and NPK dry values in parentheses (preliminary results): (1) Class-A fiber (74%; 1.4:0.6:0.8); (2) Fine Solids (80%; 2.5:0.8:0.8); (3) P-solids (70%; 2.2:2:1.5); and (4) Ammonium Sulfate Solution (65%; 8:0:0:10(S)).

Figure 10: NR products: (A) three solids, P-solids, Fine-solids, Fiber-solids clockwise from left; (B) 35% solution of ammonium sulfate and (C) first application of ammonium sulfate to fields



Tentative economics based on pilot scale results and demonstration system design is summarized in Table 2. From the table you can see that the system is designed to try to offset recovery costs as opposed to yielding significant profits although as markets mature and fertilizer prices potentially continue to rise, this scenario could change. For now though the system primarily uses AD outputs to more efficiently meet producer nutrient management needs and in turn the more robust system in terms of producer needs could lead to enhanced AD adoption, especially in the face of future potential more stringent nutrient regulations. Since completion of the commercial demonstration was delayed, resulting in a completed system not until late winter 2011, an updated economic evaluation has not been completed due to continued system troubleshooting. Updated economics as well as performance indicators are anticipated for this late spring and summer with some information hopefully available for the oral presentation later in the month.

Table 2: Tentative NR economics

Costs (\$/cow yr)		Revenues (\$/cow yr)	
<i>Electrical Power</i> : (Electrical purchase of 5¢/kwh; aeration rate of 20 gallons/cfm; power need of 20 cfm/hp; 1.2x for other electrical)	\$29.78	<i>AS Slurry</i> : (35% AS by weight; 0.25% influent concentration of NH <sub>3</sub> ; 80% NH <sub>3</sub> recovery; 3.9 lbs AS: 1 lb NH <sub>3</sub> ; \$80/ton slurry; \$200/ton AS)	\$69.00
<i>Sulfuric Acid</i> : (\$175/ton conc. acid; 2.9 lbs of Acid: 1 lb NH <sub>3</sub> recovered)	\$56.58	<i>P-rich Solids</i> : (\$175/dry ton at 3:1.5:3 NPK; 50% TS; 3.5 wet lbs/cow day)	\$55.89
<i>Labor</i> : (0.5 FTE salaried position with salary of \$40K/yr; 2,000 cow farm)	\$10.00	<i>Credits</i> : (Nutrient Trading; carbon; RECs—assumed zero for now)	\$0.00
<i>O&amp;M</i> : (2% of capital costs at \$600/cow NR only)	\$12.00	<i>Offset Savings</i> : (Reduction in engine oil with H <sub>2</sub> S reduction—zero now)	\$0.00
<b>Total</b>	<b>\$108.36</b>	<b>Total</b>	<b>\$124.89</b>

As stated earlier, the system is presently undergoing extensive troubleshooting and beta testing. Demonstration goals still hold at producing a final effluent that has 70% removal of ammonia, 80% removal of P and 50% total N as compared to values entering the digester. A partial list of particular concerns and lessons learned from the commercial demonstration are as follows, with undoubtedly more to follow as operation continues:

- Overall noise control
- Identification of optimal pumps, blowers, screens, etc. for conditions experienced
- Tuning of system to farm operations/sequences and vice versa
- Acid handling, storage, supply, pumping
- Acid tower operation, product quality, storage
- Product and solids dewatering, recovery and marketing
- Catalogue of regulations/permits
- Ammonia stripping operating parameters shifts under continuous flow
- Foam control

Field days, conference papers, extension papers, videos, webinars, marketing information, and techno-economic and performance evaluation report are envisioned for late summer, early fall of 2012.

## COMMERCIAL DEMONSTRATION—EGG LAYER MANURE

### Concerns Applying AD to Caged Layer Poultry Manure

*The problem* facing the US caged layer poultry industry and its 400+ larger CAFO-sized farms is how to annually treat 4 million tons of wet manure in a manner which responds to emerging needs in renewable energy, air/water quality improvements, and establishing new revenue streams for enhanced farm sustainability. However, next generation technology options allowing for production of renewable energy, such as gasification and anaerobic digestion (AD) have technical concerns, as applied to caged layer manure. Gasification, while suited well for dry broiler litter operations (80% solids), is poorly positioned for much wetter caged layer manure (25% solids) while AD has historically not been identified as a suitable technology for poultry manure because of its



inability to handle the higher solid content and biologically-inhibitory levels of ammonia. While digested effluent could be returned back to the front of the digester for use as grey dilution water as a means to reduce fresh water inputs, research at Washington State University (WSU) has shown that layer manure TAN levels are significantly higher than microbial thresholds and these levels become increasingly and dangerously high as AD effluent is used as reclaim water—leading to a steady decline in biogas performance with increased ammonia and use of reclaim water, especially when TAN levels exceed 4 g/L (Figure 11).

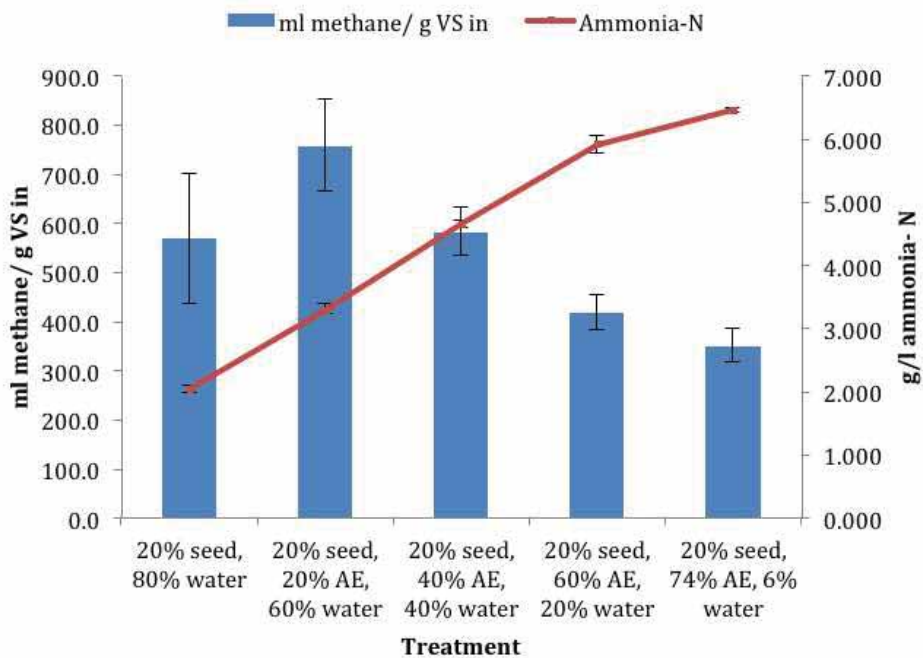
Caged poultry manure with 25% TS requires an input of dilution water in order to supply a wastewater material suitable for operation within commercially available AD technologies. On-farm, manure-based AD units within the US have traditionally used complete-mix (various European or US designs) or mixed plug-flow (DVO Inc., Chilton, WI) technology, with both technologies ideally supporting influents with TS content on the order of 4-12% (US-EPA, 2006). With caged-layer manure arriving from the belt press with TS of 25% it is clear that effective performance of the digesters require more than a 1:1 dilution with water, and at the scale of 600,000 layers for an average operation, that amounts to more than 180,000 gallons of dilution water per day—a sum that is simply not sustainable or economic, particularly in water threatened regions of the US. *The conclusion, then, is that, in order for effective AD of caged layer manure to occur, an alternative to fresh water for dilution is required and that source is the AD effluent itself, which with treatment can be used as reclaim water.*

AD effluent as source of reclaim water is viable, but only upon treatment and preparation. Since typical AD manure systems result on the order of 30-40% TS destruction, a system with influent of 11% TS leads to effluent with a 7% TS. Re-use of 7% TS effluent as dilution water makes poor engineering sense as every percentage point of solids that is re-introduced to the front of the digester results in the need for more reclaim water to attain the desired working TS flow rate. From a biological sense, the operation is non-optimal as well, as the non-digested solids are for the most part inert or recalcitrant in nature, which would lead to little further degradation upon extended digestion, thereby filling a fraction of the digester volume with non-reactive, non-biogas producing material. Fortunately, research and commercial demonstration have already shown that industrial separation of a significant portion of the solids can be accomplished (DVO, 2009). While, utilization of industrial separators to accomplish this requires additional capital and operating input, not to mention, parasitic use of produced electricity, it does serve to accomplish two very important goals. First, the effluent liquid to be used as reclaim water can be brought to a more desirable TS content on the order of 2% TS. Importantly, the remaining solids are suspended solids, which supply both nutrients and some biodegradable material to the digester while minimizing the volumetric impact to the digester. Of equal importance is research that shows during the digestion process, a significant portion of the organic phosphorus is converted to inorganic form and when in the presence of high Mg and Ca content manures, is chemically converted to phosphates bound as amorphous micro-solid salts (Gungor and Karthikeyan, 2008; Zhang et al., 2008). Thus, decanting centrifuge of the solids within

the effluent serves as a recovery mechanism and concentrator for P in the form of saleable organic solids (Frear et al, 2010).

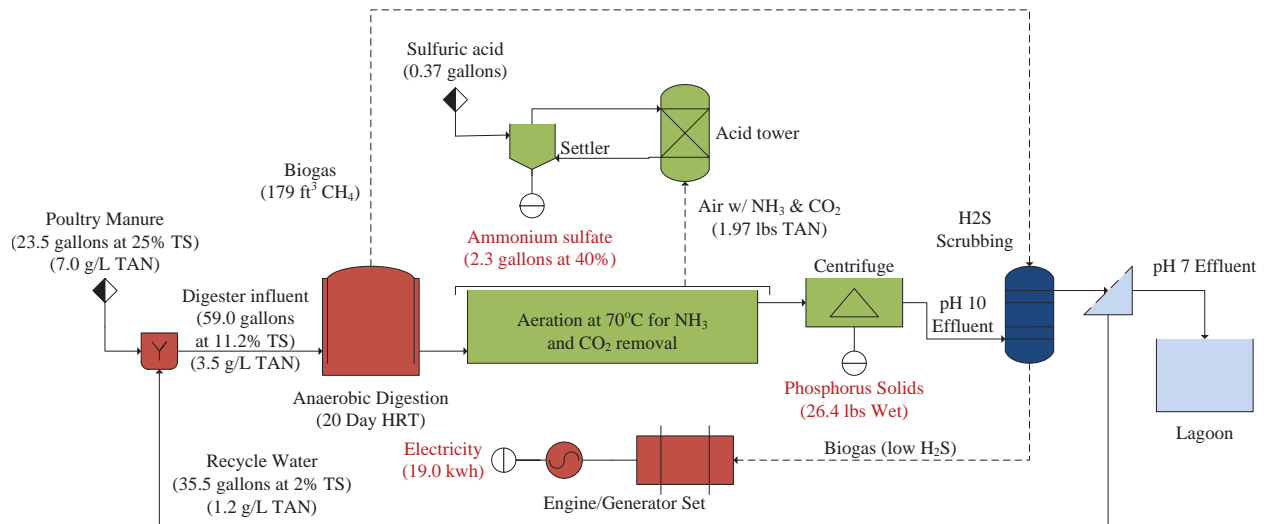
While removal of solids allows for improved utilization of AD effluent as reclaim water, it does not solve an important concern regarding retention of soluble ammonia and the inhibition that it contributes to the AD process. Ammonia inhibition has been extensively studied during the AD of poultry manure, with results showing that poultry manure has levels of total ammonia nitrogen (TAN) (Itodo and Awulu 1999; Bujoczek, Oleszkiewicz et al. 2000) at times, well above levels of threshold inhibition identified as at or above 2 g/L TAN (Koster and Lettinga, 1984). Although microbial communities can adapt to higher concentrations of sustained ammonia (Frear et al, 2010; Abouelenien et al, 2009), research at Washington State University (WSU) has shown that (1) layer manure TAN levels are significantly higher than the threshold, (2) levels become increasingly and dangerously high as AD effluent is used as reclaim water, and (3) biogas performance steadily declines with increased ammonia and use of reclaim water, especially when TAN levels exceed 4 g/L (Figure 11).

Figure 11: Methane production as factor of TAN concentration and use of AD effluent as reclaim water (i.e. 20:20:60 AE:W refers to 20% seed and 20% AD effluent mixed with 60% fresh water as source of reclaim water during digestion)



An opportunity lies in demonstrating that existing commercial AD units can be effectively and economically operated using caged layer manure IF the digester effluent is treated with a unique nutrient recovery and reclaim water system so as to overcome existing concerns with ammonia inhibition and intensive water usage needed for solids dilution (Figure 12).

Figure 12: Schematic of integration of *nutrient recovery/reclaimed water system* into poultry manure digester and farm (1,000 head/day flow rate)



Fortunately a demonstration commercial digester already exists at Wenning Poultry Farm in Fort Recovery Ohio (1 million layers), but one which is somewhat underperforming due to ammonia concerns discussed above. Industry, producer and grant funding have been made available to evaluate the NR system and its water recovery system at demonstration commercial scale. Design has been completed and as of this paper, construction has begun with a completion date and subsequent beta testing planned for late March 2012. It is hoped that oral presentation later this month can supply construction photos and an update on project completion.

## REFERENCES

- Abouelenien, F., Nakashimada, Y., Nishio, N., (2009). Dry mesophilic fermentation of chicken manure for production of methane by repeated batch culture, *J. Biosci. Bioeng.*, 107, 293–295.
- Andgar, (2011). Average digester capital cost per cow, Ferndale, WA.
- Archibeque S. L., Miller D. N., Freetly H. C., Berry E. D., Ferrell C. L. (2007) The influence of oscillating dietary protein concentrations on finishing cattle. I. Feedlot performance and odorous compound production. *Journal of Animal Science* (2007), 85(6), 1487-95.
- Battistoni, P., Fava, G., Pavan, P., Musacco, A., Cecchi, F., (1997). Phosphate removal in anaerobic liquors by struvite crystallization without addition of chemicals: preliminary results. *Water Research*, 31, 2925-2929
- Bishop, C. and Shumway, C.R., (2009). The economics of dairy anaerobic digestion with co-product marketing *Review of Agricultural Economics*, 31(3) 394-410.
- Bolan, N.S., Wong, L., Adriano, D.C., 2004. Nutrient removal from farm effluents. *Bioresource Technology*, 94, 251-260.

- Bonmatí, A. & X. Flotats (2003) Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion. *Waste Management*, **23**(3), 261-272.
- Bujoczek, G., J. Oleszkiewicz, et al. (2000). High solid anaerobic digestion of chicken manure, *Journal of Agricultural Engineering Research* 76(1): 51-60.
- Cecchi, F., Battistoni, P., Pavan, P., Fava, G., Mata-Alvarez, J., (1994). Anaerobic digestion of OFMSW (organic fraction of municipal solid waste) and BNR (biological nutrient removal) processes: A possible integration - preliminary results. *Water Science and Technology*, 30, 65-72.
- Chapuis-Lardy, L., Fiorini, J., Toth, J. and Dou, Z. (2004). Phosphorus concentration and solubility in dairy feces: Variability and affecting factors. *Journal of Dairy Science*, **87**(12), 4334-4341.
- Chellam, S., Bagga, A. and Clifford, D. A. (2008). Evaluation of iron chemical coagulation and electrocoagulation pretreatment for surface water microfiltration. *Journal of Membrane Science*, **309**(1-2), 82-93.
- Cheung, K. C., L. M. Chu & M. H. Wong (1997) Ammonia stripping as a pretreatment for landfill leachate. *Water Air and Soil Pollution*, **94**(1-2), 209-221.
- Choi, E., D. Kim, Y. Eum, Z. Yun & K. S. Min (2005) Full-scale experience for nitrogen removal from piggery waste. *Water Environment Research*, **77**(4), 381-389.
- Cordell D, Drangert J-O, White S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19:292-305.
- DVO (2009) Wenning Poultry anaerobic digester, Fort Recovery Ohio.
- Frear, C., Yorgey G.G., Liao, W., Ewing, T., Bishop, C., Shumway, R., Chen, S., Zaher, U., Li, R., Pandey, P., MacConnell, C., Zhao, Q., Zhang, T., Bowers, K., Harrison, J., Jiang, A., Leonhardt, E., Collins, H., Streubel, J., Granatstein, D., Kruger, C., Alva, A., Fransen, S., Wang, Z., Ma, J., Li, C., Yu, L, (2010). Anaerobic Digestion. Climate Friendly Farming Final Report.
- Frear, C., Liao, W., Ewing, T., Chen, S., (2012). Evaluation of co-digestion at a commercial dairy anaerobic digester, *Clean: Water, Air, and Soil.*, 39 (7), 697-704.
- Gungor, K. and Karthikeyan, K. G. (2005a). Influence of anaerobic digestion on dairy manure phosphorus extractability. *Transactions of the Asae*, **48**(4), 1497-1507.
- Gungor, K. and Karthikeyan, K. G. (2005b). Probable phosphorus solid phases and their stability in anaerobically digested dairy manure. *Transactions of the Asae*, **48**(4), 1509-1520.
- Gungor, K. and Karthikeyan, K. G. (2008a). Phosphorus forms and extractability in dairy manure: A case study for Wisconsin on-farm anaerobic digesters. *Bioresource Technology*, **99**(2), 425-436.
- Gungor, K. and Karthikeyan, K. G. (2008b). Phosphorus forms and extractability in dairy manure: a case study for Wisconsin on-farm anaerobic digesters. *Bioresource Technology*, **99**(2), 425-436.
- Guo, X., L. Zeng, X. M. Li & H. S. Park (2008) Ammonium and potassium removal for anaerobically digested wastewater using natural clinoptilolite followed by membrane pretreatment. *Journal of Hazardous Materials*, **151**(1), 125-133.
- Heathwaite, L., Sharpley, A., Gburek, W., (2000). A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *Journal of Environmental Quality*, 29, 158-166.



- Itodo, I. N. and Awulu, J.O. (1999). Effects of total solids concentrations of poultry, cattle, and piggery waste slurries on biogas yield, *Transactions of the ASAE* 42(6): 1853-1855.
- IPCC, (2007). IPCC fourth assessment report on climate change, (AR4). in: I.P.o.C. Change (Ed.), Geneva, Switzerland.
- Janus, H. M. & H. F. vanderRoest (1997) Don't reject the idea of treating reject water. *Water Science and Technology*, **35**(10), 27-34.
- Katehis, D., V. Diyamandoglu & J. Fillos (1998) Stripping and recovery of ammonia from centrate of anaerobically digested biosolids at elevated temperatures. *Water Environment Research*, **70**(2), 231-240.
- Koster, I.W. and Lettinga, G. (1984). The influence of ammonium-nitrogen on the specific activity of pelletized methanogenic sludge. *Agric Wastes* 9, 205-216.
- Liao, P. H., A. Chen & K. V. Lo (1995) Removal of nitrogen from swine manure wastewaters by ammonia stripping. *Bioresource Technology*, **54**(1), 17-20.
- Meyer, S. S. & P. A. Wilderer (2004) Treating of process water in large wastewater treatment plants in Germany - A case study. *Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering*, **39**(7), 1645-1654.
- Mulder, A., A. A. Vandegraaf, L. A. Robertson & J. G. Kuenen (1995) Anaerobic ammonium oxidation discovered in a denitrifying fluidized-bed reactor. *FEMS Microbiology Ecology*, **16**(3), 177-183.
- Murphy, J.D., Mckeogh, E. Technical, Economic and Environmental Analysis of Energy Production from Municipal Solid Waste, *Renew Energy* (2004). 29 (7), 1043.
- Pastor, L., Mangin, D., Ferrer, J. and Seco, A. (2010). Struvite formation from the supernatants of an anaerobic digestion pilot plant. *Bioresource Technology*, **101**(1), 118-125.
- Siegrist, H., W. Hunziker & H. Hofer (2005) Anaerobic digestion of slaughterhouse waste with UF-membrane separation and recycling of permeate CD after free ammonia stripping. *Water Science and Technology*, **52**(1-2), 531-536.
- Strous, M., J. A. Fuerst, E. H. M. Kramer, S. Logemann, G. Muyzer, K. T. van de Pas-Schoonen, R. Webb, J. G. Kuenen & M. S. M. Jetten (1999) Missing lithotroph identified as new planctomycete. *Nature*, **400**(6743), 446-449.
- Tchobanogolous, G., Burton, F.L., Stensel, H.D., Metcalf & Eddy, (2003). *Wastewater Engineering: Treatment and Reuse*, 4th ed., McGraw Hill, Boston, MA
- Thorndahl, U. (1993) Nitrogen removal from returned liquors. *Journal of the Institution of Water and Environment Management*, **7**(5), 492-496.
- Tilche, A., G. Bortone, F. Malaspina, S. Picinini & L. Stante (2001) Biological nutrient removal in a full-scale SBR treating piggery wastewater: results and modelling. *Water Science and Technology*, **43**(3), 363-371.
- USDA-APHIS (2004) Dairy 2002: nutrient management and the U.S. dairy industry in 2002. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Washington, DC.
- US-EPA, (1996). Environmental indicators of water quality in the United States. in: U.S.E.P.A.O.o. Water (Ed.), Washington DC.

- US-EPA (2000) Wastewater technology fact sheet: ammonia stripping. EPA Report 832-F-00-019, U.S. Environmental Protection Agency, Office of Water, Washington, DC.
- US-EPA, (2006). Market Opportunities for Biogas Recovery Systems—a Guide to Identifying Candidates for on-Farm and Centralized Systems, Washington DC, Document Number: EPA-430-8-06-004.
- US-EPA, (2008). Inventory of US greenhouse gas emissions and sinks: 1990-2006. United States Environmental Protection Agency, Washington DC.
- US-EPA, (2010). Market Opportunities for Biogas Recovery Systems—A Guide to Identifying Candidates for On-Farm and Centralized Systems. United States Environmental Protection Agency, Washington DC.
- US-EPA, (2011). Anaerobic digester database. United States Environmental Protection Agency, Washington DC.
- USDA-ERS, (2011). *Factors Contributing to the Recent Increase in U.S. Fertilizer Prices, 2002-08*, Wen-yuan Huang, AR-33, USDA, Economic Research Service, February 2009.
- Vanotti, M. (2005) Evaluation of environmentally superior technology: swine waste treatment system for elimination of lagoons, reduced environmental impact, and improved water quality. USDA Agreement 58-6657-2-202 / NCSU Subcontract #2001-0478-02 / USDA-ARS CRIS Project # 6657-13630-001-05, U.S. Department of Agriculture, Agricultural Research Service, Washington, DC.
- Zeng, L., X. Li, J. Liu & E. Jenson (2005) Feasibility study of air stripping of ammonia from digested cattle manure. *ADSW 2005 Conference Proceedings*. In B. K. Ahring & H. Hartmann (eds.), *4th International Symposium on Anaerobic Digestion of Solid Waste*, pp. 656-663. Copenhagen.
- Zeng, L., C. Mangan & X. Li (2006) Ammonia recovery from anaerobically digested cattle manure by steam stripping. *Water Science and Technology*, **54**(8), 137-145.
- Zhang, T., Bowers, K., Harrison, J. and Chen, S. (2008). Impact of calcium on struvite precipitation from anaerobically digested dairy wastewater. *Preprints of Extended Abstracts presented at the ACS National Meeting, American Chemical Society, Division of Environmental Chemistry*, **48**(1), 499.