PHOSPHORUS AND SOLIDS REMOVAL FROM ANAEROBIC DIGESTION EFFLUENT THROUGH ELECTROCHEMICAL TECHNOLOGY

USDA NRCS CIG FINAL REPORT
CONTRACT # 69-3A75-7-110

WASHINGTON STATE UNIVERSITY
SHULIN CHEN, PHD, PE
509-335-3743
chens@wsu.edu

Summarize the work performed during the project period

This project was successfully completed with all proposed objectives having been met. In addition to conducting the electro-coagulation (EC) work, the project team developed another new manure fiber treatment and phosphorus recovery technology that is potentially more economically viable and that is now patented, licensed, and undergoing commercial demonstration. Moreover, one manuscript was written for publication and extension that will expand the current body of knowledge on phosphorus treatment and EC. Additionally, results from this project were presented at the 12th Anaerobic Digestion Congress in December 2010 in Guadalajara, Mexico (Zhao, et al., 2010) as well as a producer day during pilot testing.

The pilot scale EC system was assembled in May 2009 with experiments begun in June and operated through August 2010. The system adhered to the new design that had been developed and tested in the form of a lab-scale system which was operated from February to April in 2009. Upon completion of pilot-scale research studies, the optimized pilot system was demonstrated at Monroe, WA to farmers and other interested parties for extension and outreach purposes. Optimization led to repeated performance capable of 78% TP removal during pilot tests.

Greenhouse growth trials utilizing phosphorus sludge separated during EC operation demonstrated that the fertilizer from the EC process had superior performance for triticale growth and dry matter yield when compared to a non-fertilized, negative control and a comparable inorganic mixed fertilizer treatment. However, economic analysis indicates that the value of the EC sludge based on the past three year average farm fertilizer prices is not enough to recover the total cost of the EC system. The total estimated annualized cost of a farm scale EC system, incorporating both capital and operating costs, was $321.63/cow and $68.26/cow for 100 and 1,000 cow dairies, respectively. These numbers correspond to a cost per flow rate of 4¢ and 1¢ per gallon dairy AD effluent treated, respectively. Constructing the EC settling lagoon was one of the highest construction costs associated with the project. However, existing dairies may already have a lagoon that could be used as an EC settling lagoon and avoid that construction cost which would decrease the estimated cost of the EC system.

Rising out of laboratory research directly attributable to the EC research was a new limited, non-biological aeration system for phosphorus recovery offering impressive phosphorus removal capabilities but at reduced capital and operating costs. Studies on the limited aeration process consistently showed capability in separating and recovering 80% total phosphorus from dairy anaerobic digestion effluent. Efforts are on-going in regard to further validation, demonstration and commercialization of this process via another awarded USDA NRCS CIG grant. Project results arising from this CIG research were directly utilized in the development of a recommended policy strategy for the State of Washington. Phosphorus has been shown to build up in the soil of livestock farming operations and contributes to surface water phosphorous loading through runoff (Spears, Young and Kohn, 2003). The technologies developed will help reduce phosphorus surplus in dairy farms. More details and results from the work performed during this project period are presented in the subsequent sections.

Describe significant results, accomplishments, and lessons learned. Compare actual accomplishments to the project goals in your proposal

Objective 1: Improve P and solid removal and a new process design

Task 1.1 Improvement of the process for P and solid removal

1.1.1 EC cell set-up

A bench-scale EC system with mono-polar electrodes in parallel connections was designed and set-up within the WSU laboratory as shown in Figure 1. EC treatment was carried out in batch trials. The electrode sets (both anode and cathode) were comprised of six parallel pieces of metal (304 stainless steel) plates situated 1.0 cm apart and were submerged in the effluent. The anode and cathode sets were, respectively, connected to the positive and negative outlets of a DC power supply (model CM-1 from HY Charge) at an open circuit potential of 6.0 V. Current was held at a constant of 1.0 A for each run.

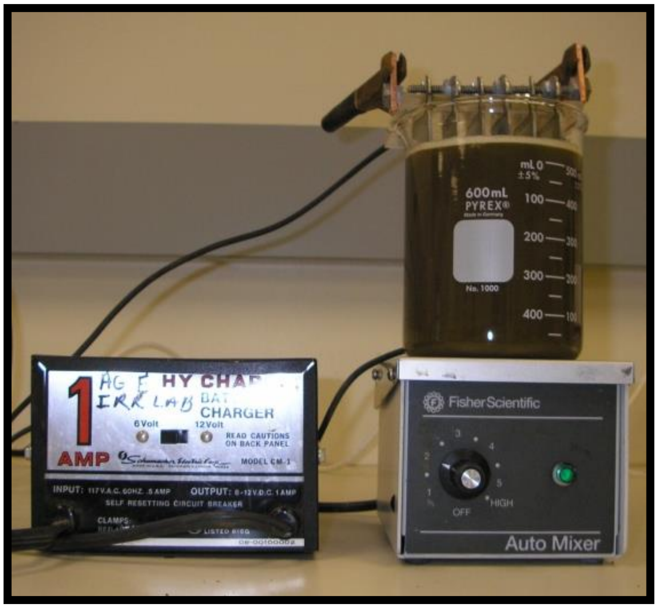

Figure 1: Bench-scale EC system with mono-polar electrodes in parallel connections

1.1.2 EC Experiments

For all tests, a working volume of 0.5 liter effluent was used and mixing of the cell contents was achieved through the use of a magnetic bar. Samples (50 mL each) were taken at intervals of 15 min with a total retention time of 90 min. The samples were settled by gravity overnight. Liquid samples from the top effluent were taken for analysis of total suspended solids (TSS) and total phosphorus (TP) to determine reductions of TSS and TP.

1.1.3 EC Results and Discussion

Figure 2 shows the effect of EC time on TSS reduction. The TSS reduction increased sharply during the first 15 minutes of EC time and then remained constant. The maximum TSS reduction was about 88%, indicating that majority of TSS was removed by the EC process. Such a high reduction in TSS is important to dairies as often the resulting effluent is not just stored and applied to fields but is also used as a flush water for hydraulic flushing or scraping of manure from the animal pens. More complete removal of suspended solids leads to a better flush water, less prone to harming animal health, notably through animal falls on the slick water.

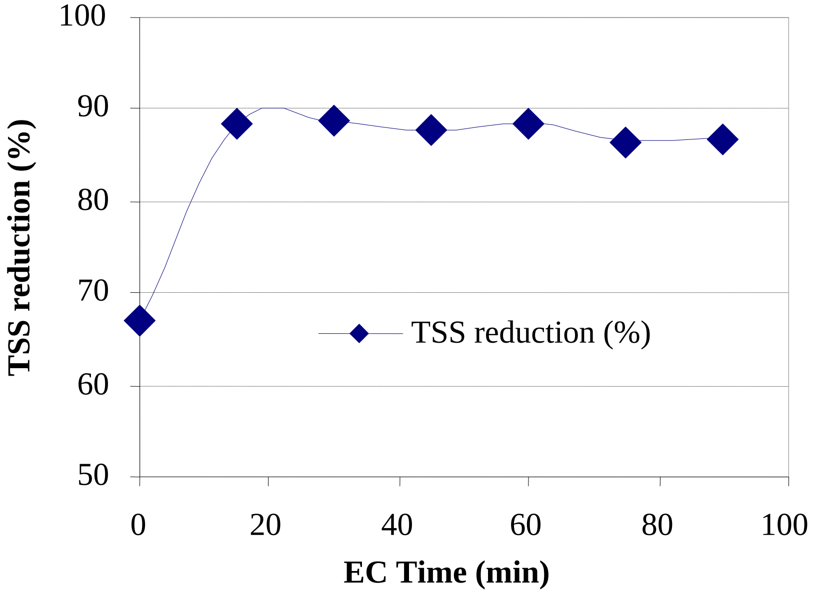

Figure 2: Effect of EC time on TSS reduction

Considerable research has shown that a majority of phosphorus contained within dairy effluent is in the form of micro-solids, not as free phosphate (Battistoni et al. 1997), findings which led directly to the focus on EC as a means to efficiently settle and separate these micro-solids that have a tendency to stay suspended without additional treatment beyond that of simple gravity settling (Zheng et al., 2009). As such it was a key hypothesis of the research that along with active and successful settling of suspended solids as described in Figure 2, there would also be notable settling and corresponding reduction in TP. As expected, Figure 3 shows that the TP reduction also increased sharply during the first 30 minutes of EC time, and then remained relatively constant. The need for increased EC time to attain higher TP removal as compared to TSS is perhaps an indication of the phosphorus micro-solids being in general composed of smaller particles offering greater resistance to settling and thus requiring more active treatment. The maximum TP reduction achieved was 83%, suggesting that the remaining 15-20% of TP within dairy effluent is either of sufficient small colloidal size to be completely resistant to the EC treatment or in the form of free phosphate, with literature evidence pointing to perhaps a combination of the two hypotheses.

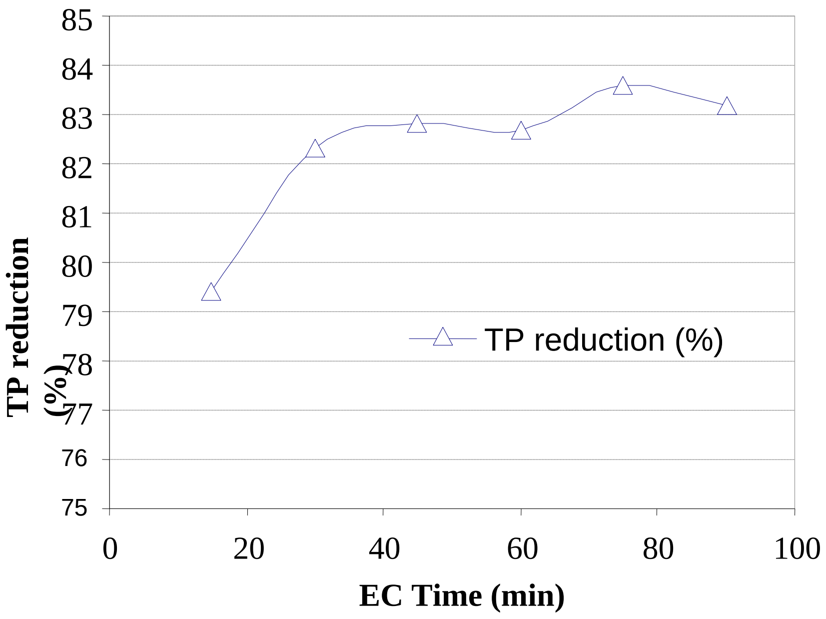

Figure 3: Effect of EC time on TP reduction

A troublesome discovery during the research was the difficulty in dewatering and collecting the EC sludge. While EC effectively overcame barriers to natural settling of these suspended solids and phosphorus-containing solids, the resulting settled material was of an extremely loosely held nature, not having formed large flocs which could be easily harvested and dewatered. Subsequent attempts to harvest and dewater led to nearly 30-50% of the volume of sludge remaining within the treated effluent, leaving rich levels of TSS and TP still within the supernatant. Subsequent commercialization of the technology, if warranted, will require the use of specialized harvesting and dewatering equipment to ensure more successful capture of these loose solids.

Task 1.2 EC System Design

Based on our current EC results and further optimization of this process, a pilot-scale continuous operation EC system was designed. This constructed pilot reactor was 6.8 liters in volume and equipped with 1-5 electrode units with electrode plates placed 1cm apart. The system as before was connected to a DC power supply (model CM-1 from HY Charge) which allowed for testing at various amperages. In addition there was a settling tank to allow for settling and collection of sludge (Figure 4).

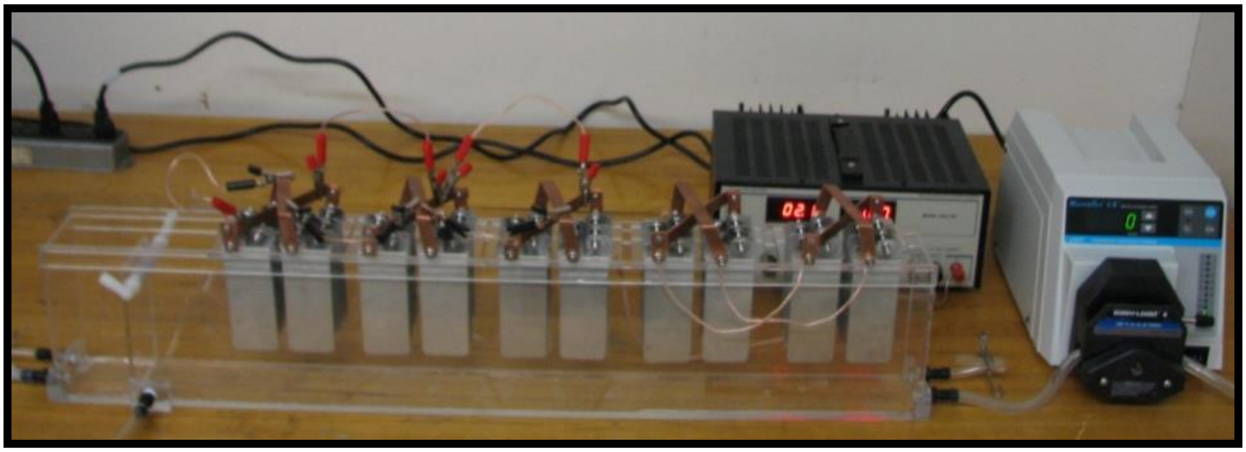

Figure 4: Pilot-scale continuous-flow EC system setup

Objective 2: Demonstrate and Improve the P Settling Process from the AD Effluent

Pilot testing of the EC system showed that TP removals as high as 80% could be achieved using a current density of 2.5 mA/cm2. Interestingly, this settling and reduction performance was not strongly correlated with ferric coagulation as would be predicted from past EC research (Bektas et al., 2004). EC research has shown that that during the EC process the sacrificial iron electrodes play a significant role in producing soluble iron ions which then in turn parlay their high positive ionic charge into the role of a chemical coagulant agent, binding with the micro-solids into a more settled floc (Lai and Lin, 2004). A review of EC literature shows that typical iron losses are on the order of 200 mg/L while our studies showed a lower reduction in iron losses (Table 1) (Zongo et al., 2009).

Table 1: Iron concentrations in fractions of effluent pre and post EC

Amperage	Effluent Iron Pre- EC (mg/L)	Iron in Sludge Post-EC (mg/L)	Iron in Liquid Post-EC (mg/L)
3.0	86.5	119	73.5
4.0	116	109	47.7
4.5	107	76.8	31.1
5.0	61.7	77.4	39.4
5.5	107	73.8	32.7
6.0	75.0	50.8	18.6

One explanation for the relatively low levels of iron ions in solution is the fact that our EC system utilized stainless steel, offering an alloy which interfered with simple release of the iron ions and leading to an overall decrease in measured iron being released.

Development of a new hypothesis was warranted then to explain the high levels of solids removal despite the relatively low levels of iron being released and available for use as a coagulant. It is well known that during AD significant amounts of CO_2 and even some CH_4 produced during the biological process can become dissolved and/or super-saturated within the effluent. This is particularly true for CO_2, which is stored within the liquid effluent as CO_2 (dissolved), H_2CO_3, 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 (Waki et al., 1987; and Battistoni et al. 1997; Suzuki et al. 2002). Upon analysis, we learned that aeration by H_2/O_2 may play an important role in removing super-saturated CO_2 and therefore enhancing solids settling and P removal, as according to Henry's law, CO_2 will release to the H_2 gas bubbles generated by EC because of low CO_2 partial pressure inside the bubbles. That new hypothesis then centers on the important fact that during the EC treatment considerable amounts of H_2 gas are produced, yielding an environment where the insoluble non-polar H_2 gas becomes saturated in solution and evolves out of solution in the headspace. Importantly, while doing so the H_2 carries with it high levels of CO_2 gas that had become saturated or supersaturated within the effluent during the AD process (Bektas, et al., 2004). The loss of supersaturated CO_2 within the effluent leads to subsequent shifts in a series of important chemical equilibriums, resulting in elevations in pH (7.9 to 8.5) and reduction in charged species and soluble gases both of which can in part interfere with natural settling of micro-solids (Figure 5).

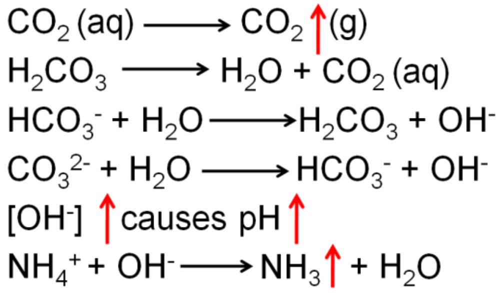

Figure 5: Chemical equilibrium associated with aeration process

To verify our hypothesis aeration experiments were set up. Experimental results confirmed that aeration not only enhanced phosphorus and solid removal from the AD effluent, but also stripped out ammonia from the AD effluent. Figure 6 below demonstrates how micro-bubbles of gas present and evolving within the AD effluent can be stripped out with aeration treatment. In this test case through insertion of air but in the case of EC also accomplished through the production and evolution of H_2 gas.

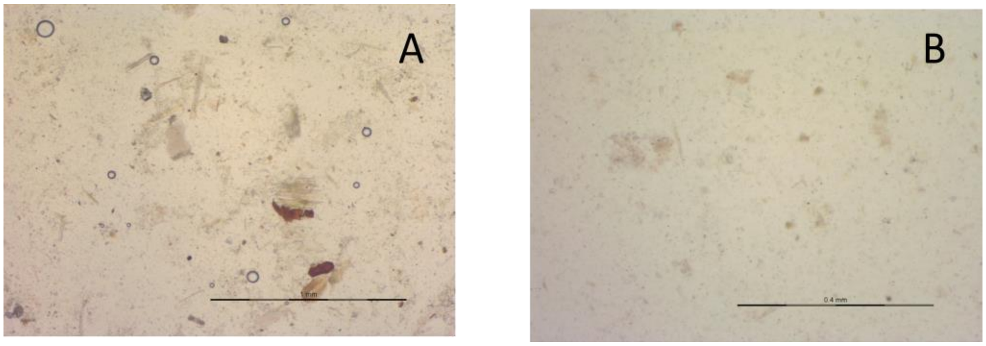

Figure 6: Microscope images of AD manure effluent with (a) micro-bubbles of gas present and evolving and (b) without gas present after aeration treatment

While the supersaturated gases are being stripped out the aforementioned chemical equilibriums shift explaining the rise in pH seen during the EC experiments. As the chemical balance moves towards the right more OH^- is generated, which makes the pH of the solution increase. Optimized flow rate and reaction time can be inferred by recording a pH/aeration profile.

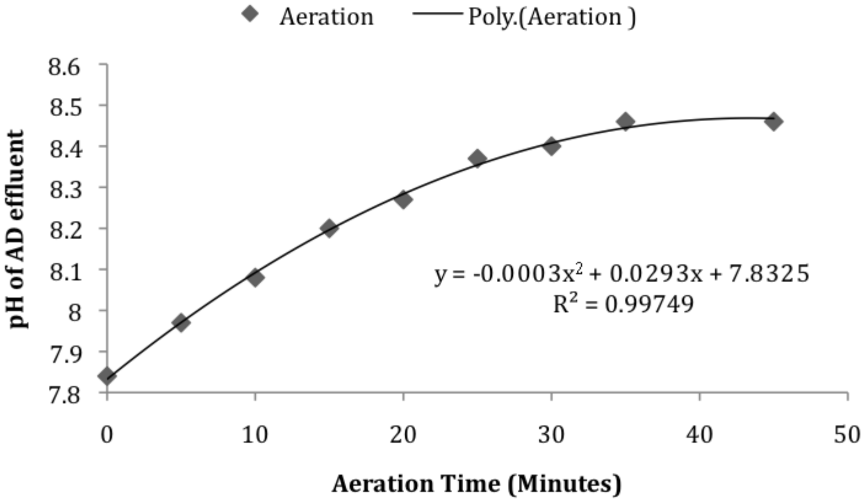

Figure 7: pH profile during aeration

Figure 7 is a pH/aeration profile for a laboratory test on AD dairy effluent. As can be seen from the figure, aeration of only 30 minutes increased the pH of the AD effluent by nearly a half of a pH point, indicating the removal of significant amounts of super-saturated CO_2. Removal of these interfering gases led to significant improvement in settling capability and solids/phosphorous removal. Without aeration, only 28.4% of TP was settled during a 24 hour period. This is in comparison to the performance after aeration and subsequent 24 hour settling where 52.3% TP was removed (Table 2).

Table 2: TP removal percentages with and without aeration

AD Effluent	Settling for 24h No Aeration		Aeration (40 min) and Settling (24 h)	
TP (mg/l)	TP (mg/l)	TP loss (%)	TP (mg/l)	TP loss (%)
1760	1260	28.4	840	52.3

Importantly, as the pH of the solution is increased beyond 9.5 not only is solids and phosphorus separation enhanced but the aqueous to gaseous equilibrium for ammonia shifts towards gaseous or free ammonia, allowing for simultaneous stripping of ammonia gas from the effluent. As shown in Figure 8, more than 50% of ammonia can be removed after 15 hours of aeration. To recover the ammonia and remove the odor, though, an acid tower is needed to absorb ammonia and produce ammonia sulfate, a saleable bio-fertilizer.

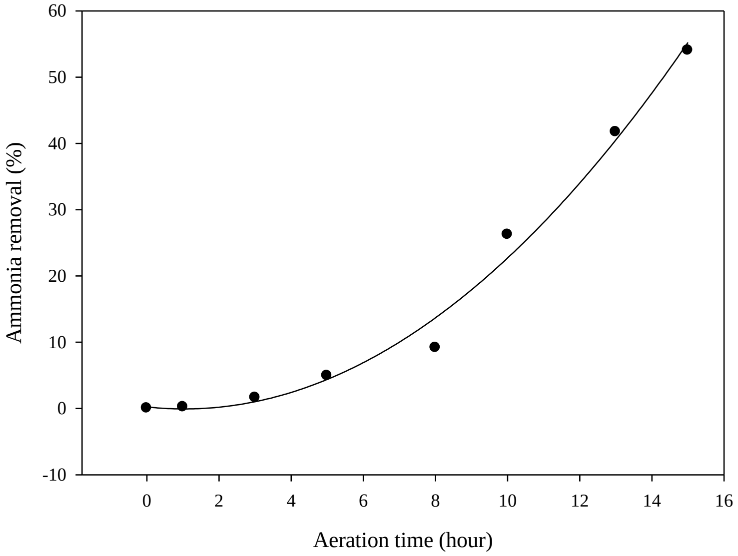

Figure 8: Ammonia removal from dairy AD effluent by aeration

Thus, from initial studies on EC, a new hypothesis for effective phosphorus, solids and even ammonia removal was developed. Notably, the aeration can be easily completed using blowers, and effluent pits available with standard, biogas-mixed plug-flow digesters. For purposes of this EC development project, conclusions can be drawn that in our EC system, a combination of iron ions, albeit at a reduced concentration due to the use of stainless steel electrodes, and evolved hydrogen gas, and its effect on the stripping out and shifting of important soluble gases and equilibriums, together resulted in effective settling of previously suspended solids and phosphorus. With subsequent testing of this hypothesis, a provisional patent on EC and aeration was written for phosphorus removal from anaerobic digester effluent.

Task 2.1 Pilot EC unit setup

A continuous-flow pilot-scale EC system with mono-polar electrodes in parallel connections was designed and set up in the laboratory as shown in Figure 4. EC treatment was carried out in both batch and continuous flow electrolytic cell systems. The electrode sets (both anode and cathode) were each comprised of ten parallel pieces of metal plates (304 stainless steel) situated 1.0 cm apart. A peristaltic pump was used to transfer manure into the EC reactor continuously.

Task 2.2 Pilot evaluation and process optimization

The pilot EC system was tested with six liters of fresh dairy AD effluent (Figure 9a) and then operated run for 30 min using 5 amps of current. After one hour of natural settling, a very satisfactory solid from liquid separation phenomenon was observed (Figure 9b).

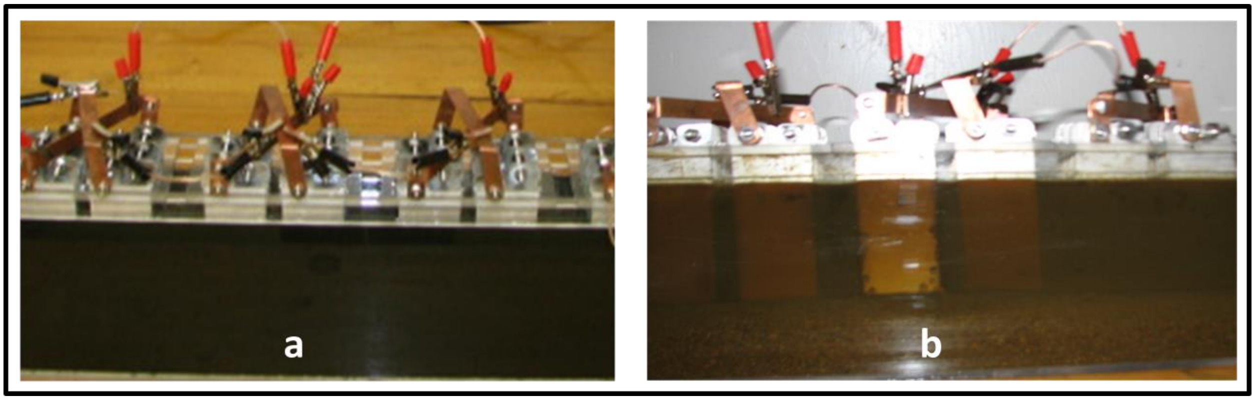

Figure 9: (a) Dairy AD effluent pre-EC and (b) settled effluent after EC treatment at 5 A

To optimize TP removal efficiency of the pilot EC system, a series of current density settings (3.0A to 6.0 A) were tested with the flow rate of 40 ml/min. The raw manure sample was taken at the beginning of each run. Liquid and solid samples were taken from the top and the bottom of the EC reactor respectively after 2 hours of run time. Figure 10 shows TP removal from the manure effluent with different electric currents. TP removal efficiencies of 78% were obtained with optimal amperage of 5.5 A however the removal efficiency could have been higher if the settling time was longer. The TP removal efficiency appears to have improved linearly with increasing amperage, although for economic purposes realistic limitations are placed on the level of amperage used, given the cost of electricity. The linear relationship fits well with theory, showing that as amperage or current increased, so did the degree of sacrificial iron ion production for use of coagulant as well as production of H_2 gas for stripping out of supersaturated gas and related chemical equilibriums interfering with the natural settling process for the solids and phosphorus.

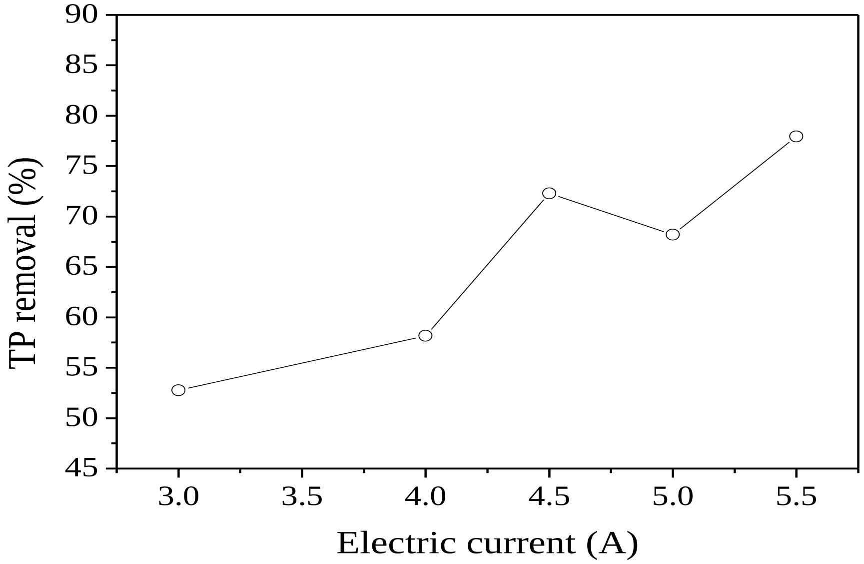

Figure 10: TP removal efficiency by EC with different amperage settings

Nutrient contents (TN, TP and K) in the solid and liquid fractions of the EC treated effluent were also analyzed as one of the major commercial reasons for EC treatment of AD effluent is not just for solids and phosphorus removal but for production of both a valuable, saleable bio-fertilizer from the sludge and a useful liquid effluent capable of discharge to associated fields that can meet both agronomic and nutrient management plan needs (Figure 11). A first interesting conclusion is that while the EC treatment process was efficient at settling solids and the associated phosphorus micro-solids (twice the P concentration in the solids as compared to the liquid) there was notably less of a tendency for nitrogen to enter the solid fraction, with 1600-2000 mg/l of TN remaining in the liquid fraction. This can in part be attributed to the fact that the AD process acts as a biological conversion mechanism of organic nitrogen to ammonia nitrogen with AD manure effluents containing 20-40% more ammonia nitrogen as compared to their influent (Jiang et al., 2010). With such a high fraction of ammonia nitrogen it is not surprising then that a majority of the total nitrogen stayed within the liquid stream. Conversely it can be safe to assume that other than some adhesion of ammonia to the separated solids, the majority of the nitrogen being stored within the solid phase was organic in nature. There was no difference in the potassium concentration of these two phases. The metal concentrations in liquid and solid parts of manure post EC are shown in Figure 12. Concentrations of Ca, Al and Fe in the solid part are higher than in the liquid part. The concentration of Ca in solids is two times higher than that of liquid. This might be due to part of calcium being bound to carbonate and phosphate to form insoluble salts, thereby being coagulated and separated from liquid by the $Fe(OH)_2$ flocs. The Fe concentration in sludge is less than 100 mg/l, which is lower than other reports (Zongo et al., 2009), with the still effective settling ability being a result of the limited iron coagulation/flocculation occurring alongside the observed pH increase, degassing and equilibrium shifts discussed earlier.

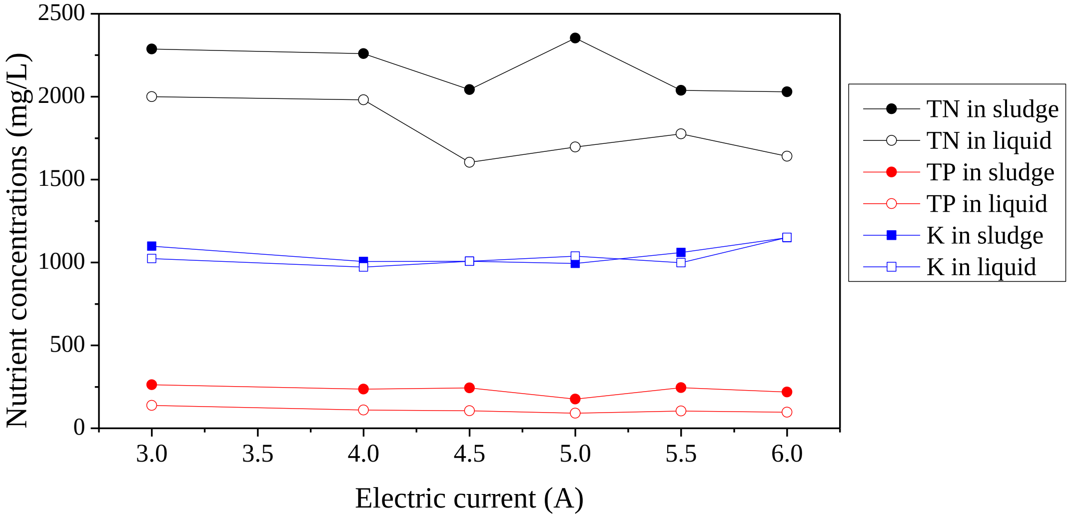

Figure 11: Nutrients in liquid and solid fractions of dairy AD effluent post EC

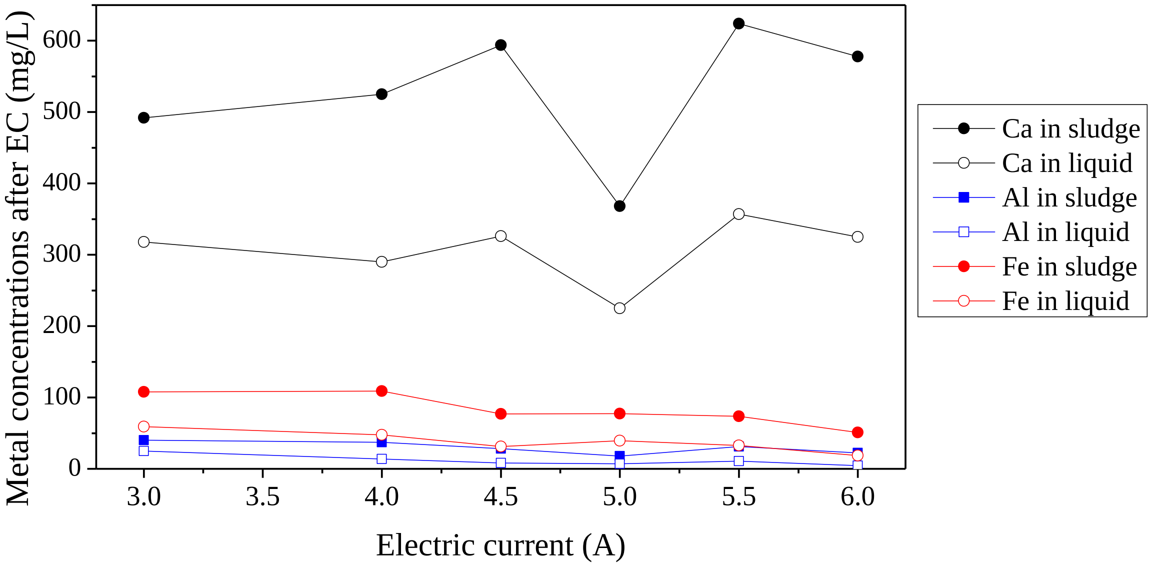

Figure 12: Metals in dairy AD effluent post EC

In summary, experimental results indicate that the pilot EC system is effective in removing phosphorus and solids from dairy AD effluent without any chemical addition. The settled solids harvested from the EC contain a higher concentration of nitrogen, phosphorus and minerals, which can be used as fertilizer. As stated before, there is though the concern about how best to harvest and dewater the produced sludge so that the most optimized removal efficiency can be attained while also producing a more marketable dry product that can be easily transported long distances.

Task 2.3 Evaluate Settled Sludge as Fertilizer

Sludge solids obtained from the EC pilot tests was used as the source of nutrients for four separate agronomic growth studies completed from December 2009 to September 2010. Specifically, dairy AD effluent was EC treated at 5.5 amps to generate the material of interest. The resulting EC sludge was applied at rates of 50, 100, and 150 pounds of P_2O_5 equivalent. The nutrient analyses of EC sludge for each trial is noted in Table 3.

Ammonium phosphate (AP) and urea (Ur) were combined into a synthetic fertilizer supplying approximate equal amounts of N and P for comparison with EC fertilizer as a control. The resulting APUR fertilizer was applied at the same rates (50, 100, and 150 pounds of P_2O_5) to as the EC fertilizer. Control pots with no added nutrients served as a negative control. Nutrient free potting soil was used as growth media. Four- inch pots were used as the growth containers. 12 seeds of triticale was used per pot, and thinned to 8 plants per pot. In trials 1 – 3, the EC sludge and commercial fertilizers were applied at time of seed planting on the surface of the potting soil while in trial 4, the EC sludge and commercial fertilizers were mixed into the potting soil and then the triticale seeds were planted. Water was applied as needed to keep the growth medium moist. Harvest occurred when plants had reached a height of ~ 8 inches. Multiple harvests occurred until now further growth was observed with harvest of 5, 6, 4, and 3 completed for trials 1-4, respectively. Samples were weighed wet, dried, reweighed, and then submitted for nutrient analyses to the Cumberland Valley Analytical Services. Wet and dry mass of triticale growth and re-growth, nutrient content of triticale, and nutrient uptake were calculated.

Table 3: Nutrient analyses of EC sludge

EP Sludge by Trial	Date sampled	Item	Value	unit
1 & 2	11/19/2009	TP	260	mg/L
		TS	1.95	%
		CALCIUM	653	mg/L
		POTASSIUM	1111	mg/L
		IRON	41.3	mg/L
		ALUMINUM	22.0	mg/L
		TN	1927	mg/L
3	4/13/2010	TP	268	mg/L
		TS	2.14	%
		CALCIUM	704	mg/L
		POTASSIUM	1067	mg/L
		IRON	56.7	mg/L
		ALUMINUM	32.8	mg/L
		TN	2440	mg/L
4	7/9/2010	TP	187	mg/L
		TS	1.46	%
		CALCIUM	410	mg/L
		POTASSIUM	752	mg/L
		IRON	60.2	mg/L
		ALUMINUM	20	mg/L
		TN	1590	mg/L

Figure 13 visually portrays the growth of triticale on the two fertilizer inputs with both treatment producing nice stands of crop. However, analysis of the growth data as described in Figure 14 shows that the EC fertilizer produced more dry matter than the negative control and perhaps more than the APUR although standard deviation (not shown) would not allow this conclusion.

Figure 13: Pictures of triticale growing test (a) EC fertilizer and (b) AP fertilizer

Trial 2 results were the only results shown for the four treatments as trials 1, 2, and 4 had extremely poor growth for the APUR treatments, potentially due to an unintended salting effect that arose with its treatment.

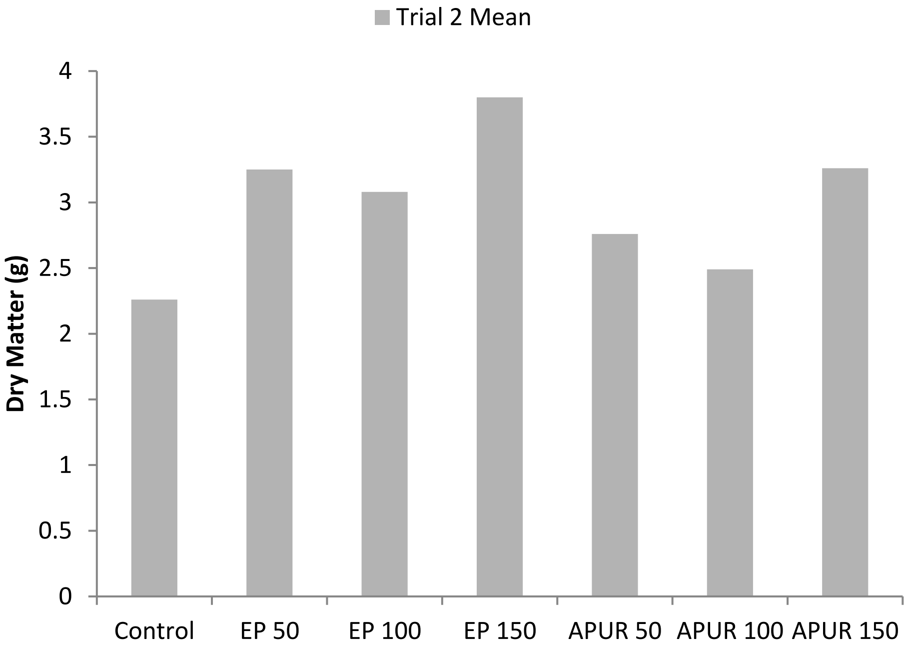

Figure 14: Dry matter yields for the various fertilizer treatment; trial 2 mean results (EP=EC)

The mineral uptake for trial 2 is summarized in Figure 15. The general pattern was as noted for DM yield, with the best performance with EC sludge treatments. Much more K uptake is found when using EC fertilizer, which is because the high K content in EC fertilizer. A little bit higher P uptake was also found when applying EC fertilizer, which shows more bio-available of P in EC fertilizer. Lower Ca uptake was found when utilizing EC fertilizer; this is because the high carbonate concentration in EC fertilizer which will form insoluble $CaCO_3$ and make Ca^{2+} less available. No significant differences are found for N and Mg uptake due to similar concentration in both two runs.

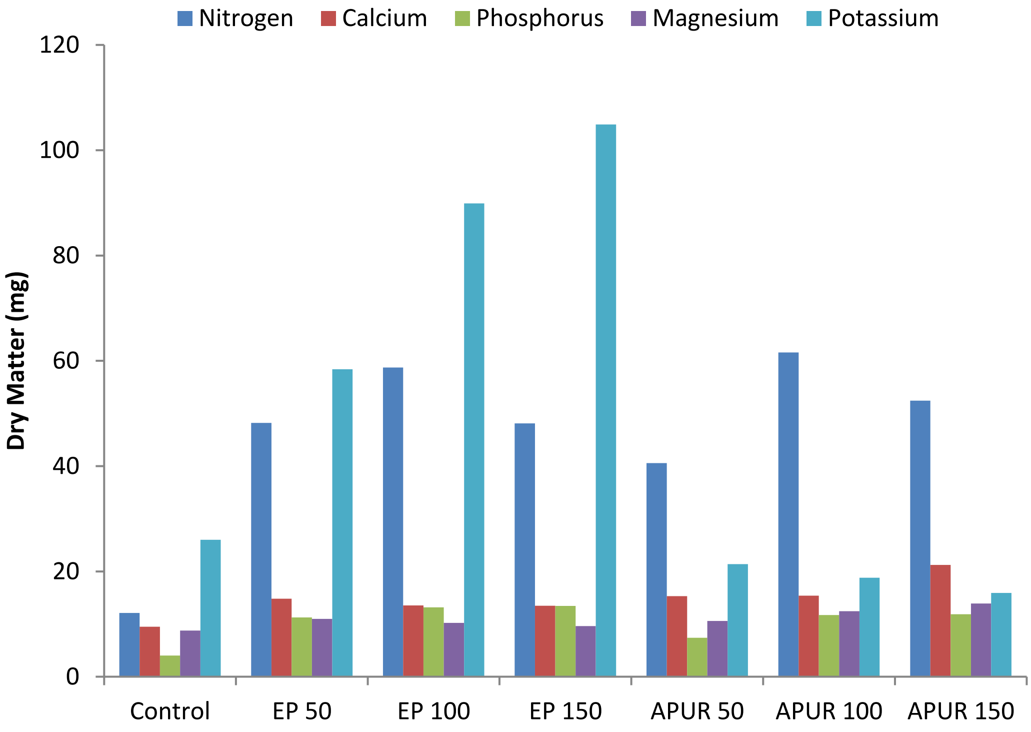

Figure 15: Nutrient dry matter in triticale trial 2 (EP=EC)

Objective 3: Conduct market and cost/benefit analysis of the process and fertilizer products

This project developed a functional bench scale EC system for dairy AD effluent. The purpose of this analysis was to design a full scale system for use on a dairy farm based on the bench scale system and then estimate its economic costs. Figure 16 provides a diagram of where the EC system will be located in a typical AD dairy waste management system. The EC system is located after solid separation which reduces the suspended solids in the effluent and improves the EC process to settle the suspended solids into a sludge contained in the EC basin. The sludge is pumped from the EC basin to a lightly sloped containment slab where gravitational dewatering and evaporation produces a fertilizer rich solid with 30% moisture. It is likely that the sludge solid could be blended with potting soil and used in a nursery application. The estimated production yield of the sludge is 3.5 lb dry sludge/cow/day with an NPK ratio of 2:1:1 (Frear et al, 2011).

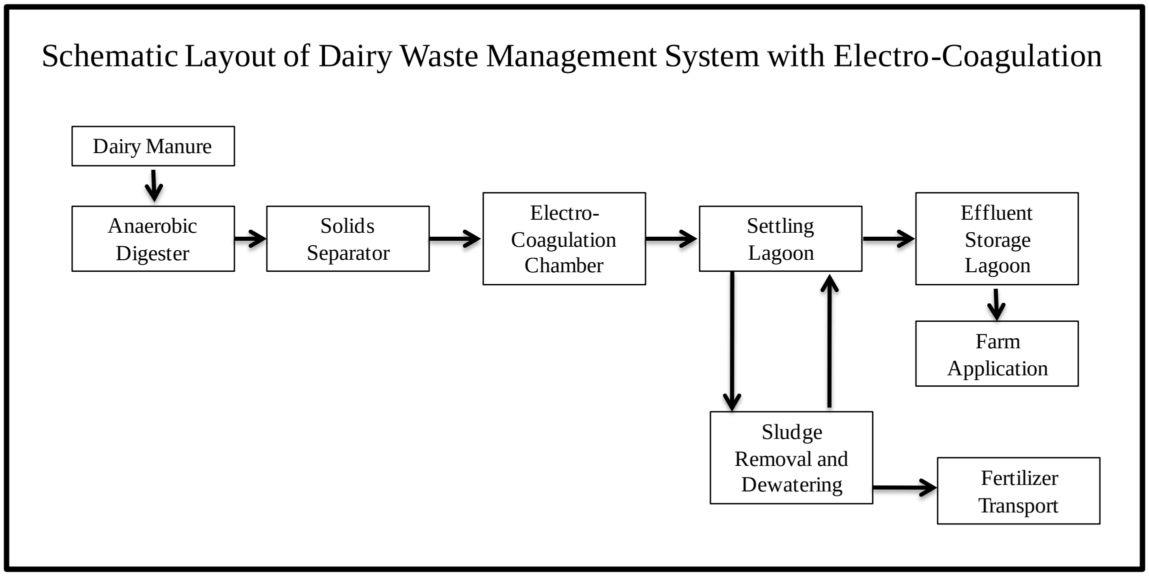

Figure 16: Dairy Waste Management System with Electro-Coagulation

The EC prototype used during the studies was scaled up to handle the volume of dairy waste water effluent for a 100 and a 1000 head dairy. Table 4 provides the estimated design parameters for a full scale EC unit. The volume of effluent handled is 2,000 gallons per day for the 100 cow dairy and it is 20,000 gallons per day for the 1000 cow dairy. The EC chamber is designed to be a concrete pit with length, width and depth dimensions provided in Table 4. The electrodes extend slightly above the pit where the electrical connections are made. The electrodes are suspended in the EC chamber using a connection system supported by the concrete sides. The waste water effluent can flow entirely around the electrodes except for the top where the wiring connections are made. There are 20 and 40 electrodes for the 100 and 1000 dairy farm sizes respectively. The electrode spacing is 50 cm for each system. The chamber also serves as a settling pit. The precipitated sludge is pumped from the bottom of the chamber to a concrete slab that serves as a natural dewatering and sludge cake storage site.

Table 5 provides the estimated construction costs associated with the EC chamber. The costs were obtained from contractor estimates on concrete components and price quotes for the iron electrode components and wiring, and the sludge pump. The site excavation and labor costs are included in the concrete costs. Labor costs are included in the electrode wiring for the constructing the electrode system. Annualized costs are calculated using straight line depreciation with the estimated life provided in the table and a zero salvage value. The total annualized construction cost estimate is $7,071 for the 100 cow system and $16,250 for the 1000 cow system.

Table 4. Farm Scale Electro-Coagulation Design Parameters

EC Design Paramter	Unit	Parameter Value	Parameter Value
Dairy Farm Size	cows	100	1,000
AD effluent	gallon/day	2,000	20,000
Retention time in EC chamber	minutes	20	20
EC chamber volume	m^3	1	5.4
EC chamber length	m	1.00	1.75
EC chamber width	m	1.00	1.75
EC chamber depth	m	1.00	1.75
Electrode length	m	0.75	1.50
Electrode height	m	0.75	1.60
Electrode numbers	pcs	38	80
Electrode area	m^2	20	190
Electrode thickness	mm	2.28	2.28
Electrode spacing	cm	2.00	2.00
Current density	mA/cm2	4	4
Total current	A	810	7,584
Voltage	volt	5	5
Power	kw	4	38
Power consumption	kwh / day	32	303
Settling time	hours	12	12
Settling chamber volume	m^3	11.70	114

Table 5. Estimated Electro-Coagulation Construction Costs

				Annualized Cost	
	100 Cows	1000 Cows	Estimated Life (years)	100 Cows	1000 Cows
	$	$		$	$
Concrete EC Chamber	5,501	14,450	15	367	963
Sludge Drying Pad	5,039	11,336	15	336	756
Electrodes	5,473	9,245	3	1,824	3,082
Electrode Wiring	6,000	12,000	3	2,000	4,000
Electrode Transformer	3,000	7,500	3	1,000	2,500
Settling Pond	18,150	127,050	15	423	307
Sludge Pump	3,363	6,726	3	1,121	2,242
Shed Enclosure	16,000	36,000	15	1,067	2400
Total	62,526	224,307		7,071	16,250

The EC system's operating costs are provided in Table 6. The operating costs are for the electricity, maintenance and operating labor of the EC system and the sludge, and a miscellaneous expense estimated as 20% of the annual capital cost. The primary cost is the labor for monitoring maintenance of the EC system. The estimated average labor per day is three hours and five hours for the 100 and 1000 cow dairies, and is paid $20 per hour reflecting the high skill level needed to manage the electrical components of the EC system. The estimated EC system annual operating costs are $25,092 and $52,007 for the 100 and 1000 dairy farm size respectively. The electricity cost is $0.0816 per kwh which is based on Pacific Northwest power costs which are relatively low. The power use parameters are provided in Table 6 and the efficiency of transferring 110AC to 5V DC through the transformer is assumed to be 85% efficient.

Table 6. Estimated Electro-Coagulation Annual Operating Costs

	Cost per Unit	100 Cows	1000 Cows
		$	$
Electricity	$0.08158 / kwh	1,121	10,615
Labor Monitoring and Maintenance	$20 / hour	21,900	36,500
Sludge Cake Loading and Management	$12 / hour	657	1,643
Miscellaneous	20% Annual Capital	1,414	3,250
Total		25,092	52,007

A summary of the EC system annual combined capital and operating costs are given in Table 7. The system's annual cost is $321.63 per cow for the 100 cow farm size and the treatment cost per gallon is 4.4 cents. There are economies of size in the EC system. The 1000 cow dairy has a cost per cow of $68.26 and a treatment cost of 0.9 cents per gallon.

Table 7. Annual Estimated Electro-Coagulation Costs

	100 Cows	1000 Cows
Annual Capital Cost	$7,070.86	$16,249.72
Annual Operating Cost	$25,092.18	$52,006.96
Total Annual Cost	$32,163.04	$68,256.68
Cost per cow	$321.63	$68.26
Cost per Gallon of AD Effluent	$0.044	$0.009

Economic Value of EC Sludge as a Fertilizer Product

Determining the economic value of the nutrients in livestock manure can be complex. Nutrients in commercial fertilizer are acquired by paying for the nutrients that are formulated in fixed and known ratios. With manure, you get the amount and ratio of nutrients that the manure contains even if it is different from the ratio needed, which complicates the determination of a value. Even when a rate that supplies the correct amount of nitrogen is applied, the amount of phosphorous and potash applied may not match what you would have purchased commercially. From an economic view, commercial fertilizer is a major crop production expense and is the main driver of manure value calculation to a crop producer whose goal is to maximize profits.

Typically dairies manage their animal waste from their confined areas by periodically flushing it away with recycled wastewater. The wastewater carrying the animal waste exits the confined areas and enters the dairy waste management system. Dairy waste water effluent is periodically withdrawn from the storage and applied onto the farm's cropland and or pasture. The application rate typically is the amount needed to meet the nitrogen needs of the crops. However, the phosphorus to nitrogen ratio in the wastewater often exceeds the phosphorus to nitrogen uptake ratio of the crops, resulting in an accumulation of phosphorus in the soil. To reduce the phosphorus application rate, the wastewater may be applied to a greater area of land, transported at high cost off of the dairy farm to new fields, or the phosphorus can be extracted, such as analyzed in this project using EC and used as a phosphorus rich fertilizer product.

Fertilizer prices have become highly variable in response to global economic conditions that affect the demand and ability to pay for food and in-turn the demand for crop production inputs such as fertilizer, and resource scarcity. Phosphorous price has increased dramatically over the past ten years. Figure 17 illustrates the change in superphosphate nominal price paid by farmers in the Northwest region, Washington, Idaho and Oregon, (USDA NASS Agricultural Statistics). The figure illustrates the increase in price for phosphorous rich fertilizer and the market price potential for the phosphorous rich sludge produced by the EC system as a fertilizer product.

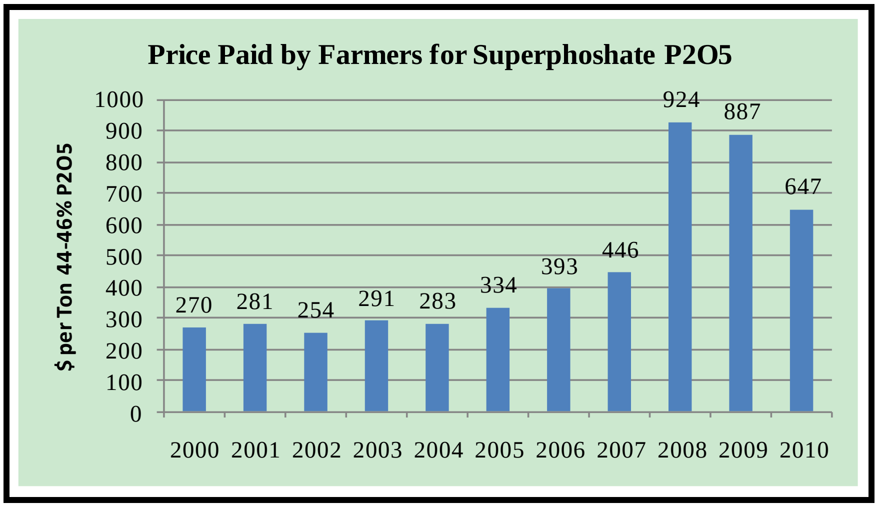

Figure 17: 2000 to 2010 Price Paid by Northwest Farmers for P_2O_5.

EC Sludge Production and Nutrient Content

The EC settled sludge will be pumped from the settling lagoon onto a concrete pad where natural dewatering from gravitational drainage and evaporation occurs. Because the EC system for this project was bench-top scale, many factors remain to be tested concerning the nutrient content of the EC sludge at a farm scale. Based on observations of the settled waste water effluent from the bench scale experiments and a review of the literature on dairy waste production and its nutrient composition, it is expected that the dewatered sludge will have 30% moisture content and that a dairy cow will produce 3.5 pounds of the dewatered sludge per day.

The 2008 to 2010 average price paid by farmers per pound for nitrogen and phosphorous was $0.70 and $0.91 respectively. Tables 8 and 9 estimate the value of nutrient production per farm for the 100 and 1000 cow dairies for a range of potential percent of nutrients per pound of EC sludge produced.

Table 8. Estimated Nutrient Production Value of EC Sludge for the 100 Cow Dairy Size

% P Available In EC Sludge	% of Nitrogen Available in EC Sludge 0.50%	0.75%	1.00%	1.25%	1.50%	1.75%	2.00%	2.25%	2.50%
	$	$	$	$	$	$	$	$	$
0.50%	1,026	1,248	1,470	1,693	1,915	2,137	2,359	2,582	2,804
0.75%	1,317	1,539	1,761	1,983	2,206	2,428	2,650	2,872	3,095
1.00%	1,830	1,830	2,052	2,274	2,496	2,719	2,941	3,163	3,385
1.25%	2,343	2,120	2,343	2,565	2,787	3,009	3,232	3,454	3,676
1.50%	2,856	2,411	2,633	2,856	3,078	3,300	3,522	3,745	3,967
1.75%	3,369	2,702	2,924	3,146	3,369	3,591	3,813	4,035	4,258
2.00%	3,882	2,993	3,215	3,437	3,659	3,882	4,104	4,326	4,548
2.25%	4,395	3,283	3,506	3,728	3,950	4,172	4,395	4,617	4,839
2.50%	4,908	3,574	3,796	4,019	4,241	4,463	4,685	4,908	5,130

Table 9. Estimated Nutrient Production Value of EC Sludge for the 1000 Cow Dairy Size

% P Available In EC Sludge	% of Nitrogen Available in EC Sludge 0.50%	0.75%	1.00%	1.25%	1.50%	1.75%	2.00%	2.25%	2.50%
	$	$	$	$	$	$	$	$	$
0.50%	10,260	12,482	14,704	16,927	19,149	21,371	23,594	25,816	28,038
0.75%	13,167	15,389	17,612	19,834	22,056	24,279	26,501	28,723	30,946
1.00%	18,297	18,297	20,519	22,742	24,964	27,186	29,409	31,631	33,853
1.25%	23,427	21,204	23,427	25,649	27,871	30,094	32,316	34,538	36,761
1.50%	28,557	24,112	26,334	28,557	30,779	33,001	35,224	37,446	39,668
1.75%	33,686	27,019	29,242	31,464	33,686	35,909	38,131	40,353	42,576
2.00%	38,816	29,927	32,149	34,372	36,594	38,816	41,039	43,261	45,483
2.25%	43,946	32,834	35,057	37,279	39,501	41,724	43,946	46,168	48,391

Because phosphorous has become more expensive than nitrogen on a per pound basis, as the percent of phosphorus increases in the EC sludge it increases in value. These estimated values are based on farmer paid prices for nutrients. It is likely that the highest and best use of the EC sludge will be in a nursery application which would further increase its value because it would be used in a higher value industry as compared to farming. Targeting the nursery industry as a market for the sludge would also likely incorporate some of the separated solids from the solid separator with the EC sludge to produce a potting quality mix.

Economic Break-Even Conclusions

The value of the EC sludge based on the past three year average farm fertilizer prices is not enough to recover the total cost of the EC system. The total estimated cost of a farm scale EC system is $32,163 and $68,256 for the 100 and 1000 cow dairies. The fertilizer value of the EC sludge in Tables 8 and 9 are insufficient to recover the projected farm scale EC system costs. However, the EC system may be a low cost alternative to reducing phosphorous loading at the farm level if more stringent environmental regulations are imposed on dairies concerning phosphorous loading. It is also likely that alternative approaches can be taken concerning the settling lagoon. Constructing the EC settling lagoon was one of the highest construction costs associated with the project. Existing dairies may already have a lagoon that could be used as an EC settling lagoon and avoid that construction cost which would decrease the estimated cost of the EC system. Alternatively higher fertilizer values would also alter the economic break-even conclusions.

Objective 4: Disseminate the information through an outreach program

A variety of presentations / consultations on research findings were made, including representation at the Conservation Innovation Grants Showcase. A nutrient management field day was hosted at the Vander Haak Dairy, which included presentations on nutrient recovery and high quality fiber. The research result from this project was presented in 12th World Anaerobic Digestion Congress in Mexico. An invited article was submitted to the Water Science and Technology.

References

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.

Bektas, N., Akbulut, H., Inan, H. and Dimoglo, A. (2004). Removal of phosphate from aqueous solutions by electro-coagulation. Journal of Hazardous Materials, 106(2-3), 101-105.

Frear, C., Liao, W., Ewing, T., Chen, S., (2011), Evaluation of co-digestion at a commercial dairy anaerobic digester, Clean: Water, Air, and Soil. (In press).

Jiang, A., Zhang, T., Zhao, Q., Frear, C. and Chen, S., (2010). Integrated Ammonia Recovery Technology in Conjunction with Dairy Anaerobic Digestion. CSANR Research Report. http://csanr.wsu.edu/publications/researchreports/CFF%20Report/CSANR2010-001.Ch08.pdf

Lai, C. L. and Lin, S. H. (2004). Treatment of chemical mechanical polishing wastewater by electrocoagulation: system performances and sludge settling characteristics. Chemosphere, 54(3), 235-242.

Suzuki, K., Tanaka, Y., Osada, T. and Waki, M. (2002). Removal of phosphate, magnesium and calcium from swine wastewater through crystallization enhanced by aeration. Water Research, 36, 2991–2998.

Spears, R. A., A. J. Young, and R. A. Kohn. (2003). Whole-Farm Phosphorus Balance on Western Dairy Farms, J. Dairy Sci. 86:688–695.

Waki N, Kondo H and Nishida M. (1987). Study of phosphorus removal from digester supernatant by aeration. Journal of Water & Wastewater, 29, 10-14.

Zhao, Q., D. Davidson, T. Zhang, J. Ma, C. Frear, S. Chen and J. Harrison. (2010). Enhanced phosphorus removal from anaerobically digested dairy manure by electro-coagulation. IWA Conference, 2010.

Zheng, X. Y., Kong, H. N., Wu, D. Y., Wang, C., Li, Y. and Ye, H. R. (2009). Phosphate removal from source separated urine by electrocoagulation using iron plate electrodes. Water Science and Technology, 60(11), 2929-2938.

Zongo, I., Maiga, A. H., Wethe, J., Valentin, G., Leclerc, J. P., Paternotte, G. and Lapicque, F. (2009). Electrocoagulation for the treatment of textile wastewaters with Al or Fe electrodes: compared variations of COD levels, turbidity and absorbance. J Hazard Mater, 169(1-3), 70-76.

In the space below, provide the following in accordance with the Environmental Quality Incentives Program (EQIP) and CIG grant agreement provisions:

a. A listing of EQIP-eligible producers involved in the project, identified by name and social security number or taxpayer identification number;
Darryl Vander Haak, Vander Haak Dairy LLC., 91-1740544

b. The dollar amount of any direct or indirect payment made to each individual producer or entity for any structural, vegetative, or management practices. Both biennial and cumulative payment amounts must be submitted.
No direct or indirect payment has been made to a producer for structural, vegetative or management practices at this time.

c. A self-certification statement indicating that each individual or entity receiving a direct or indirect payment for any structural, vegetative, or management practice through this grant is in compliance with the adjusted gross income (AGI) and highly-erodible lands and wetlands conservation (HEL/WC) compliance provisions of the Farm Bill.
No individuals received payment.