**Title:** Recovery of phosphorus and fine particles as fertilizer from swine manure by electrocoagulation **– NPB #15-037**

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revised

**Industry Summary**

Pork production is one of the most important agricultural activities in the United States, and 75% of the swine operations are geographically located in the Upper-Midwest. The environmental effects of swine manure storage systems and land application are raising significant concerns, for instance, the threats to surface water and groundwater quality by phosphorus overloading. Meanwhile, swine manure contains a significant portion of small particles with poor settling capability, challenging the solid/liquid separation process via either sedimentation, filtration, or drum screen. Land application of manure is based on crops' nitrogen requirement, which overloads phosphorus on cropland over the years because of the unbalance nutrient composition in swine manure. A cost effective relocation of excess phosphorus would allow existing animal feeding operations to successfully implement phosphorus-based nutrient management plans on their current land base, increase the valorization of the so-called swine manure waste stream, decrease the environmental impacts from swine operations and increase the national food and resources security. The electrocoagulation process developed in this project effectively assisted natural sedimentation as a separation method. After electrocoagulation and sedimentation, between 70% and 90% of phosphorus can be concentrated in sludge with a volume of only 5% to 10% of the untreated manure volume. The resulting supernatant is more nitrogen concentrated with a nitrogen:phosphorus ratio between 10 and 40, compared with initial ratio of around 2. The sludge has a phosphorus contents of between 5% and 10%. This nutrient composition change provides an opportunity of producing more nutrient balanced manure as fertilizer with less contaminating tendency and of economical long-distance transportation. Based on our pilot scale demonstration results, the techno-economic analysis revealed the capital and operational costs and we also used the present value and annualized cost to show the financial outcomes of installation of the EC into current pig operations. For instance, in a typical barn with 2400-head of pigs, installing and operating an EC in deep-pit manure management system will add $1.03 per grown-finish pig.

**Keywords: swine manure; phosphorus removal; phosphorus recovery; nutrient balance; electrocoagulation; manure management system; water reuse; volume reduction**

**Scientific Abstract**

Swine manure typically contains total solids between 1% and 5%, and approximately half of the solids has particle sizes equal to or less than 45 microns. The fine particles poses challenges to solid-liquid separation, so that a



substantial amount of solids still remains in the separated liquid layer after natural sedimentation, centrifugation

or drum screen. The issue is further worsened by the fact that an appreciable amount of phosphorus exists in the fine particles. Anode oxidation of certain metal electrodes releases metal ions that can work as coagulants, binding phosphate and neutralizing fine particles which form larger ones to precipitate or to be flocculated. This study proposed to adopt electrocoagulation (EC) technology to recover phosphorus and fine particles from swine manure to increase its fertilizer value. The objectives of this study include: 1) optimization of electrocoagulation for phosphorus and fine particles recovery from swine manure; 2) pilot scale demonstration and techno-economic analysis of the process; 3) integration of the new electrocoagulation process with current manure management practice. The study found that EC using low carbon steel effectively removed P and fine particles from the liquid manure collected from the two manure management systems of lagoon storage and deep-pit storage. Although particle size change was not obvious, settling ability of swine manure particles were improved so that natural sedimentation is effectively to separate the liquid and solids phase after EC treatment. More costly separation methods, e.g., centrifuge and filtration, were not necessary in S/L separation process. The achieved results are promising since79.5% and 91.6% of P was recovered from flushed manure, while 73.0% and 83.1% of P from deep-pit manure, resulting in concentrated P contents (5.83% to 9.24% of $P_2O_5$ in dry matter) in sludge in our pilot study. The resulting sludge had small N:P ratios of 0.52-0.53 and 0.67-0.78 for each manure types in respective. The process also substantially increased N:P ratios in supernatant. For example, the untreated flushed manure had a N:P ratio of 1.72, and deep-pit manure of 2.45. After EC treatment and sedimentation, the supernatant was more N concentrated, with N:P ratios of 17.2-38.7 and 10.7-13.3 for each manure type. The changes of nutrients proportion makes the manure more suitable to be applied in nearby croplands with reduced P loading, indicated an environmental benefit of less P runoff going to nearby receiving water bodies. The pilot-scale EC skid installed on campus swine barn had a capacity of treating 100 L/day (or 8 hrs). The total cost of setting up this skid was $3539. Manure production capacity in a typical 2400-head barn was estimated to process 20.79 thousand $m^3$/yr of flushed manure, or 2.175 thousand $m^3$/yr of deep-pit manure. Cost analysis for a scale that treats all the generated manure plus operating costs showed a net present value of the investment would be $447,647 for flush system, and $148,082 for deep-pit system. The present analysis did not take into account of the environmental benefits of P removal, the benefits of more nutrient-balanced manure, and the value of the P-enriched sludge as a potential fertilizer. A full techno-economic analysis, or cost-benefit analysis will better elucidate the entire social-economical value of the technology.

## Introduction

With the increasing scare of swine operations, better processing and value-added utilization approaches are needed for the manure management. We need to make a full use of manure nutrient components, conserve the aquatic and atmospheric environment, and most importantly, bring potential revenues to swine producers. Manure has a high fertilizer value because it contains high levels of organic matter, phosphorus (P), nitrogen (N), and potassium (K) which are intensively needed by any crops. Land application of swine manure improves soil quality by accumulating soil organic matter and reduces the cost of purchasing commercial fertilizer, and it is in fact the mainstream way that farmers are utilizing it.

Although swine manure as excreted has total solids of 10%, manure flushing practice substantially decreases the solid content down to between 1% and 5%. Assuming the same nutrients level in dry matter and a value of $100/ton-dry solids, a truckload of manure at FOB origin at 10, 30, 50, and 70% moisture content has a decreasing value of $1519, $1400, $1219 and $938 [1]. The truck transportation cost is linear to the distance between swine barns and cropland, about $3/semi-truck/mile; therefore, a solid-liquid separation process is necessary to reduce the moisture content to certain level in the manure solid at prior otherwise transportation bears too high a cost. The separated liquor can be used for flushing or irrigation.

Besides its application limits to nearby cropland due to the relatively low nutrient content and subsequent high transportation cost, swine manure especially has an imbalanced high concentration of phosphorus when used as a crop (i.e., corn) nutrient. The nitrogen: phosphorus ($N:P_2O_5$) ratio is too low as a fertilizer to be applied to a corn crop, especially in many regions where the soil has a high phosphorus level. With the increasing size of swine farms, especially in areas where livestock raising is highly concentrated, the surplus manure applied on soil increases the phosphorus concentration in agricultural runoff, causing environmental problems such as eutrophication. In contrast, many crop fields with phosphorus needs are using chemical fertilizers to provide phosphorus. At the current rate, excavation is predicted to deplete high-quality phosphorus rock for fertilizer production in 50 to 100 years. The increasing cost of extraction and refinement of poor phosphorus rock and the rising demands for food production will drastically increase the price of phosphorus fertilizer. Therefore, onsite treatment of surplus phosphorus in the swine manure reveals its importance in both the livestock raising area and the waste phosphorus, which will be valuable resources if recoverable, especially from swine production.

Solid-liquid separation of manure is a desirable approach to address all these concerns. Concentrating manure solids can reduce the volume and expense of transportation. It can also relatively separate the phosphorus with the solids while leaving most of the nitrogen with the liquids. After separation, the liquids could be land applied near the manure source as a nitrogen fertilizer. The solids could be transported and applied to fields in need of phosphorus fertilizer. Solid-liquid separation of manure can be achieved by gravity settling, mechanical separation (screen, filtration, centrifugation, etc.) and chemical separation. Measurements such as separation efficiency (the total solid difference between influent and liquor) and the related mass removal efficiency are used to evaluate the effectiveness of the separation practice. The most common separation methods in swine industry are screen and natural sedimentation. Their separation efficiency would in part depend on the particle size distribution of manure solids because there is a lower limit of particle size that each method can work on. The screen usually does not remove particles with size lower than 100 or 200 microns, and the sedimentation works on particles with around 10 to 20 microns but takes longer operating time. Although the residue solid particles in the liquid are with much small size, they can account for a large portion of the total solids; and more importantly, these fine particles (smaller than 250 microns) contain most of nutrients elements, especially phosphorus in manure.

Another scenario of manure management in swine farms is to treat manure slurry by anaerobic digestion, the currently recommended technology for bioenergy production and nutrient management for animal wastes. As a biological process that generates biogas [2], it kills pathogens such as Escherichia coli and Salmonella spp., and converts organic nitrogen to ammonium which becomes readily available for plant uptake. But a remarkable drawback of anaerobic digestion is that it does not show benefits on phosphorus removal from the liquid part so anaerobic digestion effluent still contains a high level of phosphorus either as organic or inorganic phosphate. The digestate thus has a potential to cause various environmental issues when directly discharged including eutrophication which severely damages aquatic ecological systems. The particle size distribution of solids is also shifted to smaller scale after anaerobic digestion: particles smaller than 10 microns represented 64% and 84% of total solids in raw and digested swine manure, respectively [3].

Phosphorus and fine particles separation from liquid swine manure is an important issue. Similarly, studies on methods for phosphorus and solids recovery from anaerobic digestion effluent needs investigation of the same level. In fact, recovery and recycle of P from liquid swine manure and anaerobic digestion effluent would offer a sustainable way of producing P fertilizer compared to the current approach that P is unsustainably mined from phosphate rocks of which according to some estimation that the reserve would be depleted within a century [4]. In summary, recover of P from liquid swine manure and anaerobic digestion effluent is critical to the sustainability of the swine industry and of the whole agriculture systems of the country. As aforementioned, sedimentation or direct mechanical liquid-solid separation would have little effect on fine particles separation, pretreatment of manure or combination with other processes is preferred. Most commercialized phosphorus removal processes for municipal wastewater are flocculation methods by dosing divalent or trivalent metal cations through chemicals such as iron sulfate, alum, or lime [5]. Colloids in wastewater repel from each other because of the coverage of the negative on particulates surface so that a repelling electrostatic force counteracts with van der Waals force and separate them from each other. The dispersed cations from dosed chemicals will provide positive charges in bulk liquid and neutralize the surface charge of colloids, causing an increased attraction among colloids and eventually forming larger particles of flocs. The dissolved phosphorus will also be scavenged by metal cations to insoluble forms. Coagulation may be followed by flocculation to form larger agglomerates, or the wastewater can be directly subject to some physical separation processes, such as screen, sedimentation, or filtration.

The traditional way of coagulation is conducted by the addition of coagulants such as divalent or trivalent metal cations in salt, but the cost for per ton of iron ions is close to $1200 for ferrous and $2000 for ferric. We are proposing in this study to use electrochemical methods to realized coagulation, a process never tried for swine manure as far as we know. Electrochemically generated iron ions cost only $500 to $600/ton from mild steel and carbon iron, and the electrocoagulation (EC) method is easier to maintain and operate and is more environmentally benign as it does not bring about contaminating anions to the manure media. This technology will concentrate phosphorus in a small volume of sludge, increase $N:P_2O_5$ ratio, and decrease manure transportation cost for long-distance land application.

**Objectives**

Swine manure typically contains total solids between 1% and 5%, and approximately half of the solids has particle sizes equal to or less than 45 microns. The fine particles pose challenges to solid-liquid separation, so that a substantial amount of solids still remains in the separated liquid layer after natural sedimentation, centrifugation or drum screen. The issue is further worsened by the fact that an appreciable amount of phosphorus exists in the fine particles. Anode oxidation of certain metal electrodes releases metal ions that can work as coagulants, binding phosphate and neutralizing fine particles which form larger ones to precipitate or to be flocculated. This study proposes to adopt electrocoagulation technology to recover phosphorus and fine particles from swine manure to increase its fertilizer value. The objectives of this study include: 1) optimization of electrocoagulation for phosphorus and fine particles recovery from swine manure; 2) pilot scale demonstration and techno-economic analysis of the process; 3) integration of the new electrocoagulation process with current manure management practice.

**Materials and Methods**

***Brief technology description of electrocoagulation***

The stability of colloidal system in manure is maintained principally by two ways: the coverage of the negative charge on particulate surface so that a repelling electrostatic force counteracts with van der Waals force and separates particulates from each other; and the hydration of the surface layers of colloids. Destabilization of colloidal systems is the first step for coagulation. The efficacy of aluminum and iron coagulants principally originates from their ability to form multi-charged poly-nuclear complexes that enhance their adsorption capability. Hydrated metal ions ($Al^{3+}$ and $Fe^{3+}$) with one or more hydroxyl ions are observed to substantially improve absorptivity and coagulation, but it is not clear through what mechanisms the hydrolysis and the poly-nuclear complexation improve adsorption (sweep flocculation). The formation of insoluble amorphous metal hydroxide precipitate also provides an important way as adsorbents for phosphate to attach. Generally, the hydrolyzed cations generated from dosed chemicals (applied in solid or solution forms depending on the chemicals used) will provide positive charges in bulk liquid and neutralize the surface charge of colloids, causing an increased attraction among colloids and destabilizing the colloidal system. The destabilized particles are followed by flocculation process through metal hydroxo complexes to form larger agglomerates, eventually forming larger particles of flocs. This mechanism can be especially useful because it is well accepted that the majority of manure phosphorus already exists in the colloidal form rather than dissolved phosphate anions, so crystallization of phosphate salts may be unnecessary prior to coagulation. Precipitation of insoluble phosphate salts, e.g., $FePO_4$ and $Fe_5(PO_4)_2(OH)_9$ when ferric is added, is another significant factor contributing to phosphate removal. When chemical dosing is high, insoluble metal hydroxides are precipitated from liquid, which will also enmesh particulate materials by a sweep action. After flocculation the wastewater can be directly subjected to some physical separation processes, such as floating, gravitational sedimentation, screw press, or filtration.

Electrochemical coagulation (electrocoagulation, EC) is an alternative to chemical coagulation. The main mechanism responsible for coagulation is similar in electrocoagulation and chemical dosing, except the self-generation of metal cations by anode oxidation. The electrocoagulation offers some advantages over chemical dosing; as it has simple equipment requirement and can be readily automated; reduces the chemical cost by using cheaper materials; gas bubbling provides gentle mixing that promotes coagulation and helps form bigger flocs; pH is easily maintained because cathode reaction consumes protons; and gas bubbling carries some particles up to the top of liquid in a way of flotation, which may be easily separated. So electrocoagulation is not only an alternative to the conventional way, but also a promising method due to its effectiveness and low cost, which has been used for phosphate removal from drinking water, turbidity reduction, and wastewater remediation.

***Electrode evaluation***

Electrode evaluation was based on medium of dairy manure. Four electrodes were evaluated for their coagulation performance. The compositional information on the materials was listed in Table 1, and price information was listed in Table 2.

Table 1. Properties of electrode materials in the screening experiments

| **Parameters** | **304 Stainless steel** | **Al** | **Low carbon steel** | **Grey cast iron** |
|---|---|---|---|---|
| Iron or Al content/% | 53.48-74.5 | 96-97.35 | 98.06-99.42 | 92.11-95 |
| Carbon content/% | 0-0.08 | - | 0.13-0.2 | 2.6-3.75 |
| Manganese content/% | 0-2 | 0-0.15 | 0.3-0.9 | 0.6-0.95 |
| Silicon content/% | 0-1 | 0.4-0.8 | 0.15-0.3 | 1.8-3 |
| Phosphorus/% | 0-0.2 | - | 0.04 (Max) | 0.12 (Max) |
| Other elements | Chromium (17.5-25%), Nickel (8-15%), Copper, Molybdenum, Sulfur, Cobalt, Nitrogen | Iron (0.7), Copper (0.15-0.4), Chromium, Zinc (0.25), Others | Sulfur (0.5 max) | Sulfur (0.07 max) |
| Electrical Resistivity/ microhm/cm @ 68 ℉ | 69.97-77.95 | 39.9 | 19.5 | 110 |
| Price/ $/lbs | 8.79 | 9.75 | 5.37 | 18.64 |

Table 2. FOB price ranges for metal bars listed at Alibaba *

| ***Metal*** | ***Product or products series*** | ***Alibaba Listed FOB Price range per Ton*** |
|---|---|---|
| **Low carbon steel** | *Q235 low carbon steel flat bar* | $410 - 860 |
| | *Low carbon flat steel bar* | $375 - 440 |
| | *Mild steel flat bars* | $300 - 500 |
| **Grey cast iron** | *ductile/grey cast iron bar/round flat bar* | $850 - 1,250 |
| | *GG25 continuous cast Iron bar* | $700 - 1,000 |
| **SS AISI 304** | *SS 304 flat bar for industrial use* | $1,300 - 4,000 |
| | *304 304L316 316L SS Flat Bar* | $800 - 2,500 |
| | *304 SS flat bar* | $800 - 3,000 |
| **Aluminum** | *Aluminum flat bar* | $670 - 800 |
| | *DIN ASTM BS aluminum flat bar* | $700 |
| | *Aluminum Flat Bar* | $500 - 2,555 |
| **Magnesium** | *Magnesium metal bar* | $6,000 - 6,500 |

* FOB prices were retrieved from Alibaba website on October 20$^{th}$, 2015.

Figure 1 shows different phosphorus (total P) removal efficiencies of electrocoagulation with four electrode materials. Phosphorus removal efficiency by aluminum electrode reached 96.4% of total phosphorus at 70 min, while the iron-containing electrode materials achieved the removal efficiencies as follows at 100 min: 87.1% by low carbon steel, 76.9% by cast iron, and 90.9% by stainless steel. Although the removal with stainless steel 304 was the highest among the three iron containing electrodes (SS, low carbon steel and cast iron), it went slow during the initial half an hour. From the composition information, it can be seen that anode oxidation of SS potentially releases other heavy metals besides iron, therefore making SS not suitable material. Problem with aluminum was that during operation, electrode surface needed to be continually cleaned to have enough contact with liquid manure for maintaining electrical current level; otherwise the contact was blocked by the deposits on anode. The comparison between low carbon steel and cast iron persuaded us to adopt the former one because: 1, the former one had similar or slightly higher P removal efficiency than that of the latter at any time point; 2, low carbon steel had a relatively lower prices based on listed Alibaba FOB prices; and 3, low carbon steel had a lower resistivity which may consume less power than cast iron.

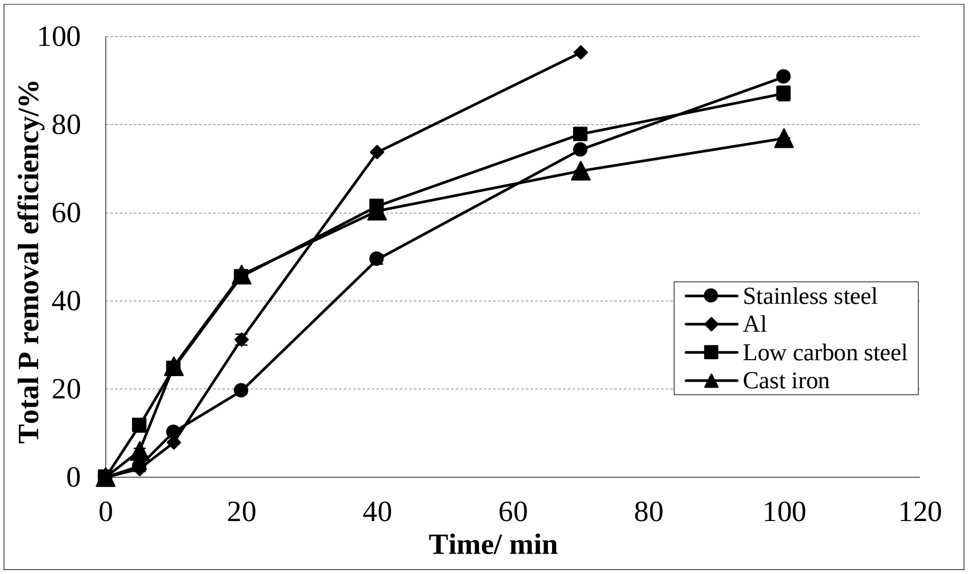



Figure 1. Total phosphorus removal efficiency with different electrode materials (Current=1 A, initial pH=6, initial phosphorus concentration=100 mg/L, agitation speed=150 rpm).

***Solids and Nutrients Analysis***

Samples were taken before and during electrocoagulation process. Total phosphorus concentration in the supernatant after 3000×g centrifugation for 12 min was tested by ascorbic acid reduction method with Hach kits (TNT 845 and TNT 843, purchased from Hach Company, Loveland, CO). Particle size distribution of manure was tested with the well mixed manure samples. The sample was serial filtrated by sieves with 45 µm, 150 µm, 250 µm, 425 µm, 850 µm and 2000 µm pore sizes. The particles smaller than 45 µm were separated by vacuum filtration with pore sizes of 2.7 µm, 8 µm, 25 µm (Waterman, company). The particles with different sizes and total solids were dried at 100 ºC overnight, respectively, and the weight was measured after cooled down to room temperature. Total phosphorus content in particles larger than 45 µm: Particles with different sizes were collected as described above; a specific amount of collected solids was incinerated at 550 ºC for 30 min, followed by 1 mL of 1 N H2SO4 solution to dissolve the solid and 1 mL of 1 N NaOH solution to neutralize the solution; then total phosphorus was measured by Hach kits. Total phosphorus content in particles between 0.45 µm and 45 µm: The filter papers were cut into small pieces and immerged into 10 ml 1 N HCl; the phosphorus was extracted overnight on a table shaker; the extraction was neutralized by 1 N NaOH before test.

***Real density test for manure particles***

The settling velocity of the particles with diameter of 25-45 µm was evaluated by Stokes' law:

$$V = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2 \qquad 1$$

where V is the flow settling velocity (m/s), $\rho_p$ is the mass density of the particles (kg/m$^3$), ρf is the mass density of the fluid (kg/m$^3$), g is the gravitational acceleration (m/s$^2$) and μ is the dynamic viscosity (kg/m·s). The average radium of the particles was considered as 35 μm. The solids were first dried at room temperature for one day and grinded into powder before freeze drying at -80 °C for two days. The particle density, $\rho_p$, was tested by helium pycnometer (Micrometrics AccuPycTM 1330 Pycnometer). $\rho_f$ was determined by measuring the volume and weight of the background fluid (liquid manure after filtration of 25 μm) at 20±1 °C. U-tube viscometers were used to measure the viscosity of the background fluid at 20±1 °C.

**Results**

***<u>Results for objective #1: optimization of electrocoagulation for phosphorus and fine particles removal</u>***

***Performance for foaming and non-foaming swine manure***

Non-foaming and foaming swine manure showed an initial reactive P content of 56.5 and 71.9 mg/L, and total P content of 67.3 and 99 mg/L (Figure 2), respectively. For reactive phosphorus, the removal efficiency reached over 80% for both types of manure; for total phosphorus, the removal efficiency for non-foaming and foaming manure was 69.1% and 81.3% at 100 min. There were lag phase of reactive P removal, which roughly took 10 min when EC started; while total phosphorus removal did not display an obvious lag phase for both manure types. After the lag phase, reactive P removal underwent a linear pattern until maximal removal efficiency (82.9%-85.8%) or low P content (9.68-10.2 mg/L) was achieved. Total phosphorus removal directly went through a linear pattern against contact time until maximal removal efficiency (69.1%-81.3%) or low P content (18.48-20.78 mg/L) was achieved.

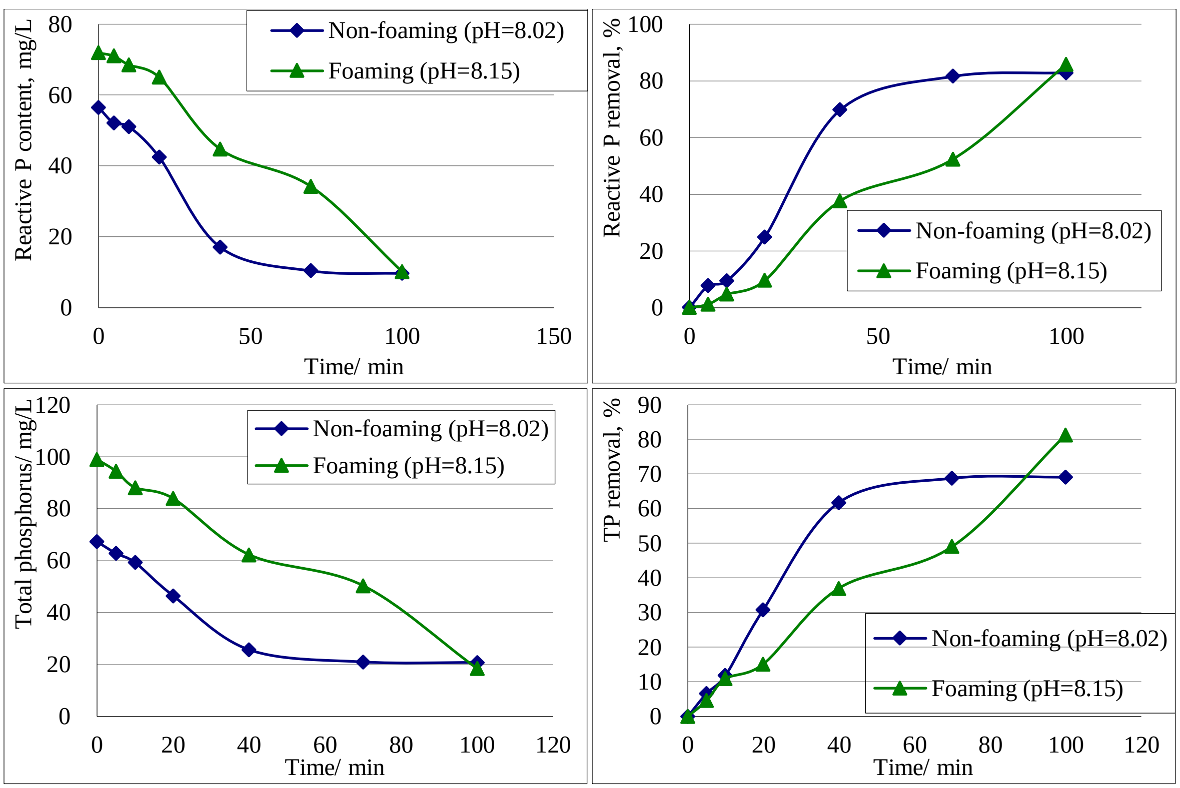


Figure 2. Total and reactive phosphorus removal efficiency for non-foaming and foaming swine manure.

***Removal of fine particles***

For both non-foaming and foaming manure, solids content with particle size larger than 425 μm was increased after EC treatment (Figure 3), which indicated the occurrence of coagulation and flocculation. For the foaming manure, solids with particle sizes smaller than 45 μm was slightly decreased from 2.4% to 2.26%. For the non-foaming manure, solids with particle sizes smaller than 45 μm kept almost unchanging.

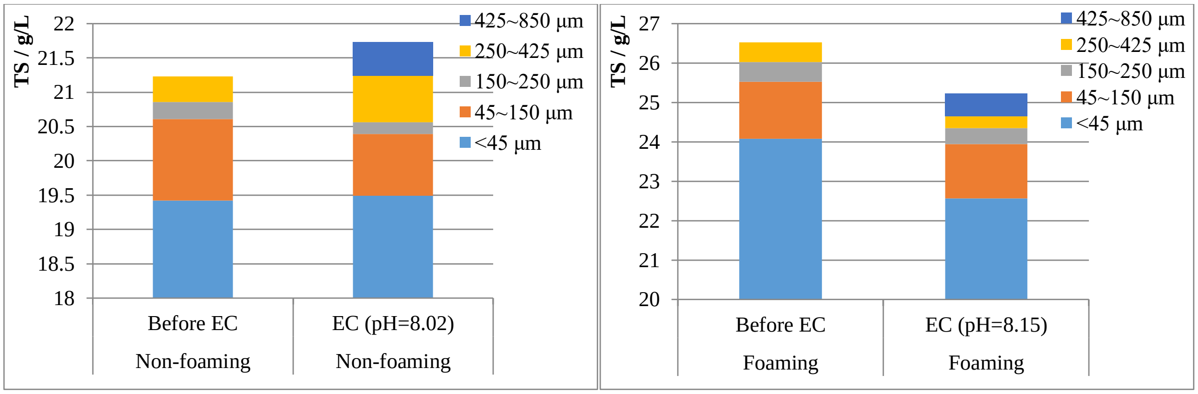



Figure 3. Total solids of different particle size.

Further solids quantification was carried out between particle sizes between 0.45 to 45 µm. Again, TS of smaller particles (e.g., <0.45 µm) was not decreased but showed a slight increase for both non-foaming (NF) and foaming (F) manure (Figure 4). The TS increase of this portion can be explained by release of iron to manure media because part of the iron would be in the form with small particle sizes, which was in accordance with a substantial increase on TS of the whole sample.

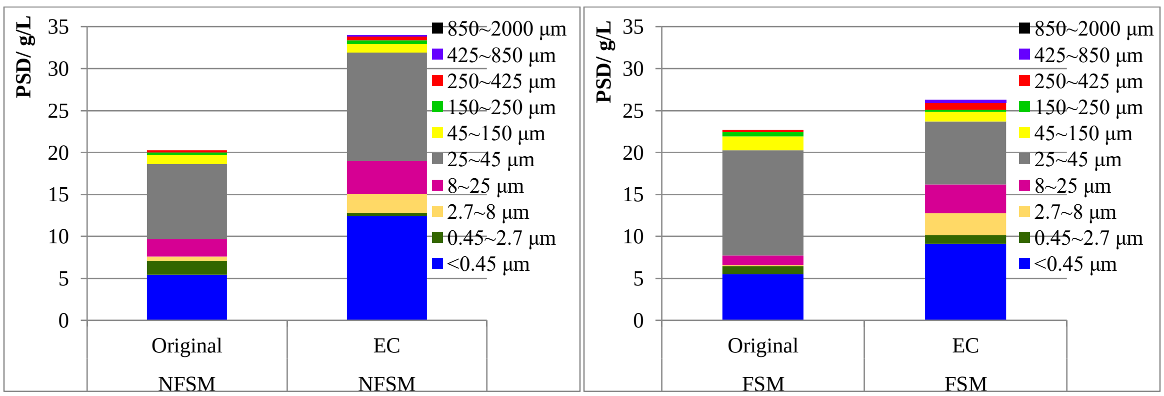
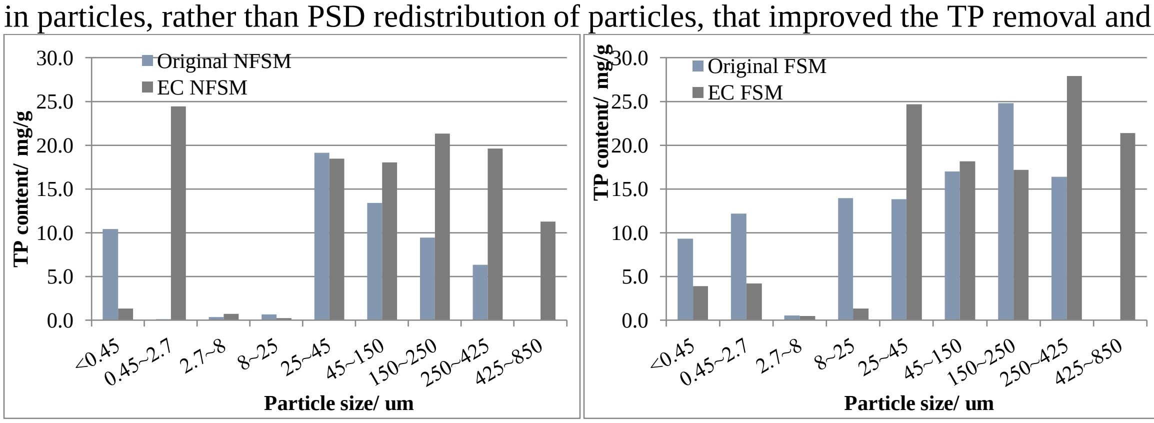



Figure 4. Total solids of different particle size (including separation between 0.45 and 45 µm).

Analysis on the TP contents in solids of different particle sizes further indicate the occurrence of coagulation (Figure 5). Generally, TP content decreased substantially for particles with sizes smaller than 25 µm (except for the fraction of non-foaming manure with particle sizes between 0.45 and 2.7 µm), and TP content constantly increased for particles with sizes greater than 25 µm. While the PSD distribution was only slight modified by EC, this redistribution of TP content yielded an decrease of TP amount in solids with particle sizes smaller than 25 µm which was relatively more difficult to separate using centrifugation than larger size particles. Therefore, these results indicated that for both non-foaming and foaming swine manure, it was principally the TP content change in particles, rather than PSD redistribution of particles, that improved the TP removal and recovery (Figure 3).



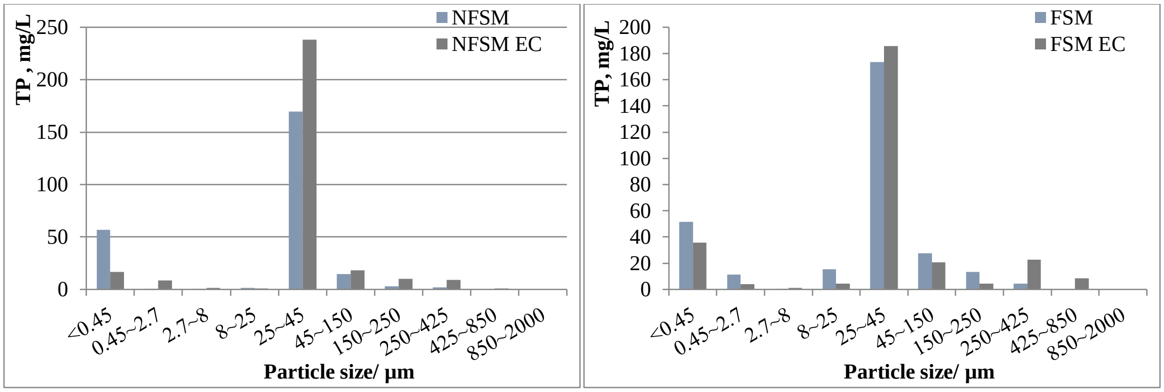



Figure 5. TP contents in solids of different particle size and total amount of P retained in solids of different particle size.

### *Effect of pH*

The adjustment of manure pH to 6 by hydrochloric acid apparently increased both the reactive and total phosphorus in the centrifuge supernatants, because some of insoluble phosphate minerals were dissolved to orthophosphate in supernatant due to the lower pH and the increased solubility of those minerals such as struvite, calcium phosphate and hydroxyapatite, etc. For both non-foaming and foaming manure, the reactive P removal reached over 98% and the remaining reactive P was as low as 1-5 mg/L. Total phosphorus removal reached over 95% with the remaining TP concentration of 7.5-28 mg/L. Those results suggested that although pH decrease dissolved large amount of phosphorus to liquid phase, it actually didn't affect EC phosphorus removal (Figure 6).

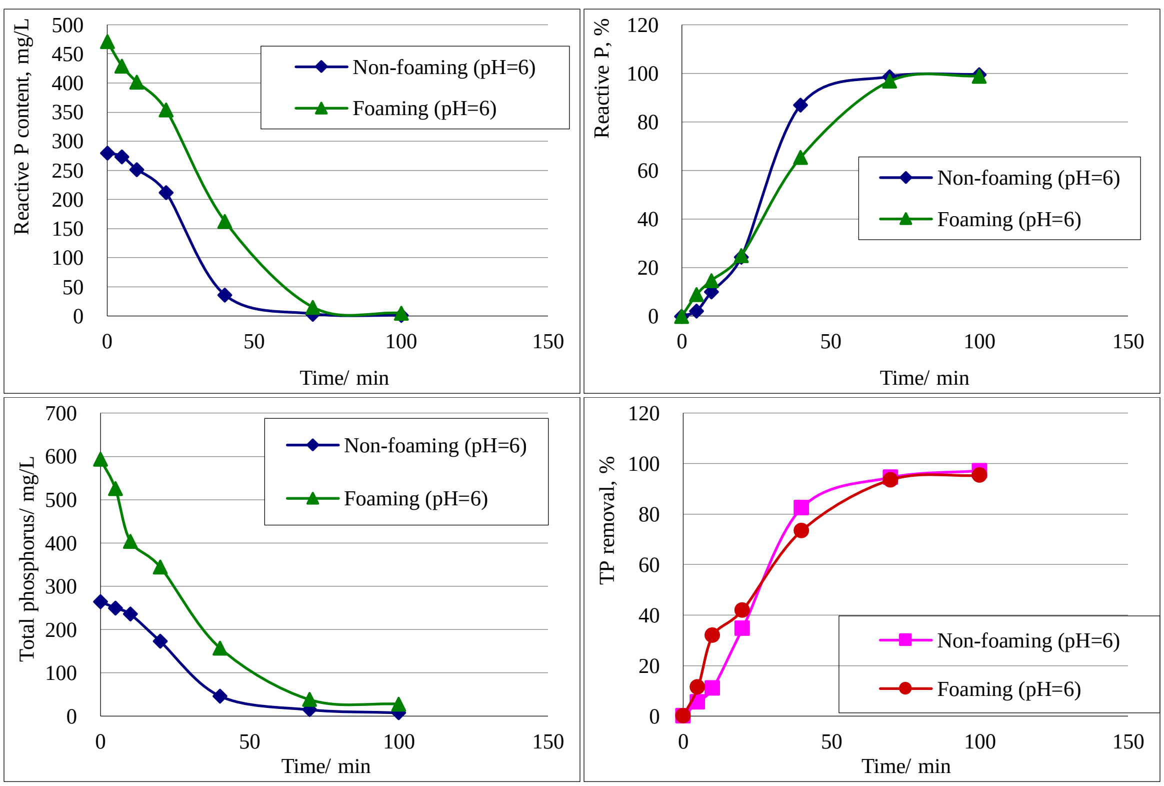



Figure 6. Total and reactive phosphorus removal efficiency for non-foaming and foaming swine manure at adjusted pH of 6.

In EC process, pH is an important parameter because it influents the solubility of some phosphorus compounds, such as calcium phosphate and iron phosphate [6]. The initial pH of SM 1 and SM 2 (diluted) were 8.02 and 8.15, respectively. Two levels of initial pH, original pH and pH=6, were investigated in this experiment. From Figure

7 we can see that the total phosphorus concentration in the supernatant significantly increased after pH adjusted to 6. It increased from 67.3 mg/L to 264.3 mg/L for SM 1 and from 99.0 mg/L to 593.0 mg/L for SM2. This indicated that there are large amount of calcium phosphate in SM 1 and SM 2. The calcium phosphate was insoluble when pH was around 8 so it's easy to be settled down by centrifugation. When the pH was adjusted to 6, calcium phosphate was dissolved in the acidic condition which results the high phosphorus concentration in the supernatant after pH decreased. Since EC is a buffering process, either the runs with original initial pH or with adjusted initial pH, the final pH was buffered to 8.12~8.89 with 100 min's EC treatment (Table 3). The total phosphorus concentration in the supernatant decreased to 20.78 mg/L (initial pH=8.02) in SM 1 and 18.48 mg/L (initial pH=8.15) in SM 2, which reached the phosphorus removal efficiency of 69.1% and 81.3%, respectively. Although adjusting initial pH to 6 increased the initial total phosphorus in the supernatant a lot, the pH buffering function makes most of the calcium phosphate precipitate again so that the final phosphorus concentration in the supernatant was 7.52 mg/L (SM 1) and 27.8 mg/L (SM 1). This data suggests that decreasing the initial pH contributes to phosphorus removal in SM 1 but it shows the opposite results in SM 2. The average particle size change in Table 3 shows some reasons for this. Before EC, the average particle size was 34.3 μm (SM 1) and 36.0 μm (SM 2). The major mechanism of EC to remove contaminants is coagulation and it leads to the increase of particle size [7]. In this experiment, the average particles size increased by 16.4 μm (SM 1) and 11.3 μm (SM 2), which indicates phosphorus was coagulated by the coagulants, i.e. iron hydroxides, and therefore more phosphorus may be precipitated by centrifugation. However, the change was not as obvious as EC treated dairy manure under the same operation condition. After adjusting the initial pH to 6, the average particle size in SM 1 was 57.4 μm after EC, higher than that without pH treatment. Figure 8 shows that more large particles (≥250 μm) were generated after EC, especially when the initial pH decreased to 6. The amount of particles smaller than 45 μm was decreased while more solids between 45 μm and 250 μm were formed. Maybe more phosphorus that used to combine with calcium complexed with the coagulants after dissolved. On the contrary, the adjustment of initial pH in SM 2 leaded to the increase of the amount of the small size particles (<45 μm). Although there were particles larger than 425 μm generated, the amount was too small to affect the phosphorus removal. Comparing the phosphorus removal data, initial pH adjustment is not proper for all the swine manure treatment by EC. Besides, a large amount of $H_2SO_4$ was used to decrease the pH from 8 to 6 due to the high content of carbonate in the manure. It adds additional ions and increases the cost as well. Therefore, adjusting initial pH is worthless.

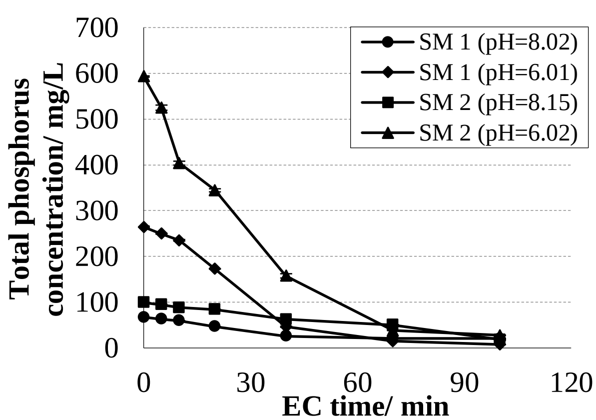



Figure 7. Total phosphorus concentration in the supernatant during EC (Current=1 A, initial pH: original and adjusted, agitation speed=150 rpm, retention time=100 min).

Table 3. pH and average particle size change before and after EC

| | | SM 1 | | SM 2 | |
|---|---|---|---|---|---|
| pH | Before EC | 8.02 | 6.01 | 8.15 | 6.02 |
| | After EC | 8.89 | 8.24 | 8.80 | 8.12 |

| | | | | | |
|---|---|---|---|---|---|
| Average particle size (μm) | Before EC | 34.3 | - | 36.0 | - |
| | After EC | 50.7 | 57.4 | 47.3 | 37.8 |

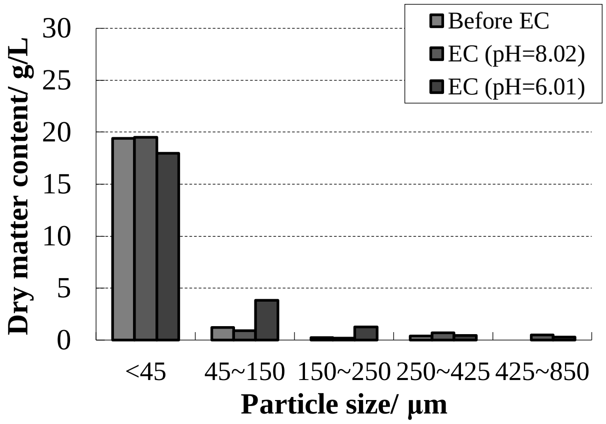



Figure 8. Particle size distribution of SM 1

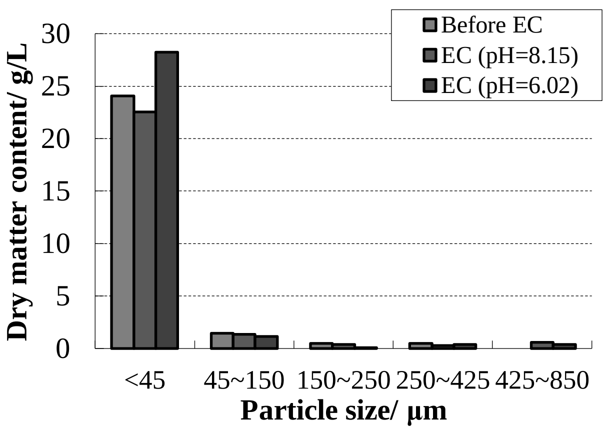



Figure 9. Particle size distribution of SM 2

***Effect of EC on settling capability***

The settling ability is evaluated by the phosphorus concentration and the total solids in the supernatant at different natural setting time (without centrifugation). Figure 10 shows that the phosphorus concentration in the raw manure decreased from 439.0 mg/L to 358.0 mg/L for SM 1 and from 770.0 mg/L to 597.5 mg/L for SM 2 after EC due to the formation of form and electrode deposits. The colloidal particles make manure become a stable and therefore the solid-liquid separation process is more difficult. However, the phosphorus concentration in the supernatant of raw swine manure was decreased along with the precipitation time in this experiment because the dilution of the manure destroyed the stability. For SM 1, 50.5% phosphorus was removed in raw manure at 120 min while 63.0% was removed in EC treated manure at the same time period. After one day's precipitation, only 94.1 mg/L and 33.78 mg/L phosphorus was left in the supernatant, respectively (data shows in Table 4). The results of two day's precipitation were comparable with the results of centrifugation at 3000 g for 12 min, which was 83.5 mg/L in the raw manure and 15.82 mg/L in the EC treated manure. The total solid amount at different settling time matches the phosphorus removal very well (Figure 11), in which the TS in the supernatant of EC treated manure decreased at a faster rate than that of raw manure and decreased 4.7 g/L in 120 min. It indicates that improving the settling ability of the phosphorus-contained particles contributes to phosphorus removal. The phosphorus in SM 2 was not as easy to be separated as that in SM 1 because the phosphorus concentration was much higher. In the raw SM 2, there was 153.5 mg/L phosphorus left in the supernatant after 1 day's precipitation and 145.5 mg/L left after 2 days' precipitation. While in EC treated SM 2, it was 81.5 mg/L and 65 mg/L phosphorus in the supernatant, respectively. Neither of them reached the results of SM 2 by centrifugation. Figure 12 also shows that the settling ability of SM 2 was not improved a lot after EC. Optimization of EC and separation process for SM 2 is needed.

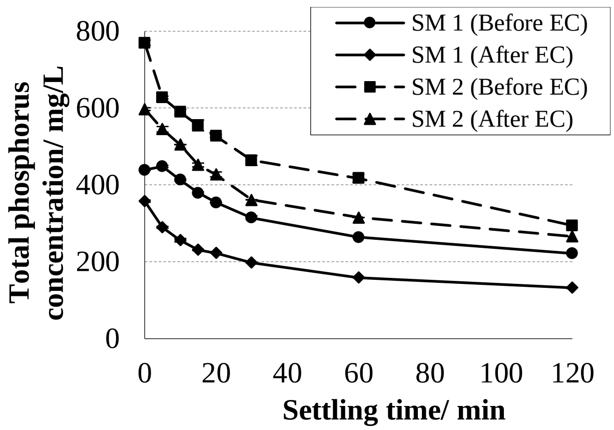



Figure 10. Total phosphorus concentration in the supernatant at different settling time before and after EC (Current=1 A, initial pH: original, agitation speed=150 rpm, retention time=100 min)

Table 4. Phosphorus removal by different separation methods

| | | In total | Supernatant after centrifugation | Supernatant after 1 day's settling | Supernatant after 2 days' settling |
|---|---|---|---|---|---|
| Lonetree barn (SM 1) | | | | | |
| P concentration/ mg/L | Before EC | 439.0 | 67.3 | 94.1 | 83.5 |
| | After EC | 358.0 | 20.0 | 33.8 | 15.8 |
| P removal efficiency/ % | By precipitation | | 72.8 | 61.9 | 84.7 |
| | By EC | | 70.3 | 64.1 | 70.3 |
| | Overall | | 91.9 | 86.3 | 95.4 |
| Kelso barn (SM 2) | | | | | |
| P concentration/ mg/L | Before EC | 770.0 | 99.0 | 153.5 | 145.5 |
| | After EC | 597.5 | 18.5 | 81.5 | 65.0 |
| TP removal efficiency/ % | By precipitation | | 66.7 | 48.3 | 87.1 |
| | By EC | | 81.3 | 46.9 | 81.3 |
| | Overall | | 93.8 | 72.6 | 97.6 |

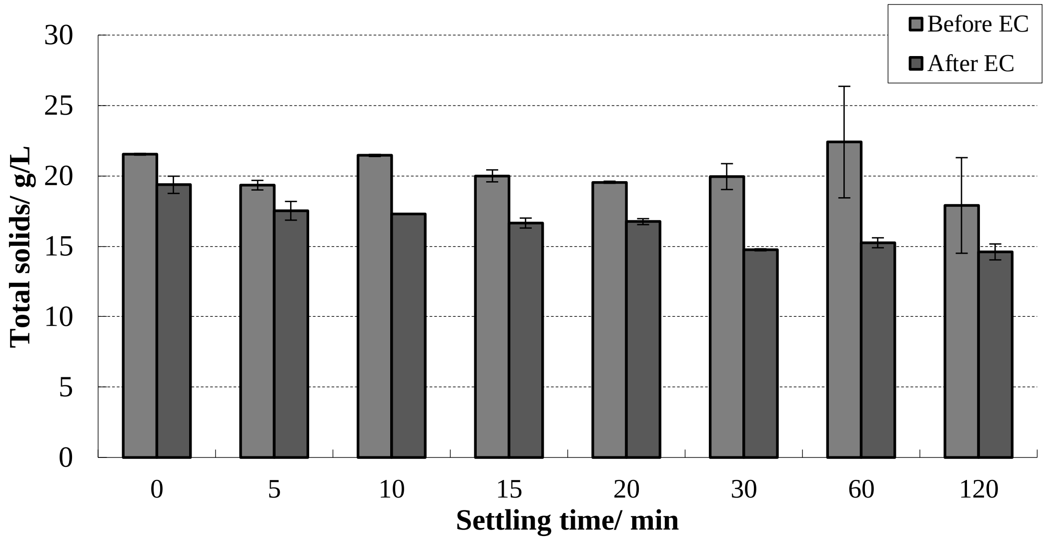


Figure 11. Total solids of SM 1 at different settling time before and after EC

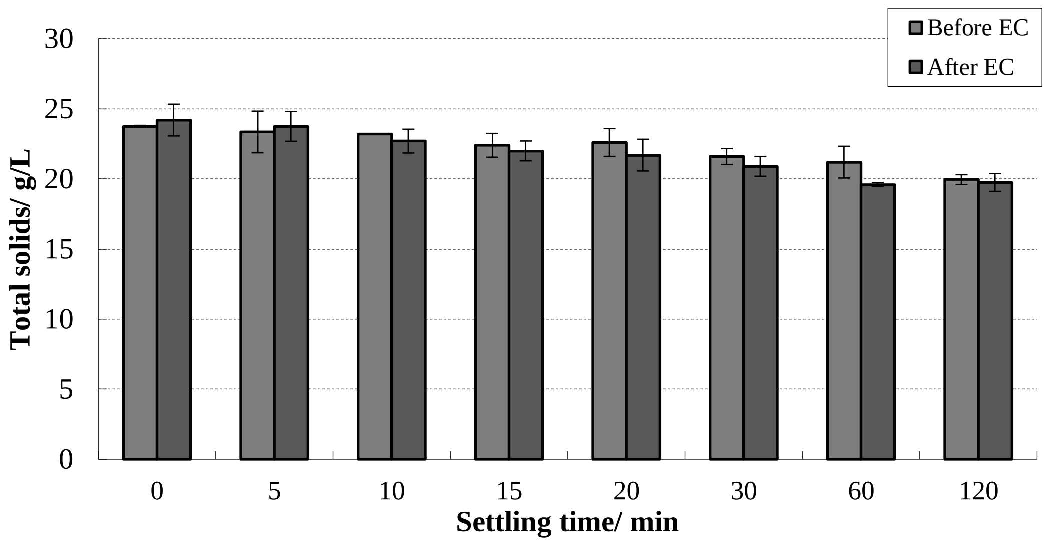


Figure 12. Total solids of SM 2 at different settling time before and after EC

***Particle density and stokes' law***

According to the previous results mentioned in this paper, about 90% of the solids were smaller than 45 μm, therefore, particle size distribution with more specific size ranges were analyzed. The data shows that solids with the size of 25-45 μm were the largest amount wherever in the raw manure or the EC treated manure. It was the same for total phosphorus content which was much higher in 25-45 μm portions. Comparing with the raw SM 1 and the EC treated SM 1, the TP content in <0.45 μm-portion was decreased by 70% after EC while it was increased in the other parts of solids. It indicates that phosphorus was "transferred" from soluble form (considering the portion smaller than 0.45 μm as soluble salts) to more insoluble form (larger than 0.45 μm) during EC process. However, the change of TP distribution in SM 2 was more complicated. It was decreased in the parts of <2.7 μm, 8-25 μm and 45-250 μm, and increased in the other parts.

Table 5 Particle size and phosphorus distribution (Current=1 A, initial pH: original, agitation speed=150 rpm, retention time=100 min)

| Filter size | SM 1 | | | | SM 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Before EC | | After EC | | Before EC | | After EC | |
| | Dry matter | TP | Dry matter | TP | Dry matter | TP | Dry matter | TP |
| μm | g/L | mg/L | g/L | mg/L | g/L | mg/L | g/L | mg/L |
| <0.45 | 5.45 | 56.60 | 12.46 | 16.85 | 5.51 | 51.40 | 9.13 | 35.60 |
| 0.45~2.7 | 1.67 | 0.20 | 0.35 | 8.56 | 0.92 | 11.22 | 0.99 | 4.13 |
| 2.7~8 | 0.46 | 0.16 | 2.21 | 1.60 | 0.17 | 0.09 | 2.62 | 1.28 |
| 8~25 | 2.13 | 1.44 | 3.97 | 0.84 | 1.11 | 15.49 | 3.44 | 4.48 |
| 25~45 | 8.87 | 169.77 | 12.89 | 237.97 | 12.56 | 173.42 | 7.53 | 185.74 |
| 45~150 | 1.09 | 14.57 | 1.02 | 18.38 | 1.63 | 27.67 | 1.14 | 20.70 |
| 150~250 | 0.32 | 3.02 | 0.47 | 10.02 | 0.54 | 13.40 | 0.25 | 4.29 |
| 250~425 | 0.29 | 1.83 | 0.47 | 9.23 | 0.26 | 4.27 | 0.82 | 22.88 |
| 425~850 | 0.00 | 0.00 | 0.08 | 0.90 | 0.00 | 0.00 | 0.39 | 8.34 |

Table 6. Stokes' law parameters

| Samples | | $\rho$ | $\rho_p$ | $\rho_f$ | $\mu\times10^3$ | V (Natural precipitation) |
|---|---|---|---|---|---|---|
| | | kg/m$^3$ | kg/m$^3$ | kg/m$^3$ | kg/m*s$^2$ | cm/min |
| SM 1 | Before EC | 1346 | 1289 | 981 | 1.99 | 0.62 |
| | After EC | 1413 | 1361 | 981 | 1.64 | 0.93 |
| SM 2 | Before EC | 1462 | 1338 | 991 | 3.35 | 0.41 |
| | After EC | 1526 | 1380 | 984 | 2.34 | 0.68 |

*Note: $\rho$ is the solid density of the whole manure solids. $\rho_p$ is the solid density of 25-45 μm portion, $\rho_f$ is the liquid density of <25 μm portion. The gravitational acceleration is 9.81 m/s$^2$.

As stated in Table 6, the density of raw manure solids was 1346 kg/m$^3$ for SM 1 and 1462 kg/m$^3$ for SM 2. After EC treatment, the density increased to 1413 kg/m$^3$ and 1526 kg/m$^3$, respectively, which increased by 4~5%. Since the particles between 25 and 45 μm were the majority and contained most of the phosphorus, further studies about the particles within this size range were did and the liquid portion after filtration by 25 μm was considered as background fluid. The parameters of Stokes' law are shown in Table 6. The density of SM 1 solids between 25 and 45 μm ($\rho_p$) increased from 1289 kg/m$^3$ to 1361 kg/m$^3$ (increasing 72 kg/m$^3$), while $\rho_{p,\ MS\ 2}$ increased by 42 kg/m$^3$. That indicates that under this operation condition, electrocoagulation mainly works on coagulation (increasing the particle density) rather than moving on to flocculation (increasing particle volume). However, no matter SM 1 or SM 2, $\rho_p$ was less than the density of the whole manure solids, which suggests that there should be particles in other sizes that were much denser than the particles with size of 25-45 μm. The density of the liquid portion with <25 μm was in the range of 981-991 kg/m$^3$, close to the density of water, but the viscosity was much higher than that of water. The data shows that the viscosity of background liquid was decreased after EC treatment, and this contributes to the precipitation of solids. The natural precipitation velocity is calculated by Stokes' law as shown in Table 6. It was increased by 49.8% and 63.6% for particles of 25-45 μm in SM 1 and SM 2, respectively. The settling ability of EC treated solids is increased significantly.

***Results for objective #2: pilot-scale reactor demonstration and techno-economic analysis for electrocoagulation process for swine manure***

Based on the previous results of TP removal from liquid portion of swine manure, pilot-scale EC treatment skid was designed and installed at compositing building on St. Paul Campus at University of Minnesota (Figure 13).

Two EC tanks were tested, a 15 L capacity aquarium tank and a 10 gal capacity cone-shaped tank, with a designated operating volume of 10 and 20 L, respectively. Manure samples for treatment were flushed manure collected from campus barn and liquid portion of deep-pit manure collected from a local commercial deep-pit storage in a swine barn located in Gaylord, MN.  After EC treatment, the combined manure from all batches was pumped to a 30 gal sedimentation tank for overnight separation. Operating parameters were listed in Table 7. The volumes of supernatant (liquid portion) and sludge portion from each operation were measured, and three samples of each portion were collected for nutrient analysis.

Figure 13. Left, skid for electrocoagulation; right, alternate placement of anode and cathode in an EC tank.

Table 7. Operating conditions for pilot-scale EC skid treating flushed manure and deep-pit manure

| **Aquarium  tank with flushed manure** | | | **Corn-shape tank with flushed manure** | | |
|---|---|---|---|---|---|
| Vol, one batch | 10 | L | Vol, one batch | 20 | L |
| Elecrical current | 8 | A | Electrical current | 16 | A |
| Voltage | 8-8.9 | V | Voltage | 6.5 | V |
| Operating time of one batch | 30 | min | Operating time of one batch | 40 | min |
| Number of batches | 7 | | Number of batches | 4 | |
| Energy consumption | 0.237 | kWh | Energy consumption | 0.069 | kWh |
| **Aquarium  tank with deep-pit manure** | | | **Corn-shape tank with deep-pit manure** | | |
| Vol, one batch | 10 | L | Vol, one batch | 20 | L |
| Electrical current | 12 | A | Electrical current | 19 | A |
| Voltage | 3.4 | V | Voltage | 2.6 | V |
| Operating time of one batch | 70 | min | Operating time of one batch | 120 | min |
| Number of batches | 5 | | Number of batches | 2 | |
| Energy consumption | 0.048 | kWh | Energy consumption | 0.099 | kWh |

The results of nutrients composition are given in Table 8. The untreated flushed manure had a total nitrogen to phosphate (P2O5) ratio (N:P) of 1.72, and deep-pit manure of 2.45. Compared to the nutrient balance requirement corn-corn rotation of 3.33 (Table 9), both manure showed surplus of phosphorus and short of nitrogen. The EC process recovered 79.5% and 91.6% of P in sludge from flushed manure, while recovered 73.0% and 83.1% of P in sludge from deep-pit manure. The corresponding P2O5 contents were 7.59% TS and 8.16% TS for flushed manure, and 5.83% TS and 9.24% TS for deep-pit manure. Therefore, the resulting sludge was more P concentrated, with N/P ratios of 0.52-0.53 and 0.67-0.78 for each manure types in respective. Meanwhile, the supernatant was more N concentrated, with N:P ratios of 17.2-38.7 and 10.7-13.3 for each manure type. The changes of nutrients proportion indicated that when the treated manure was applied to nearby croplands, it had a less tendency of P overload, and that the P concentrated sludge, especially after drying, could be used or sold as

P-enriched fertilizer. The volume of the solid manure was reduced 93.7% and 94.6% for flushed manure, and 87.6% and 89.2% for deep-pit manure, of the volume before treatment, and therefore the P transportation for long-distance application would become tremendously more possible.

Table 8. Change of nitrogen to phosphorus ratio before and after electrocoagulation

| | Flushed manure | | Deep-pit manure | | Unit |
|---|---|---|---|---|---|
| | 7 batches of aquarium tank | 4 batches of cone-shaped tank | 5 batches of aquarium tank | 2 batches of cone-shaped tank | |
| | Amount or conc. | Amount or conc. | Amount or conc. | Amount or conc. | |
| Ratio of TN/P2O5 in untreated flush manure | 1.72 | | 2.45 | | Dimensionless |
| Volume of liquid after separation | 74.14 | 68.15 | 41.65 | 34.60 | L |
| Volume of sludge after separation | 4.22 | 4.56 | 5.91 | 4.20 | L |
| Total volume of manure | 78.36 | 72.71 | 47.56 | 38.80 | L |
| P2O5 in liquid | 1.10 | 0.47 | 8.25 | 6.25 | g |
| P2O5 in sludge | 4.26 | 5.09 | 40.42 | 16.87 | g |
| TN in liquid | 18.93 | 18.17 | 109.32 | 66.66 | g |
| TN in sludge | 2.22 | 2.70 | 26.92 | 13.13 | g |
| TS in liquid | 246.63 | 146.52 | 603.89 | 518.04 | g |
| TS in sludge | 56.11 | 62.43 | 437.62 | 289.13 | g |
| P2O5 content in sludge | 7.59 | 8.16 | 9.24 | 5.83 | % based on TS |
| Volume reduction | 94.61 | 93.73 | 87.58 | 89.18 | % |
| P2O5 recovery in sludge | 79.51 | 91.56 | 83.05 | 72.95 | % |
| TS recovery in sludge | 18.53 | 29.88 | 42.02 | 35.82 | % |
| Ratio of TN/P2O5 in liquid | 17.24 | 38.72 | 13.25 | 10.66 | Dimensionless |
| Ratio of TN/P2O5 in sludge | 0.52 | 0.53 | 0.67 | 0.78 | Dimensionless |

Table 9. Nutrient balance requirement by plants and change of nitrogen to phosphorus ratio before and after electrocoagulation

| | Ratio of N/P2O5 | Ref |
|---|---|---|
| Recommended for corn-corn rotation | 3.33 | Iowa swine manure calculator |
| Recommended for corn-soybean rotation | 1.44 | Iowa swine manure calculator |
| Swine manure slurry: fresh raw manure | 1.43 | Managing Manure Fertilizers in Organic Systems |
| Liquid manure: flushed manure | 1.72 | This study |
| Liquid manure: deep-pit manure | 2.45 | This study |
| (Flushed manure) liquid portion: after EC treatment and sedimentation | 17.24 and 38.72 | This study |
| (Flushed manure) sludge portion: after EC treatment and sedimentation | 0.52 and 0.53 | This study |
| (Deep-pit manure) liquid portion: after EC treatment and sedimentation | 10.66 and 13.25 | This study |
| (Deep-pit manure) sludge portion: after EC treatment and sedimentation | 0.67 and 0.78 | This study |

Cost analysis for the pilot-scale EC skid (treating 100 L/day) showed that it took $3539 of capital cost to install the skid on site (Table 10 and Table 11). The annual cost of operating and maintaining the skid showed it cost $2717 and $2725 for reaching the treatment capacity for each manure type, respectively.

Table 10. Cost analysis for a pilot-scale EC device treating 100 L flushed manure daily

| *Items* | | | *Description* | *Unit price ($)* | *# of item* | *Cost ($)* |
|---|---|---|---|---|---|---|
| **Capital cost** | Equipment | Aquarium EC tank | From Petsmart. Glass-made, 20 L volume | 14.99 | 1.00 | 14.99 |
| | | 10 gal inductor EC tank with stand | Ordered from USPlastic | 187.96 | 1.00 | 187.96 |
| | | 30 gal inductor sedimentation tank with stand | Ordered from USPlastic | 293.22 | 1.00 | 293.22 |
| | | Pipe and skid components | From HomeDepot. Shelf, CPVC pipes, ball valves, clips, connectors, electrode holders, clapms, tapes, pails, etc., and general tools like pipe cutter | Not specified | Not specified | 564.74 |
| | | Pumps | Used pumps. SHURflo Liquid Transfer Pumps, 3.8 gal/min | 134.00 | 2.00 | 268.00 |
| | | Electrodes | From McMaster-Carr. Low carbon steel | Not specified | Not specified | 154.80 |
| | | DC power supply | Ordered from CircuitSpecialist | 165.02 | 1.00 | 165.02 |
| | | Other electronic parts | From HomeDepot. Switches, GFCI panel, charging clips, power strips, etc. | Not specified | Not specified | 78.28 |
| | | *Total equipment cost* | *Sum of the above* | | | *1727.01* |
| | Labor cost of installation | Labor spent for preparation and installation | Postdoc | 20.80 | 16.00 | 332.80 |
| | | | Graduate student | 18.49 | 80.00 | 1479.20 |
| | | *Total labor cost* | *Sum of the above* | | | *1812.00* |
| | **Total capital cost** | | **Sum of the above** | | | **3539.01** |
| **Annual cost** | | Electricity | Fluid handling capability for a flow rate of ca. 100 L/day | 0.14 | 21.47 | 3.01 |
| | | | EC energy consumption at 100 L/day | 0.14 | 110.05 | 15.41 |
| | | Electrode consumption | Estimated to change electrode set every 3 months | 154.80 | 4.00 | 619.20 |
| | | Labor-related operations | Automatic operation | | 0.00 | 0.00 |
| | | Maintenance | Weekly inspection of an hour, $40 direct wage and salary | 40.00 | 52.00 | 2080.00 |
| | **Total annual cost** | | | | | **2717.61** |
| **Net present value** | | **(P/A, 8%, 20), 9.8181, Ref for i [8]** | **Assuming 20 yrs operation and 8% i** | | | **30220.80** |
| **Uniform amount per year** | | **(A/P, 8%, 20), 0.1019, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | **3079.50** |

The above estimate is for 100 L flushed manure

Table 11. Cost analysis for a pilot-scale EC device treating 100 L deep-pit manure daily

| *Items* | | | *Description* | *Unit price ($)* | *# of item* | *Cost ($)* |
|---|---|---|---|---|---|---|
| **Capital cost** | Equipment | Aquarium EC tank | From Petsmart. Glass-made, 20 L volume | 14.99 | 1.00 | 14.99 |
| | | 10 gal inductor EC tank with stand | Ordered from USPlastic | 187.96 | 1.00 | 187.96 |
| | | 30 gal inductor sedimentation tank with stand | Ordered from USPlastic | 293.22 | 1.00 | 293.22 |
| | | Pipe and skid components | From HomeDepot. Shelf, CPVC pipes, ball valves, clips, connectors, electrode holders, clapms, tapes, pails, etc., and general tools like pipe cutter | Not specified | Not specified | 564.74 |
| | | Pumps | Used pumps. SHURflo Liquid Transfer Pumps, 3.8 gal/min | 134.00 | 2.00 | 268.00 |
| | | Electrodes | From McMaster-Carr. Low carbon steel | Not specified | Not specified | 154.80 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | DC power supply | Ordered from CircuitSpecialist | 165.02 | 1.00 | 165.02 |
| | | Other electronic parts | From HomeDepot. Switches, GFCI panel, charging clips, power strips, etc. | Not specified | Not specified | 78.28 |
| | | *Total equipment cost* | *Sum of the above* | | | *1727.01* |
| | Labor cost of installation | Labor spent for preparation and installation | Postdoc | 20.80 | 16.00 | 332.80 |
| | | | Graduate student | 18.49 | 80.00 | 1479.20 |
| | | *Total labor cost* | *Sum of the above* | | | *1812.00* |
| | **Total capital cost** | | **Sum of the above** | | | **3539.01** |
| **Annual cost** | | Electricity | Fluid handling capability for a flow rate of ca. 100 L/day | 0.14 | 21.47 | 3.01 |
| | | | EC energy consumption at 100 L/day | 0.14 | 164.25 | 23.00 |
| | | Electrode consumption | Estimated to change electrode set every 3 months | 154.80 | 4.00 | 619.20 |
| | | Labor-related operations | Automatic operation | | 0.00 | 0.00 |
| | | Maintenance | Weekly inspection of an hour, $40 direct wage and salary | 40.00 | 52.00 | 2080.00 |
| | **Total annual cost** | | | | | **2725.20** |
| **Net present value** | | **(P/A, 8%, 20), 9.8181, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | **30295.30** |
| **Uniform amount per year** | | **(A/P, 8%, 20), 0.1019, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | **3087.09** |

Manure production capacity estimated that in a typical 2400-head barn, it would produce 20.79 thousand $m^3$/yr of flushed manure, or 2.175 thousand $m^3$/yr of deep-pit manure (Table 12). Cost analysis was conducted to calculate the investment required to build and operate an EC apparatus for treating the generated amount of swine manure with each manure management system, the lagoon storage system with flushed manure (Table 13), or deep-pit management system (Table 14). The net present value of the investment would be $447,647 for flush system, and $148,082 for deep-pit system. The incorporation of EC with deep-pit system costs far less than the incorporation with flush system, partially because of the smaller amount of the generated manure. Assuming a 20 year service-life of the skid, the annual cost was estimated to be $15089 for the deep-pit system. The present analysis did not take into account of the environmental benefits of P removal, the benefits of more nutrient-balanced manure, and the value of the P-enriched sludge as a potential fertilizer. A full techno-economic analysis, or cost-benefit analysis will better elucidate the entire social-economical value of the technology.

Table 12. Estimation on manure production in a typical 2400-head swine barn: lagoon storage system and deep-pit storage system

| | Estimation on pig manure excretion (finisher) | | American unit system | | SI unit system |
|---|---|---|---|---|---|
| Deep-pit storage | Pigs in a typical swine barn | 2400.00 | Head | 2400.00 | Head |
| | Average total solids of manure as excreted | 8.00 | % wet wt | 8.00 | % wet wt |
| | Manure excretion per pig per day | 1.20 [9] | gal/pig/d | 4.54 | L/pig/d |
| | Manure produced per barn | 2880.00 | gal/barn/d | 10886.40 | L/barn/d |
| | Manure of barn | 1051200.00 | gal/yr | 3973.54 | m^3/barn/yr |
| | Dry mass produced per day per barn | 1920.36 | lb/barn/d | 870.91 | kg/barn/d |
| | Dry mass produced per year per barn | 700931.75 | lb/barn/yr | 317.88 | m^3/barn/yr |
| | Deep-pit width | 80.00 | ft | 24.38 | m |

| | | | | | |
|---|---|---|---|---|---|
| | Deep-pit length | 200.00 | ft | 60.96 | m |
| | Deep-pit depth | 8.00 | ft | 2.44 | m |
| | Total storage capacity of deep-pit | 128000.00 | ft^3 | 3624.56 | m^3 |
| | Ratio of liquid to total manure volume | 0.60 | Dimensionless | 0.60 | Dimensionless |
| | Total solids of liquid portion of manure | 2.29 | % wet wt | 2.29 | % wet wt |
| | P2O5 of liquid portion of manure | 10.73 | lb/1000 gal | 1.29 | kg/m^3 |
| | N of liquid portion of manure | 26.26 | lb/1000 gal | 3.15 | kg/m^3 |
| | Ratio of N:P2O5 in liquid manure | 2.45 | Dimensionless | 2.45 | Dimensionless |
| | Volume of liquid manure to be treated per day | 1.58 | 1000 gal/d | **5.96** | **m^3/d** |
| | Volume of liquid manure to be treated per year | 575.33 | 1000 gal/yr | 2174.73 | m^3/yr |
| Lagoon storage | Total solids of flushed manure | 0.16 | % | 0.16 | % |
| | P2O5 of liquid portion of manure | 1.08 | lb/1000 gal | 0.13 | kg/m^3 |
| | N of liquid portion of manure | 1.86 | lb/1000 gal | 0.22 | kg/m^3 |
| | Ratio of N:P2O5 in liquid manure | 1.72 | Dimensionless | 1.72 | Dimensionless |
| | Estimated volume of liquid manure to be treated per day | 15.07 | 1000 gal/d | **56.96** | **m^3/d (see ref)** |
| | Estimated volume of liquid manure to be treated per year | 5500.00 [10] | 1000 gal/yr | 20790.00 | m^3/yr |

Table 13. Cost analysis [11] for a full scale EC device treating all flushed manure (57 $m^3$/day) produced by 2400-head grown-finish pigs

| ***Items*** | | | ***Description **** | ***Unit price ($)*** | ***# of item*** | ***Cost ($)*** |
|---|---|---|---|---|---|---|
| **Capital cost** | Equipment | 2000 gal EC tank | Fiberglass tanks: Cp=18*V^0.73 | 4624.07 | 1.00 | 4624.07 |
| | | 16000 gal sedimentation tank | Fiberglass tanks: Cp=18*V^0.73 | 21099.89 | 1.00 | 21099.89 |
| | | Pipe and skid components | Assuming 31% of the sum of tanks and pumps, Table 16.17 | 14487.81 | 1.00 | 14487.81 |
| | | Pumps | Stainless steel; 500 gpm; Estimated via Eq. 16.15 | 10505.45 | 2.00 | 21010.91 |
| | | Electrodes | Assuming proportional to flow rate factor, 570 | 88236.00 | 1.00 | 88236.00 |
| | | DC power supply | Bench power supply at kW power rating, e.g., XHR 1000W | 2075.00 | 1.00 | 2075.00 |
| | | Other electronic parts | Assuming 10% of the sum of tanks and pumps | 4673.49 | 1.00 | 4673.49 |
| | | *Total equipment cost* | *Sum of the above* | | | 156207.16 |
| | Labor cost of installation | Equipment preparation, construction, and test | assuming 66% of the total equipment cost | | | 103096.72 |
| | | *Total labor cost* | *Sum of the above* | | | 103096.72 |
| | **Total capital cost** | | **Sum of the above** | | | 259303.88 |
| **Annual cost** | | Electricity | Fluid handling capability for a flow rate of 57 m3/day | 0.14 | 12238.24 | 1713.35 |
| | | | EC energy consumption at 57 m3/day | 0.14 | 62727.08 | 8781.79 |
| | | Electrode consumption | Estimated consumption rate of 0.676 kg/m3 manure in treatment | 471 | 14.03 | 6608.13 |
| | | Labor-related operations | Automatic operation | | 0.00 | 0.00 |
| | | Maintenance | Weekly inspection of an hour, $40 direct wage and salary | 40.00 | 52.00 | 2080.00 |
| | **Total annual cost** | | | | | 19183.27 |
| **Net present value** | | **(P/A, 8%, 20), 9.8181, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | 447647.18 |
| **Uniform amount per year** | | **(A/P, 8%, 20), 0.1019, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | 45615.25 |

Table 14. Cost analysis for a full scale EC device treating all deep-pit manure (6 $m^3$/day) produced by 2400-head grown-finish pigs

| *Items* | | | *Description* | *Unit price ($)* | *# of item* | *Cost ($)* |
|---|---|---|---|---|---|---|
| **Capital cost** | Equipment | 200 gal EC tank | Fiberglass tanks: Cp=18*V^0.73 | 861.04 | 1.00 | 861.04 |
| | | 1600 gal sedimentation tank | Fiberglass tanks: Cp=18*V^0.73 | 3928.98 | 1.00 | 3928.98 |
| | | Pipe and skid components | Assuming 31% of the sum of tanks and pumps, Table 16.17 | 7998.29 | 1.00 | 7998.29 |
| | | Pumps | Stainless steel; 500 gpm; Estimated via Eq. 16.15 | 10505.45 | 2.00 | 21010.91 |
| | | Electrodes | Assuming proportional to flow rate factor, 60 | 9288.00 | 1.00 | 9288.00 |
| | | DC power supply | Bench power supply at kW power rating, e.g., XHR 1000W | 2075.00 | 1.00 | 2075.00 |
| | | Other electronic parts | Assuming 10% of the sum of tanks and pumps | 2580.09 | 1.00 | 2580.09 |
| | | *Total equipment cost* | *Sum of the above* | | | 47742.31 |
| | Labor cost of installation | Equipment preparation, construction, and test | assuming 66% of the total equipment cost | | | 31509.93 |
| | | *Total labor cost* | *Sum of the above* | | | 31509.93 |
| | **Total capital cost** | | **Sum of the above** | | | 79252.24 |
| **Annual cost** | | Electricity | Fluid handling capability for a flow rate of ca. 1600 gal/day, assuming proportional to flow rate | 0.14 | 1288.24 | 180.35 |
| | | | EC energy consumption, assuming proportional to flow rate | 0.14 | 9855.00 | 1379.70 |
| | | Electrode consumption | Estimated consumption rate of 1.26 kg/m3 manure in treatment | 471 | 2.74 | 1290.54 |
| | | Labor-related operations | Automatic operation | | 0.00 | 0.00 |
| | | Maintenance | Weekly inspection of two hours, $40 direct wage and salary | 40.00 | 104.00 | 4160.00 |
| | **Total annual cost** | | | | | 7010.59 |
| **Net present value** | | **(P/A, 8%, 20), 9.8181, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | 148082.94 |
| **Uniform amount per year** | | **(A/P, 8%, 20), 0.1019, Ref for i** | **Assuming 20 yrs operation and 8% i** | | | 15089.65 |

Table 15. Cost analysis for a full scale EC device treating all manure produced by 2400-head grown-finish pigs *

| ***Item*** | ***Number*** | ***Units*** |
|---|---|---|
| Barn construction cost, 8 sqft/pig | 350 | $/pig |
| Marketing weight | 350 | lb/pig |
| Capacity of a barn | 2400 | Pigs |
| Price of pork (based on pig weight) | 0.5 | $/lb |
| Rotation cycle for grow-finish | 3 | cycle/yr |
| Operating year of a barn | 20 | Yrs |
| Overall construction cost | 840000 | $ |
| Annual value of pigs with grow-finish | 1260000 | $/barn/year |
| NPV of pigs with 20 yrs barn operation | 12370806 | $ |
| NPV of 20 yrs EC installed in addition to deep-pit | 148083 | $ |
| Ratio of EC (deep-pit) cost to barn construction cost | 17.63 | % |
| Ratio of EC (deep-pit) cost to pig value | 1.20 | % |
| Additional cost by EC (deep-pit) | 1.03 | $/pig |
| NPV of 20 yrs EC installed in addition to lagoon | 447647 | $ |

| | | |
|---|---|---|
| Ratio of EC (lagoon) cost to construction cost | 53.29 | % |
| Ratio of EC (lagoon) cost to pig value | 3.62 | % |
| Additional cost by EC (lagoon) | 3.11 | $/pig |

* Parameters for barn construction cost and pig value estimations were obtained by personal communication with swine extension researcher, Dr. Larry Jacobson at University of Minnesota.

In summary, compared to the barn construction cost of $840K ($350 per pig space for 2400 pigs), the installation of EC system to the lagoon system will account for 31% of additional capital cost and will add $2.66 per grown-finish pig on the annual operational annual cost (7200 pigs in one 2400 pig barn). The installation of EC system to the deep-pit system will account for 9.4% of additional capital cost. If we combine the capital cost and annual operational cost together and use the present value (cost) to estimate, the 20 years net present value (cost) of both EC installation and operation accounts for 17.63% of the additional cost in deep-pit system, and for 53.29% in lagoon system. When compared to the pig value ($12M) that can be generated in 20 years, the annualized cost would account for 1.20% and 3.62% of the value in two management systems, respectively. Equivalently, it adds $1.03 and $3.11 per pig of additional annualized cost in the two management systems, respectively.

***Results for objective #3: feasibility study of applying electrocoagulation with current manure management practice***

The current study evaluated the P removal and recovery for the flushed manure and liquid portion of deep-pit manure, and P separation efficiency of 90% was achieved. However, there are still some technical and economical questions need to be answered before the swine industry can adopt this technology.

Possible modifications are suggested as shown in Fig. 14 and Fig. 15 for the lagoon system and deep-pit system respectively to incorporate the EC operation. The lagoon system is relatively simpler to implement EC operation since it is the only step to be added and then we will be able to have better separation of phosphorus enriched solids. The deep-pit system, however, will require to transfer the liquid manure for EC operation and return the supernatant back to the pit. The detailed design of the process is missing and how to make the logistics still needs significant input.

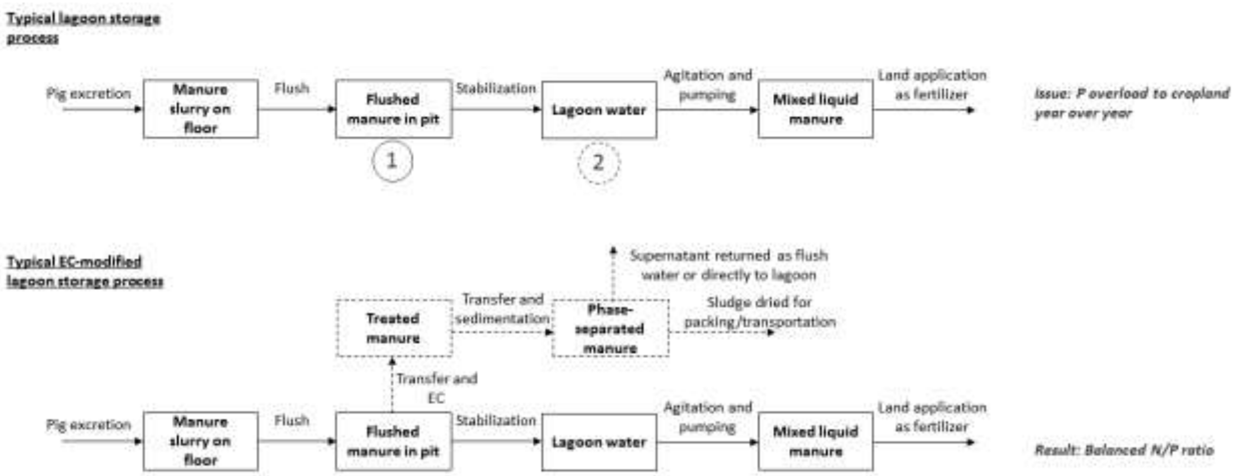


Figure 14. Process modification of lagoon manure storage system with electrocoagulation.

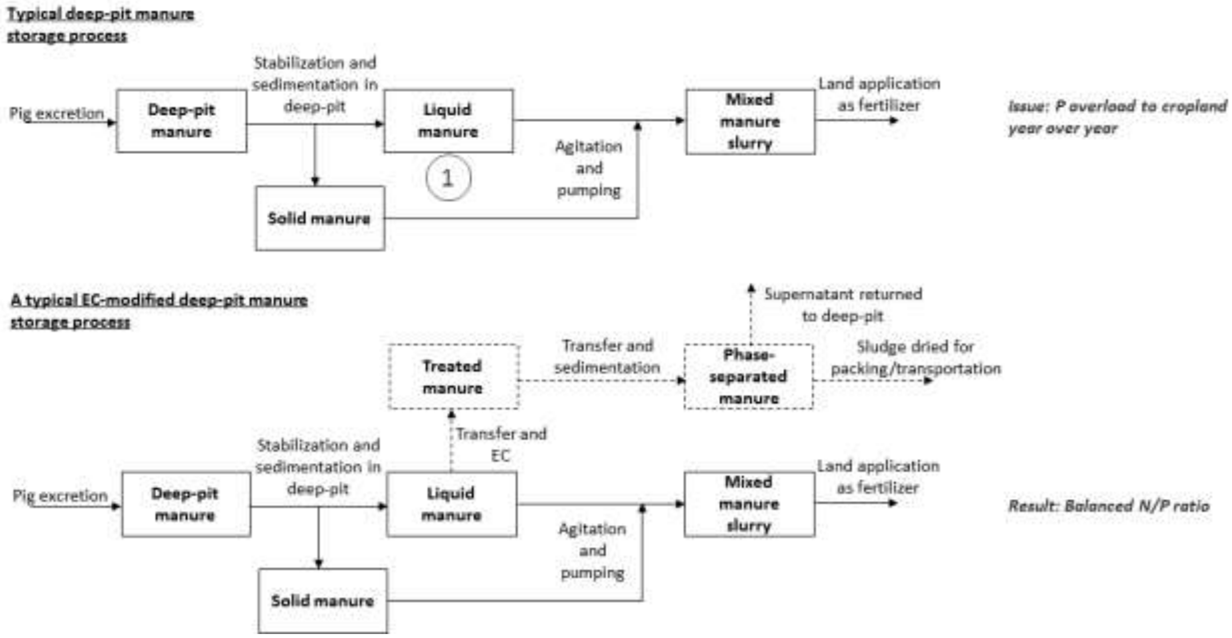



Figure 15. Process modification of deep-pit manure storage system with electrocoagulation.

**Discussion**

Pork production is one of the most important agricultural activities in the United States, and most of the pork production is geographically located in the Upper-Midwest which represents about 75% of the total American production. The environmental effects of swine manure storage systems and land application are raising significant concerns, for instance, the threats to surface water and groundwater quality. The application of manure is limited to the land around the livestock facility due to the transportation cost, and the soil can be saturated with nutrients, especially phosphorus, with the size increase of livestock operations. It is also considered an important contributor of pollutants entering surface waters and considerable efforts have been carried out in the United States to change practices in order to reduce this pollution. Another existing problem about swine manure utilization lies in solid-liquid separation: the separation is energy-intensive and is incomplete. The liquid layer from most separation methods still contains a high level of phosphorus and fine particles which are relatively high in nutrient values. Studies to increase the fertilizer use of swine manure will undoubtedly contribute to bringing in diversified revenues for swine producers and conserve the environment. Meanwhile, phosphorus is completely produced from non-renewable resources mainly phosphate rocks. Although predictions about the depletion of phosphorus are under intensive debate, mining rates are increasing in order to sustain the rising food and biomass energy demand. An increase of the price of phosphorus in 2007 and 2008 has created concern related with the security of the supply. Therefore, everyone wins with the recovery of phosphorus from swine manure. A cost effective relocation of excess phosphorus would allow existing animal feeding operations to successfully implement phosphorus-based nutrient management plans on their current land base, increase the valorization of the so-called swine manure waste stream, decrease the environmental impacts from swine operations and increase the national food and resources security.

Therefore, this project proposed to use electrocoagulation (EC) technology to recover fine particles and phosphorus from liquid portion of swine manure in sludge. Corresponding experimentation and analysis were conducted to evaluate technical and economic feasibility. Survey on opinions of incorporating EC with lagoon storage and deep-pit manure storage systems will be updated when information is collected from related experts like swine producers and manure management researchers.

EC effectively removed P and fine particles from the liquid manure collected from the two manure management systems. Although particle size change was not obvious, settling ability of swine manure particles were improved so that natural sedimentation is effectively to separate the liquid and solids phase after EC treatment. More costly separation methods, e.g., centrifuge and filtration, were not necessary in S/L separation process. The achieved results are promising because in pilot study, it recovered 79.5% and 91.6% of P from flushed manure, while 73.0% and 83.1% of P was recovered from deep-pit manure, resulting in concentrated P contents (5.83% to 9.24% of $P_2O_5$ in dry matter) in sludge. The resulting sludge had small N:P ratios of 0.52-0.53 and 0.67-0.78 for each manure types in respective. The process also substantially increased N:P ratios in supernatant. For example, the untreated flushed manure had a N:P ratio of 1.72, and deep-pit manure of 2.45. After EC treatment and sedimentation, the supernatant was more N concentrated, with N:P ratios of 17.2-38.7 and 10.7-13.3 for each manure type. The changes of nutrients proportion makes the manure more suitable to be applied in nearby croplands with reduced P loading, indicated an environmental benefit of less P runoff going to nearby receiving water bodies. The P concentrated sludge could be used or sold as P-enriched fertilizer. The volume of the manure was reduced 93.7% and 94.6% for flushed manure, and 87.6% and 89.2% for deep-pit manure, compared to the whole manure volume before treatment. If anaerobic digestion process is meanwhile installed, it has a chance of decreasing water content in sludge with on-farm generated heat, and the resulting dry sludge could be transported further with less burden of transportation cost.

The pilot-scale EC skid installed on campus swine barn had a capacity of treating 100 L/day (or 8 hr). The total cost of building this skid showed that it took $3539 of capital cost. Manure production capacity in a typical 2400-head barn was estimated to produce 20.79 thousand $m^3$/yr of flushed manure, or 2.175 thousand $m^3$/yr of deep-pit manure. Cost analysis for a scale that treats all the generated manure plus operating costs showed a net present value of the investment would be $447,647 for flush system, and $148,082 for deep-pit system. Assuming a 20 year service-life of the skid, the annual cost was estimated to be $15089 for the deep-pit system, which is more economical compared to its installation and operation in lagoon storage system. The present analysis did not take into account of the environmental benefits of P removal, the benefits of more nutrient-balanced manure, and the value of the P-enriched sludge as a potential fertilizer. A full techno-economic analysis, or cost-benefit analysis will better elucidate the entire social-economical value of the technology.

The feasibility of the suggested incorporation of the EC to current pig operations is still to be discovered, as it may primarily be determined by the willingness to put additional costs for better fertilizer use and minimizing the environmental impacts. There are still some more research work to do in order to clarify uncertainty about the technical and economic feasibility of the technology. We need to further identify the most suitable points for EC installation in manure management systems, to evaluate the possibility of incorporating anaerobic digestion and EC on a typical farm. We also need to explore the phosphorus fertilizer value of the EC sediment, its effectiveness and bio-availability, and its potential market as a cash product in order to boost industries' willingness to invest the installation of EC into their manure management system.

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