RESEARCHREPORT

ENVIRONMENT

Title: Sustainability Evaluation of a Solid-Liquid Manure Separation Operation - **NPB#16-094**

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Industry Summary:

The objectives of this research were to evaluate performance of a solid-liquid separation finishing barn in improving manure nutrient management, potential nutrient/water recycling based on filtration, and barn construction and operating costs. A full-scale barn in Missouri was closely monitored for the solid and liquid manure productions and nutrient contents. Laboratory scale pretreatments and filtrations were conducted to evaluate the practicality of nutrient/water recycling from the separated liquid manure. The daily liquid manure production averaged 885 gallons, and daily solid manure production averaged 299 gallons. The solid separation system removed 61.7%, 41.7%, 74.8%, and 46.2% of nitrogen, ammonium, phosphorous, and potassium, respectively, from the total manure production. The filtration results indicate that the microfiltration was capable of removing most if not all of the solids but not the dissolved nutrients. The reverse osmosis process was time and energy intensive, with only minimal nutrient removal, but was probably constrained by the relatively small-scale (inefficient compared with larger units), small filter surface area, and high dissolved nutrients in the liquid manure. The construction cost of the solid-liquid separation barn was comparable (17% higher than) to the deep-pit barn. Additional electricity cost was $331 per year for daily operation of the scraper and conveyor systems, and pumping the liquid manure. The additional maintenance of the scraper system averaged $1,342 per year. The solid-liquid separation barn was shown to have better air quality when compared with deep-pit barns.

Keywords: Feasibility, manure treatment, nutrient management, reverse osmosis, water recycling

Scientific Abstract

Field monitoring and laboratory tests were conducted to evaluate efficacy and practicality of a solid-liquid separation barn. The alternative swine finishing barn design made use of V-shape gutter and mechanical scraper system to separate manure into solid and liquid portions. The objectives were to evaluate performance of a solid-liquid separation barn and impact on manure management while considering factors including characteristics of the separated manure, potential nutrient and water recycling, and changes of barn construction and operating costs. This research also incorporated testing the pretreatment and various membrane filtrations for the liquid manure to be repurposed, as well as studying potential economic and environmental impacts. Waterproof pressure loggers were used to monitor the level of separated liquid manure in a collection pit. Volume of the separated solid manure was also monitored, along with barn inventory and feed consumption. The daily liquid manure production ranged from 298 to 1840 gallons, and averaged 885 gallons. The daily estimated solid manure production averaged 299 gallons. Nineteen monthly manure samples were collected for both the liquid and solid manure portions. Eight of the liquid manure samples were excluded from the database because they were outliers due to rainfall dilution, barn washing, or maintenance failure. Based on the averaged nutrient contents and overall production rates, the separated solid manure removed 61.7%, 41.7%, 74.8%, and 46.2% of nitrogen, ammonium, phosphorous, and potassium, respectively, from the total manure production. The removal efficiencies can be verified by the solid removal rate, that the separated solid manure contained 80.2% of the total solids when compared with the liquid manure portion.

The solid-liquid separation barn was shown to have better air quality when compared with deep-pit barns. Only discrete, monthly sampling of ammonia and hydrogen sulfide were conducted for this research. Ammonia concentrations measured at the wall and pit fans ranged from 0.26 to 6 ppm, with an average concentration below 2 ppm. Hydrogen sulfide concentration was below the detection limit of the Dräger tube method, and averaged 0.10 ppm when using the Jerome meter during the last few months of the research. Monthly samples of the separated liquid manure were collected and tested with various pretreatment and filtration, including microfiltration and reverse osmosis. A total of 26 samples were tested for the comparison of the unfiltered, microfiltration and reverse osmosis tests. Filtration of the liquid manure was conducted using a bench-scale crossflow membrane system. The filtration results indicate that the pH values change significantly during the filtration stages, the microfiltration was capable of removing most if not all of the solids but not the dissolved nutrients. The reverse osmosis process was time and energy intensive, with only minimal nutrient removal. Additional tests were conducted to confirm the filtration efficiency using salt solutions and different types of nanofiltration and reverse osmosis membranes, but no significant improvement could be made even after consulting with the crossflow filter system manufacturer. The construction cost of the solid-liquid separation barn was comparable to (17% higher than) the deep-pit barn. The additional operating costs included daily operation of the scraper and conveyor systems and pumping the liquid manure away from the collection pit. The overall additional electricity cost was $331 per year. The additional maintenance of the scraper system included replacement of motors and scraper components, and averaged $1,342 per year.

Introduction

Practical and feasible methods for manure land application are critical to animal farming to comply with stringent environmental regulations. In particular, improper storage and handling of animal manure can result in significant environmental issues, such as algal blooms and depletion of oxygen in water bodies. Environmental regulations dictate maximum thresholds of application of certain heavy metals and nutrients and in utilizing raw manure, those components, especially phosphorous, can become a limiting factor necessitating additional treatment if the needed content for other nutrients, like nitrogen, cannot be reached. Those additional treatments also result in additional cost on farmers for the transportation and application of the treatment. Problems with runoff also exist when manure mixes with rainwater and mobilizes certain nutrients, such as phosphorous into nearby watersheds (Kleinman et al., 2001). High moisture content and uneven nutrient concentration can contribute to these issues and, as a result, research on processing methods by which moisture and nutrient levels can be better controlled for land application of the manure is necessary.

The most common manure management systems for pork production in the U.S. are deep-pit or lagoon systems. An alternative management system, which may alleviate existing nutrient management challenges, separates the solid and liquid manure produced within the barn, using gravity draining and a scraper system (von Bernuth et al., 2005). In doing so, the design allows the ability to quickly separate the solids from liquid manure. The intent of this design is to produce solid manure with lower moisture content than in a non-separated system. Being able to separate the solid and liquid streams is important, as the urine produced by swine typically has a significantly different make up when compared to the solid manure, due to factors like nutrient crystallization and how those products separate in the manure, leading to the solid and liquid manure being quite different in overall nutrient content (Hjorth et al., 2010). The separation process leads to a need to find a use for the separated liquid manure produced by the process, so investigation was also conducted to find ways to process that portion of the manure for practical farm use.

In evaluating performance of the newly designed barn for separating solid and liquid portions of the manure, analysis include the separation and storage methods, production rates of solid and liquid manure, and the characteristics of the manure. Frequent sampling is needed throughout the growth cycles and seasons to understand the effects of annual variability. In this work, the separated liquid manure was tested with different pretreatment processes and membrane-based filtration, with cost and practical considerations taken into account. The intent was to discover to what degree the liquid manure can be processed, even to the point of near-to-complete removal of all contaminants. Accomplishing that goal would potentially allow for procedures like water-recycling to be pursued if deemed practical, allowing for the barn design to also be useful for reducing farm water dependence (Le-Minh et al., 2010).

A Missouri producer has constructed a finishing barn with solid/liquid manure separation and a mechanical scraper system (Lim et al., 2017). The barn was designed for better air quality and flexible manure management, with design similar to that of the Michigan research barn (von Bernuth et al., 2005); but for commercial-scale (1,200-head capacity) and with a few improvements. The use of automated manure scraper was proven to reduce odor emission when compared with commercial flush barns (Lim & Parker, 2011; Parker, 2010).

The objectives of this paper were to report evaluation of the modified solid/liquid manure separation finishing barn with regards to manure management and recovery, and filtration of the liquid manure procured from the barn.

Objectives:

1) Systematic evaluation of a modified solid/liquid manure separation finishing barn for manure nutrient stabilization and recovery;

2) Identification of the minimal or different levels of pretreatment and filtration of the liquid manure, for practical fertilizer concentrate, transportation, and potential water recycling; and

3) Projection of the cost implications and returns of the barn, storage systems, and different levels of nutrient and water recycling, while considering carbon, water, and land footprints.

Materials & Methods

Finishing Barn

The finishing barn utilized for this research represents a unique process for separation of the solid and liquid manure portions. The commercial finishing barn was located near Versailles, Missouri. The barn was 80 feet wide and 132 feet long, with an east-west orientation. The barn had four individual rooms, each had a capacity for 300-head finishing pigs, which matched the farm's farrowing schedule and capacity. The barn design also featured a shallow pit basement, which allowed for gravity-based draining and automatic scraper removal of the manure.

Manure management consisted of a V-shaped pit with automated scrapers installed beneath a slatted floor, and a central pipe that collected the liquid fraction of manure, as seen in Figure 1. The four individual finishing rooms each had four automated scrapers. Solid manure was scraped multiple times per day following feed auger operation. The scrapers were programmed to operate after 200 lbs of feed was delivered. Scrapers operated an estimated six times a day, with cycle time of 4 minutes per room. Solid manure from scrapers was mechanically conveyed out to a manure storage shed. The conveyor system utilized three, 2-hp motors and operated during scraper operation. The operation time for the conveyor system was 15 minutes, an estimate provided by the farm.

Figure 1. The V-shape pit with automated manure scraper and trough at center (Left), and gravity draining of liquid manure from the trough to the collection pit (Right).

Separated Manure Storage

The liquid manure drained to a collection pit located outside the barn to the south, which limited the potential for solid manure to become trapped in the channel. The drain was sloped and directed the liquid manure out to the collection pit. The collection pit was designed with rectangular geometry, with the dimensions of six feet by eight feet uniform for the entire pit depth. Several times each day, a float switch trigger activated an automated pumping process to move the collected liquid manure to a nearby lagoon as the pit became full. Meanwhile, the solid manure was scraped from the V-gutter and then conveyed upwards to a secondary conveyor system connected to the open storage shed where the solid manure was stored. The shed structure is a rectangular storage area, with three concrete walls and a fourth wall constructed out of concrete blocks, which could be removed for manure removal. The storage shed (25 feet x 75 feet) was located to the north of the finishing barn and is shown in Figure 2.

Figure 2. The storage shed for solid manure to the north of the modified scraper barn (Left), and stored solid manure (Right).

Monitoring of Liquid Manure Production

For evaluation of the liquid manure production, the fluid level of the collection pit was continuously monitored by using of a liquid pressure data logger (U20L-04, HOBO Water Level, Onset Computer Corporation, Bourne, MA). The fluid level sensor was secured to the bottom of the collection pit. The depth of the liquid manure was monitored by measuring the change in pressure experienced in the pit in two minute intervals.

With knowledge of the collection pit dimensions and liquid (manure) level variations, estimation of the liquid manure pumped to the lagoon on a daily basis could then be made. However, the initial logger used did not measure atmospheric pressure and atmospheric pressure influenced the liquid level determination. Atmospheric pressure data derived from a nearby weather station was available only in hourly intervals, which limited the accuracy when normalizing data derived from the collection pit. Tests to estimate liquid level with the initial logger and the weather station's hourly atmospheric pressure were carried out until the acquisition of a new, dual-sensor data logger (MX2001, Onset Computer Corporation), which utilized a second logger to measure atmospheric pressure simultaneously. The new sensor acted as a secondary check to confirm the accuracy of the water level measurement, and improved consistency between trials. Not having to remove the new sensor pit for data downloading reduced variance between trials. Calibration checks of the pressure loggers were conducted before and after the field monitoring. The sensors were kept at bottom of a container, and exposed to different water depths: 0", 6", 12", 18", 24", and 30".

The liquid manure level (pressure) from the logger within the receiving pit was recorded every two minutes. The measurement and sampling rate was frequent enough to consistently track the liquid manure pumping cycles. There was some credence to the idea that pumping could occur at a point between recording intervals. However, there has not been any indication that the two-minute interval was causing significant sampling error. The pressure data was then converted to liquid manure height (depth of liquid) (H), and the volume was calculated with the known pit dimensions (WxL) along with the liquid height in tank.

Precipitation was found to somehow have entered the liquid manure collection system, which resulted in erroneous readings. The majority of the days with rainfall events had increased daily liquid manure volume. This precipitation factor was not known initially, and better care was then taken to avoid sampling on dates with or around rainfall, although avoiding rainfall events could not always be accomplished due to scheduling. The abnormal volume readings and excessive pumping that occurred required many daily data groups to be identified and excluded from the final dataset. While initial attempts were made to identify abnormal daily production rates through visual observation, it was determined that examination of the diurnal data for each day was needed to effectively identify outliers. It was also decided that if there were abnormal data on a day, the whole day would be removed, regardless of how long the abnormal flow rate occurred.

In addition to the data collected at the farm, weather data was acquired to account for effects outside the barn. Weather data was downloaded from a local weather station, which was located about six miles southwest from the farm, giving information on various factors like air temperature and rainfall in the local area. These datasets, particularly the rainfall data, were applied to cross check the abnormal measurements, as rainfall or groundwater could seep into the liquid manure collection system, possibly causing major alteration to the liquid manure production rate.

Monitoring of Solid Manure Production Rate

The amount of solid manure produced was more difficult to monitor. Production rate of the solid manure could not be monitored with a device such as a water level sensor as was the case with the liquid manure. While routine trips to the farm provided an opportunity for manual measurement of the manure pile size, and records of total manure shipment helped confirm volume being spread, more frequent and consistent manure production was not available. The initial plan was to have farm staff perform weekly monitoring and reporting but the data were inconsistent. To compensate for this issue, a camera was purchased and installed on February 1st, 2017 at the storage shed, to closely monitor the pile height. The camera (BCC100 Construction Time Lapse Camera, Brinno, Taipei City, Taiwan) was set on an hourly timer and was installed on a support beam connected to the East wall. The hourly images were recorded as a video file, which was collected upon each trip to the farm.

Information from the video file was analyzed to determine the solid manure production rate. The removable wall, which served as the background for the images, was constructed out of three levels of concrete blocks, with a uniform height of 24 inches (0.61 m) each. By combination of the pile height against the concrete wall, and the shed dimensions, solid manure volume was approximated via pixel measurement. The pile volume was estimated by assuming a flat surface and uniform distribution of the solid manure. Due to the larger size of the storage shed, the height measurements were broken down into weekly data points initially, but were then changed to daily, to improve data (volume changes) resolution. To keep results as consistent as possible, the time when images were analyzed was kept constant, with the daily time checked being the image closest to noon each day. Use of the noon image was decided as it limited interference in the image due to sunlight, although occasionally we had to utilize an image an hour prior or after the noontime image, due to insufficient image clarity, which could occur due to strong rains and winds blurring the lens at that noon interval.

Sampling and Analysis of the Manure for Nutrient Contents and Water Quality

Both solid and liquid manure samples were collected monthly during trips to the farm. The solid samples were collected directly from the storage shed, from the upper layer of the solid pile closest to the removable wall. The liquid samples were gathered by manually activating the pump switch and collecting the liquid as it entered the lagoon. The collected solid and liquid samples were kept on ice for transport and kept frozen until analysis by the University of Missouri Soil and Plant Testing Laboratory. A standard manure test package was selected, for both the solid and liquid manure samples, and each month a sample of each was collected and analyzed. Analysis included moisture/total solids, total nitrogen, phosphate, potash, pH, total carbon, and conductivity. This information was then compiled and compared to records, such as known points of technical issues with the scraper system, and rainfall records, to identify and exclude outliers from the dataset. The system operation information was compared to the nutrient analysis results, to act as a secondary check to confirm the results. Additionally, 32 liquid manure samples were also submitted for water quality analysis as irrigation water samples. The samples submitted included untreated liquid manure (as baseline), and samples that had undergone microfiltration, up through reverse osmosis.

Live Mass and Feed Consumption

Calculation of Live Mass

The farm management provided feed records and nursery pig inventory used to establish initial room stocking rates. Other records including sale date, number, and weight. The farmer reported an average mortality rate of 4% during the monitoring period. It also should be noted that the barn began raising the pigs with an antibiotic-free diet prior to the start of this research. While daily mass and mortality of the pigs were not available, a growth model predicting daily weight gain as reported in the literature (Jin et al., 2012), was applied, based on initial and final weights of the finishing pigs. For each room, daily weight gain was calculated using the growth curve fitted to the beginning weights at the nursery room (13 lbs), the finishing barn (50 lbs), and the sale weights. The provided estimate for mortality by the farmer originally was 4%, but was later reevaluated and confirmed with the farm that a maximum mortality of 8% occurred from March to July 2017. The individual room inventory was estimated using a linear mortality rate for each growth period.

There were five growth cycles where inconsistency in pig numbers indicated alteration due to holding underweight pigs, and were moved to another barn. These occurrences generally manifested as either the comparison between initial and sales headcount indicating an abnormally high mortality rate greater than 8%, which indicated pigs being kept longer. The average pig inventory and weight information were then adjusted to compensate for these inconsistent values, using the given mortality rate range for those groups with data skewed by holding of pigs to estimate headcount over the growth cycle for those groups. The gap in time between the start of one pig group to another on average was 35 days, and the general growth cycle for a group of pigs typically followed a pattern of 20 days weaning, 35 days in a separate nursery room onsite, and 140 days in the finishing barn, for a full growth cycle of 195 days. The curve values are estimated on the initial and final weights that were provided and for the final groups where sales weights and dates were not available due to still being ongoing, the average sale weight and a predicted sale date via the given growth cycle were used. Sale dates often were done so the next group could be moved in by the end of the next day, but on occasion, there would be a gap of two-three days with a room empty.

Analysis of Feed Consumption

Feed data were gathered from an automated monitoring system utilized by the farm, which recorded the amount of feed delivered to each of the four rooms, sorted by date and grouping. As a result, feed data served also as a secondary check on the start and end dates for each group of pigs to compare to the live mass data. The provided data separated the feed consumed into individual components, including corn, soybean mass, grower base, and finisher base. For the purposes of analysis, the feed was simply analyzed as a sum of those components. A biweekly distribution of the feed, with overlap between each week was performed to better normalize the feed consumption rate over time.

Filtration of Liquid Manure

Liquid manure samples for the filtration tests were stored at room temperature, and tested soon after collection to limit settling and alteration of any consistency. This handling procedure was best to simulate the characteristics of the manure as it was separated and left the barn. Mixing was performed on the samples to re-suspend the settled solids to return to fairly uniform solid contents before filtration. Mixing was done for consistency, as settling can occur very rapidly, altering potential results based on time of filtration (Suzuki et al., 2002). Between 5 to 10 gallons of liquid samples were taken monthly. As filtration testing continued, the filtration rate carried out did not require 10 gallons of volume. Many different processing techniques were tested throughout the course of the filtration tests, ranging from attempts at pre-treating the manure to use of additives to improve the filtration, which had a mixed range of successes. The first few months of the filtration treatment was delayed by the late shipment of the filtration unit. Also, there were technical issues with proper pretreatment of the liquid manure and improvement to the manure reservoir.

Pretreatment Techniques

The first few trials of the filtrations confirmed a need to at least remove the coarse solids. The first of these pretreatment processes focused on pre-filtering the manure, before attempting the finer filtration processes. Pre-filtering was incorporated through two separate techniques, both utilizing a mesh screen (coffee) filter with a pore size of 75 microns and small membranes with pore sizes ranging from 40 to 10 microns. The pre-filtering began as a solution to deal with issues of solid particle collection when running filtration in the bench-scale unit. Without pre-filtering, loose particles would collect in the filter area, leading to flow blockage resulting in cell over-pressurization, which generally led to filter tearing and destruction of O-rings in the filter cell. Beyond filtration techniques being utilized prior to the primary membrane filtration, a couple additives were utilized to pretreat manure filtrate. The first additive tested was sulfuric acid (6.0M and 10.0M), used to maintain pH during testing and to try to avoid some issues with foam formation. The second additive tested was calcium carbonate ($CaCO_3$) powder, which was tested for floccing of solid particles prior to pretreatment and membrane filtration.

Primary Membrane Filtration

A commercial crossflow membrane cell was purchased to perform the filtrations. The filtration cell used was a crossflow (Sterlitech Corporation, Sepa CF Med/High Cell, Kent, WA), bench-scale filtration cell. The cell, which housed the filter, was pressurized by a hydraulic hand pump, while a Hydra-Cell hydraulic pump was used to pressurize and maintain flow through the filters. The first step of the crossflow filtration utilized a polyvinyl difluoride (PVDF) membrane with a 0.2 micron pore size, followed by a temperature correction factor (TCF) reverse osmosis membrane. The reverse osmosis filter used was GE Osmonics™ SG series, Polyamide-TFC, chlorine resistant, for pH range of 1-11, flux of 22 gpd, and rated as 98.2% rejection rate. Various options can also be applied in the system, such as permeate carriers and membrane spacers to improve flow.

After addressing pretreatment, the primary filtration process was initially performed with two different membranes, one being a microfiltration membrane, while the other was a reverse osmosis membrane. The general progression used in filtering the manure was pretreatment, leading to the microfiltration membrane, and then leading to using the microfiltration filtrate to perform the reverse osmosis. Pretreatment was conducted to reduce the total solids at a better flow rate for later steps if the filtration worked as expected. The membranes were also tested with distilled water prior and after testing the membrane with manure, to try and compare the effect of solid accumulation and blockage on the membrane after filtering of the manure. The general collection method used was to collect filtrate in 15 minute intervals and compare the separate periods to observe any change in average flow rate.

The original design incorporated a basin with a flat bottom which had a drain installed in the bottom, leading to inconsistent flow as the volume present in the tank diminishes. A conical tank was later installed and allowed for more consistent flow recycling even when the feed solution was low in volume. Figure 3 shows the altered system set up, with the new tank.

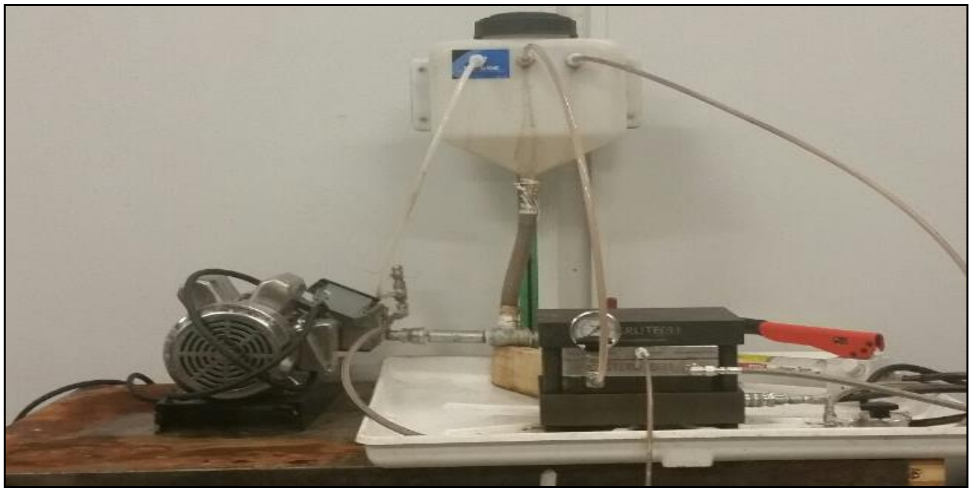

Figure 3. Sepa filtration setup including a conical tank for better filtration and recycling flows.

Seeing relatively inefficient filtration with the crossflow cell and using information provided by the filtration company, additional procedures were conducted to explore the cause of the incomplete filtration. The first option was to determine if other types of membranes could improve the filtration efficiency. Three other types of membranes were purchased and tested alongside the membranes utilized in the previous tests. Those new membranes consisted of GE Osmonics HL TFC nanofiltration membrane (pore size approximated to as low as 1 nanometer, based off a 200-400 Dalton molecular weight cut-off (MWCO)); TriSep X201 PA-UREA reverse osmosis membrane (designed for industrial/wastewater, with a pore size estimated at 0.76 nanometer, from the 100 Dalton MWCO); and Dow Filmtec SW30XLE PA-TFC reverse osmosis membrane (pore size estimated at 0.76 nanometer, with an identical MWCO to the TriSep membrane) (Yoon, 2016). Samples were taken of the manure for the month of April, and the liquid manure was filtered through the various membranes, in the same way as was performed in previous months. Adjustments were made to the crossflow unit to improve the overall system flow rate from the initial setup.

Another test was conducted to operate the reverse osmosis treatment by filtering 2 g/L concentration of salt water. This was performed to identify reason as to why filtration was not as effective as initially expected. The concentration was measured using a conductivity meter and was measured in 15 minute increments as with filtration rates to see how the concentration of salt in the membrane would alter over time and through the reverse osmosis membrane that was estimated for a minimum 80% rejection rate.

Economic and Environmental Analysis

Cost Analysis for Barn Construction and Operation

Costs for the building and maintenance of the finishing barn were provided by the farm owner. Meanwhile, electrical costs for various components (scraper system, conveyor system, filtration unit), were estimated by calculating consumption in kW-h, and then converting to cost via a recent average electricity cost. A significant cost that could not be properly estimated was cost of implementation of a farm-scale filtration unit. The electricity cost estimation was extrapolated from in-lab testing which utilized a relatively small motor compared to the source of power used at scale. As a result, the information obtained for the power consumption for filtration is not likely representative of the commercial scale operation power demand or the resulting cost, as the values calculated in-lab could only be extrapolated linearly without other considerations being accounted for.

Air Quality Measurement

One potential benefit of the quick removal and separation of the manure is improved air quality for the animal and human worker, both in reduction of emissions and odor (Jacobson et al., 1999). Concentrations of ammonia (NH_3) and hydrogen sulfide (H_2S) were measured within the finishing barn as air quality indicators. Particulate matter and odor measurement were not included. Discrete concentration measurements were performed monthly at all running exhaust fans. A Dräger hand pump (Dräger Accuro®, Draeger, Inc., Houston, TX) was utilized, by use of chemical gas tubes to draw sample air through. The tube used for ammonia had a measureable range of 2 to 30 parts per million (ppm), while the hydrogen sulfide tube had a measurable range from 0.5 to 6 ppm. When the gas concentration measured was below or very close to the detection limits, extra pump strokes were given and results averaged to ensure more accurate measurement.

One notable issue of the use of the Dräger tube method was that the H_2S concentrations at the exhaust often did not register due to the relatively low levels. As a result, another option had to be pursued to better measure the H_2S concentration. A Jerome 631-X hydrogen sulfide analyzer (Arizona Instrument LLC., Chandler AZ) was acquired for this purpose. The Jerome analyzer, with a minimum detectable range of 0.003 ppm, per the estimated variance in potential accuracy, with an upper range of 50 ppm, provided a better detection range for the purposes of this research. The primary issue with the Jerome analyzer was the potential of drift. In particular, the analyzer had a tendency for drift in the recorded hydrogen sulfide concentrations as the analyzer was used over the course of a day. To monitor this, the logger was checked on testing days, measuring the concentrations before and after field measurement, with two gases: zero air, and a span gas with hydrogen sulfide at 1.7 ppm. This testing should make drift over the course of testing apparent, and will help in determining the overall accuracy of the tests. The Jerome analyzer was acquired in June 2017, and started being utilized in testing the hydrogen sulfide concentration of the fans soon after, alongside tests with the other chemical gas tubes. Results reported are the average of five tests performed for the same source of testing, to make sure outlier results did not strongly skew the measured concentrations.

Results

1) *Systematic evaluation of a modified solid/liquid manure separation finishing barn for manure nutrient stabilization and recovery;*

<u>Liquid Manure Production Rate</u>

<u>Calibration Checks of Pressure Loggers</u>

Comparisons of the calibration checks of the two pressure data loggers are presented in Figure 4. The records were of the original logger in September 2016, and the new logger having records in January 2017, September 2017, and April 2018. The loggers were exposed to tap water at various depths, and recorded every ten seconds. The comparisons indicate the loggers were relatively consistent, with the new logger being more accurate, especially in the later tests. The reason for this higher accuracy is likely because the new logger had an additional atmospheric sensor for simultaneous pressure compensation, whereas the first sensor relied on hourly weather station data. Results also indicate the old data logger was capable of providing accurate measurement, but due to the simpler and immediate process to obtain a calculated depth, the new logger was an improved tool for use in the field.

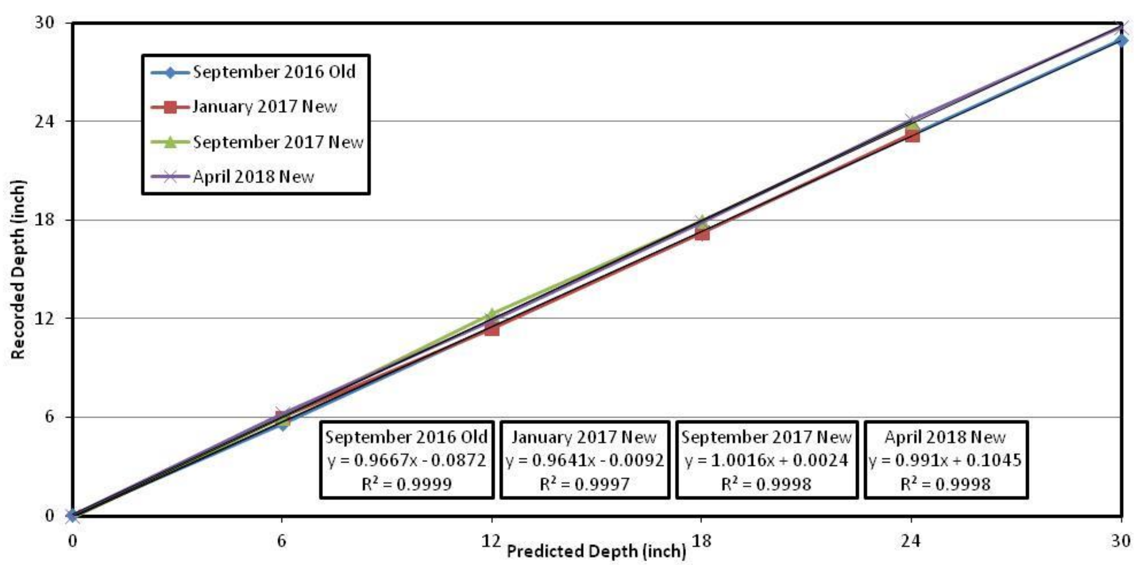

Figure 4. Results of calibration checks for the two pressure sensors, showing actual water depth and the depth recorded.

<u>Daily Liquid Depth Analysis</u>

The as measured daily liquid manure production ranged from 6 to 17,146 gallons, and averaged 1,549 gallons, Figure 5. The relatively high variance in daily production rate indicated the need to identify the cause of abnormal readings.

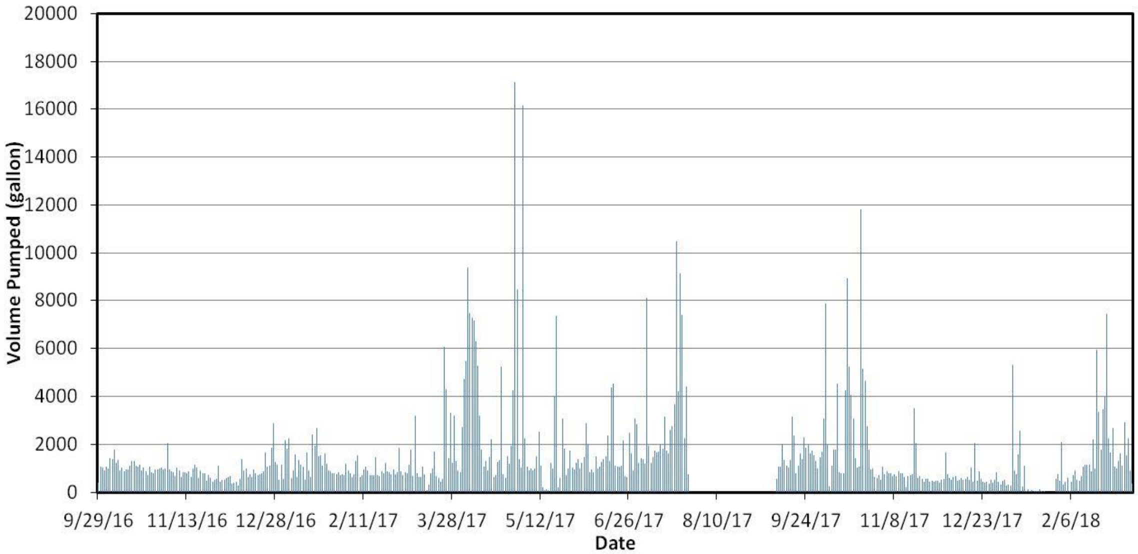

Figure 5. As measured daily liquid manure flow rate.

By comparing the diurnal pit level data, a general depth change pattern was noticed, and thus could be used to identify abnormal data. The general flow pattern involves steady increases in volume until reaching a certain height to activate the float switch, followed by a rapid decrease in depth, and then a steady increase. Manure production rates are typically decreased in the early and late hours of the day. Figure 6 displays the common and abnormal liquid pumping patterns, with the figure on the left demonstrating more manure production and pumping in the day time (while pigs were active), and the figure on the right having over 14 pumping events in a day, and over 10 pumping events within a 4-5 hours period. The day was identified to have abnormal manure production, indicating events like these are contributing to increased volume production.

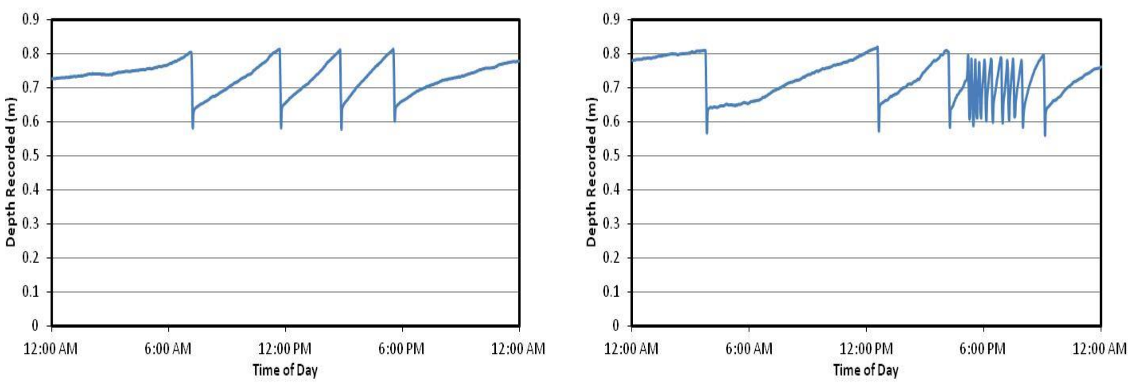

Figure 6. Comparison of normal (left, October 17, 2016) and abnormal (right, October 18, 2016) liquid manure production rates in a 24-hour period.

While not all abnormalities could be explained, several causes were identified. Dates without a complete record of liquid flow rate, due to the removal of the logger were excluded, as records were incomplete and many of the points where the loggers were removed had manual pumping of the collection pit for sample collection. A couple of periods existed where the logger was completely removed from the collection pit for multiple days, due to issues with the barn. As well, the farm would power-wash the rooms after the sale date.

The largest contributor to abnormal data identified, however, was rainfall. While not every rainfall event had caused abnormal flow rate, days with over 0.40 inch (10 mm) of rainfall throughout the day ended up exhibiting abnormal flow patterns. Often the abnormal flow rate manifested in rapid filling of the collection pit and inconsistent pumping cycles, but there was no single pattern that the problem followed. The reason is not entirely known, although the owner of the farm theorized that it may be the result of issues such as backflow from the lagoon during heavy rainfall, or rainfall pooling and potentially seeping into the collection pit as a result. Figure 7 shows that, before rainfall, the first 2/3 of the day exhibited normal manure accumulation and pumping events. When the heavy rainfall occurred, the rate of change in depth increased dramatically.

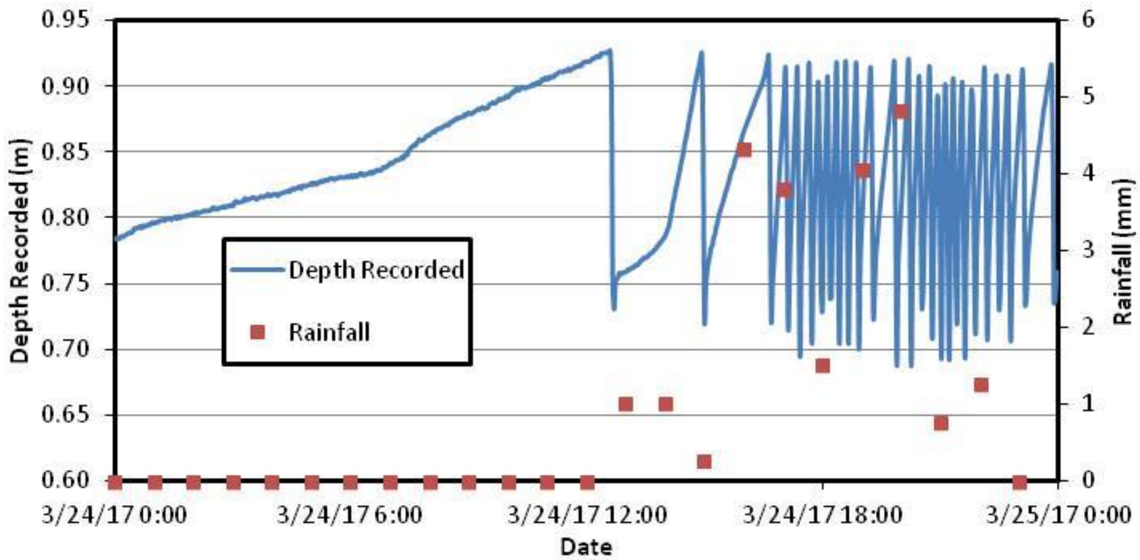

Figure 7. Depth logger records compared to the hourly rainfall records

For the days data had to be excluded, 70% of the abnormal data has an identified cause. The rest of the 30% abnormality could not be explained. There was no system in place to track dates where any additional cleaning or other events introducing additional water to the liquid stream. In addition, it is not known if there were any unidentified sources through which excess water could enter the sump pit.

Adjusted Liquid Volume Results

After cross-checking the daily flow rate and diurnal liquid level fluctuations, many abnormal data were excluded. The daily liquid manure production ranged from 298 to 1,840 gallons, and averaged 885 gallons, Figure 8. While these data are much more consistent, with the combination of the abnormal flow removal, the removal of incomplete recording days and dates where the logger was not present, 50% of the data recorded was excluded.

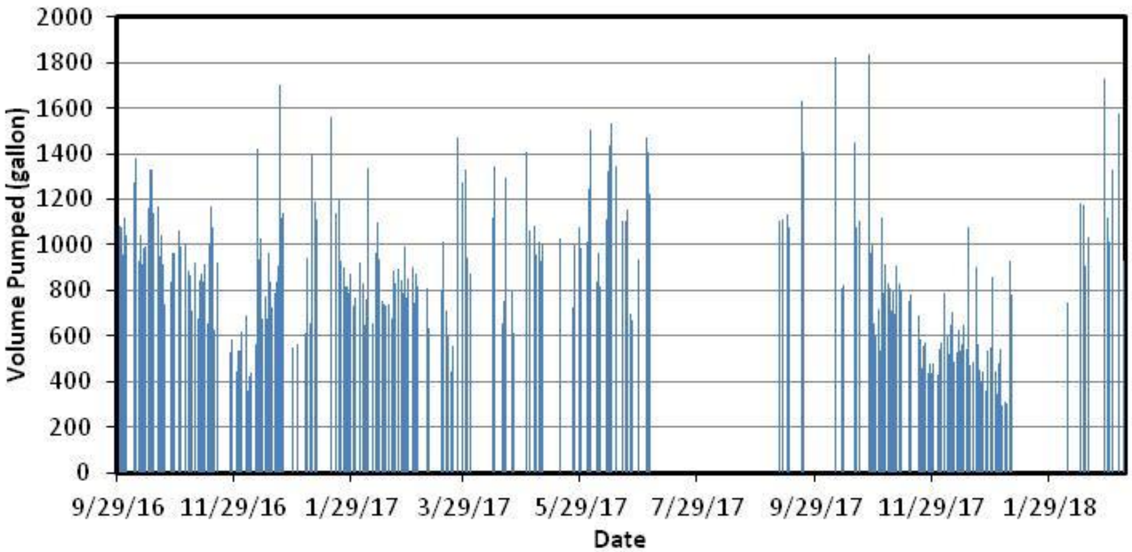

Figure 8. Daily liquid manure production rates, with abnormal data excluded.

All valid liquid manure productions rates were then presented as weekly averages. Weeks where there was not a majority of the days (<4) with normal data were removed and the averages are presented as the average daily flow rate during that weeklong period in Figure 9. It also provides an easier point of comparison when utilizing liquid manure flow rates to evaluate factors such as nutrient flow.

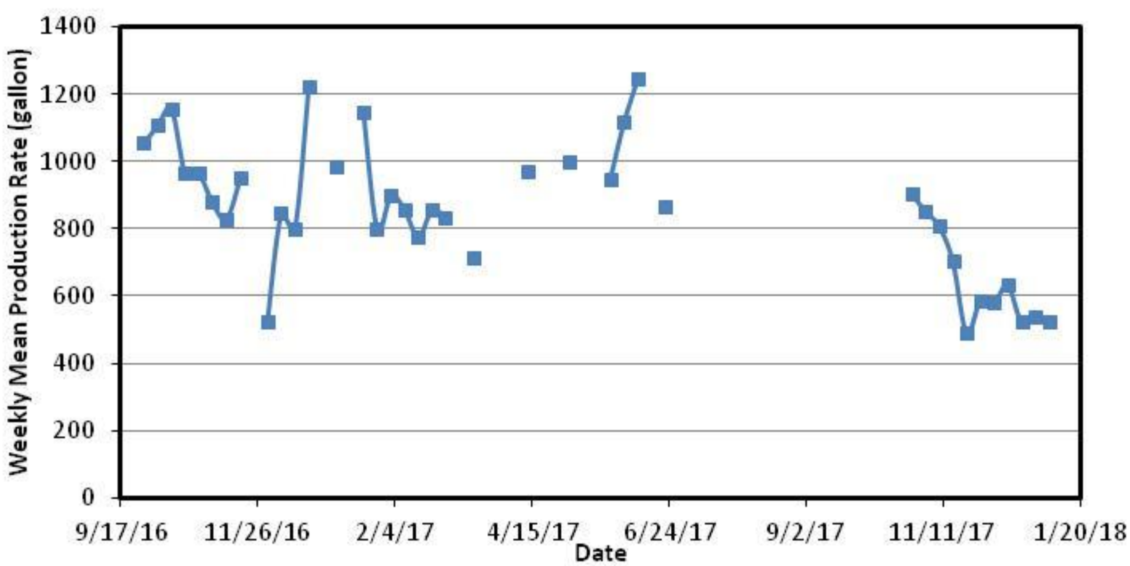

Figure 9. Weekly averages of liquid manure production rate, only weeks that had 4 or more data points were included in the final dataset.

Solid Manure Production Rate

Figure 10 depicts the height of solid manure in the storage area, over the measurement period when the camera system was installed, from February 2017 to April 2018, in comparison to the range of dates for the liquid data records of September 2016 to March 2018. Issues with the solid manure production were observed for mid-June 2017 to early September 2017, and late September 2017 to late January 2018, in which the manure height did not change, Figure 10. The first period of abnormality was attributed to maintenance issues with the scraper system, which also resulted in the lack of data around the same period for the liquid production, while the second period resulted from a recursion in some of those issues. The effects of these issues will be discussed later. The slight variance present in these periods is explained as a combination of noise produced in analysis, alongside factors such as the farm utilizing an auger system at the solid storage shed to remove pooled liquid manure.

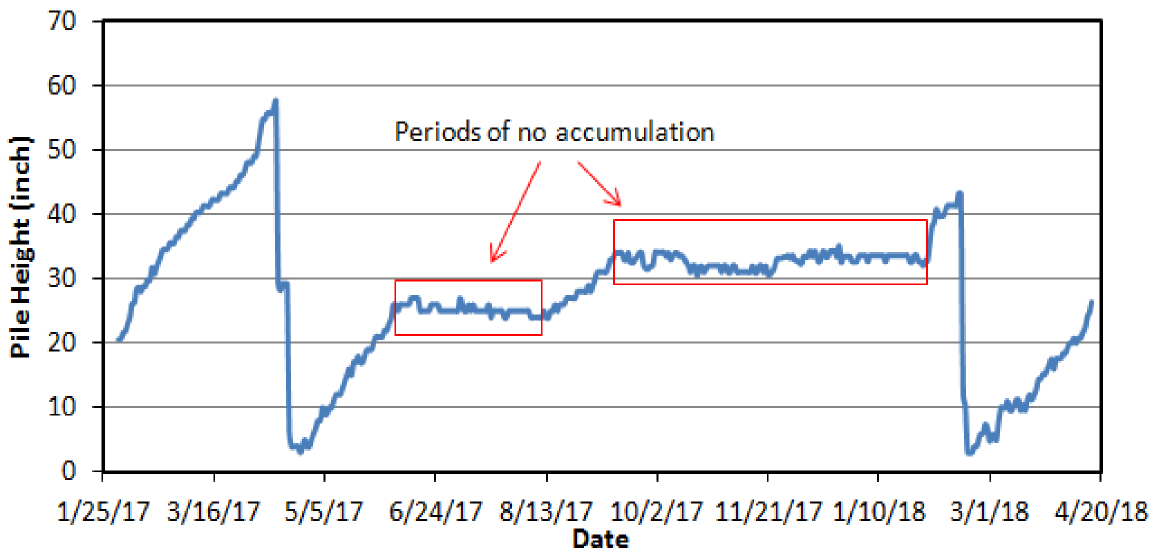

Figure 10. Daily heights of solid manure pile in the storage shed.

The daily solid manure production ranged from 0 to 1,388 gallons, and averaged 299 gallons. This range does not explicitly indicate that there were days where no solid manure was moved to the storage shed. Instead, the measurement was partly limited by the image quality of the camera utilized. It was possible that the conveyor was not operated daily, which may contribute to that daily accumulation discrepancy. As a result, there were days with zero manure production, followed by several hundred gallons of manure production due to accumulation over days. Compared with the liquid manure measurements, solid manure volume typically accumulated at a much steadier rate, most likely because the storage area was not affected by the rainfall like the liquid manure collection pit. The information was then presented as weekly means, Figure 11. This dataset also excluded the period of time where solid manure was being removed from the shed for land application, as it was incomplete data. Similar to the liquid data, the weekly means helps with comparisons with other factors such as nutrient flow and barn total live mass data.

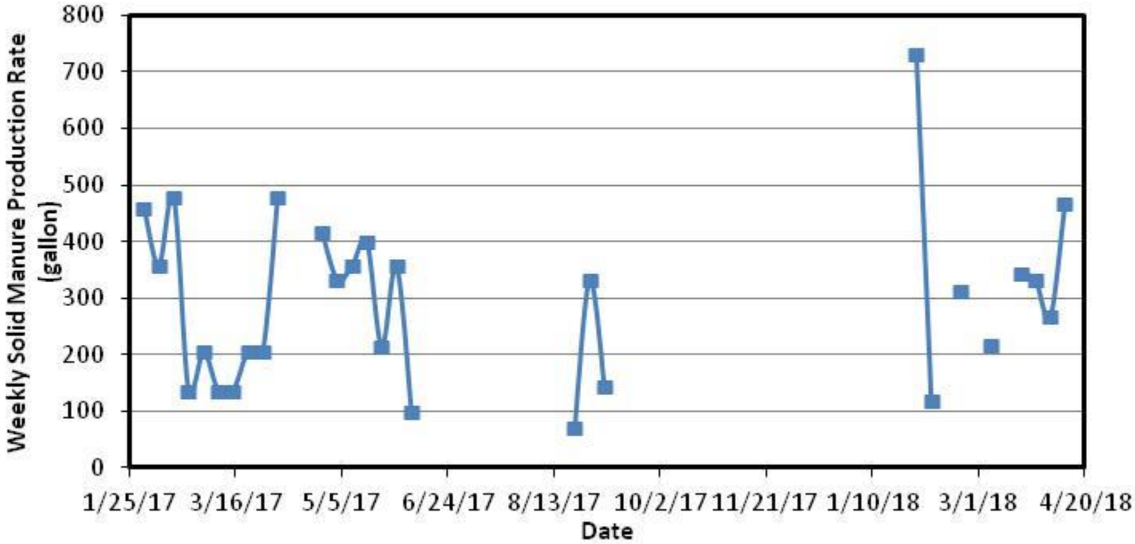

Figure 11. Weekly averages of the solid manure flow.

Live Mass and Feed Data

Figure 12 shows the calculated total live mass in the finishing barn, along with the pig inventory as a comparison. There were four staggered groups of finishing pigs raised in the barn. The total live mass had a smaller range than the all-in-all-out operation. In general, the total live mass values kept on increasing until sale dates, which then dropped rapidly, as would be expected. The typical spacing for each group was around 35 days.

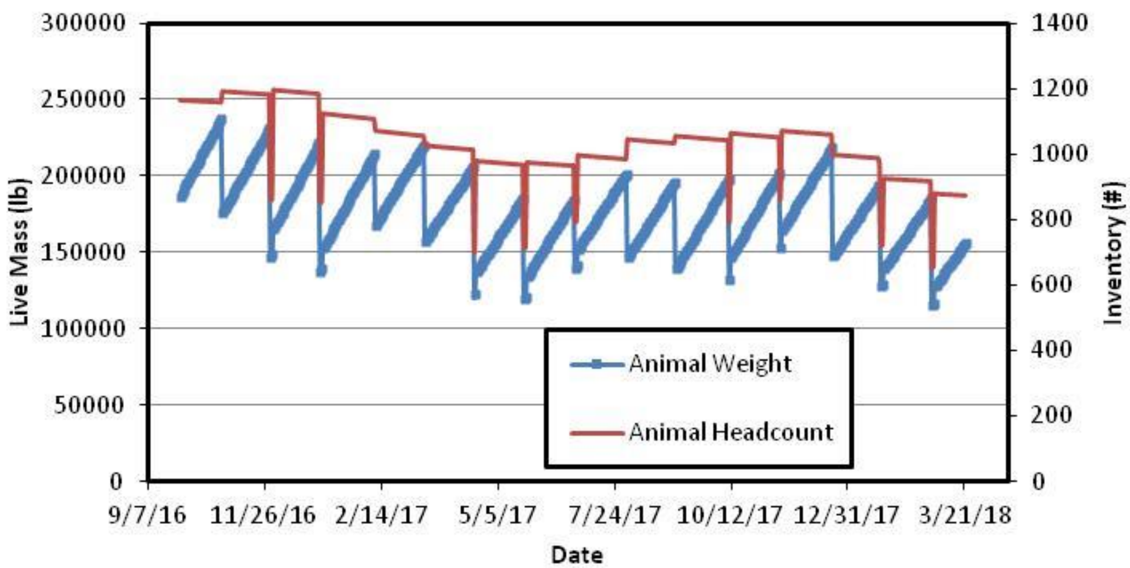

Figure 12. Daily comparison of total animal weight (live mass) and inventory.

An important point to provide in making the analysis on how the finishing barn operated is comparing the results to what is typical for a finishing barn. To do this, data were compared with those listed for industry benchmarks provided on the Pork Checkoff website for the most recently available year (Pork Checkoff 2018). Mortality estimates during finisher activity were at 5.34%. Given the 4% average provided by the farmer, while considering a brief period approaching 8% mortality the mortality rates line up fairly well. The more interesting results lie in the average finishing weight, time in the finisher and daily weight gain per pig. Pork Checkoff lists an average value of 272.8 lbs for finishing weight, 119.2 days average spent in the finishing barn, and an average weight gain of 1.86 lb/day. In comparison, average sale weight for the finishing barn monitored in this study was 265.3 lbs, the average time in the finishing barn was 139.1 days, and the average daily weight gain was 1.58 lb/day. The Pork Checkoff numbers indicated 221.7 lbs gained in the finisher, while the values for the separation barn equaled to 220.3 lbs gained in the finisher. These values, combined with the sale weights indicate a slight difference in average weight entering the finisher (51.1 lbs vs. 45.0 lbs comparing national average to this study). One thing that is not known is whether some of these differences are related to the antibiotic-free operation in this study, which could have led to the slower than expected growth. As well, the Pork Checkoff numbers seem to include finishing barns operating with use of antibiotics, which have been noted in the past to improve animal growth (Gustafson & Bowen 1997).

Feed records generally correlated well with the barn total live mass, except for a few discrepancies. Feed records were calculated in a biweekly fashion, to reduce bias as a result of feed records being checked early or late in a week. Figure 13 shows the comparison between daily live mass and biweekly feed consumption data. While the overlap is difficult to line up, the general rises and drops in feed consumption tend to follow the sale dates, which confirms the sales information provided by the producer. This research does not consider the composition of the feed would have, in terms of use of different grains and how they affect growth, as well as alteration of the feed mass given a particular point in development (Shinckel et al., 1996).

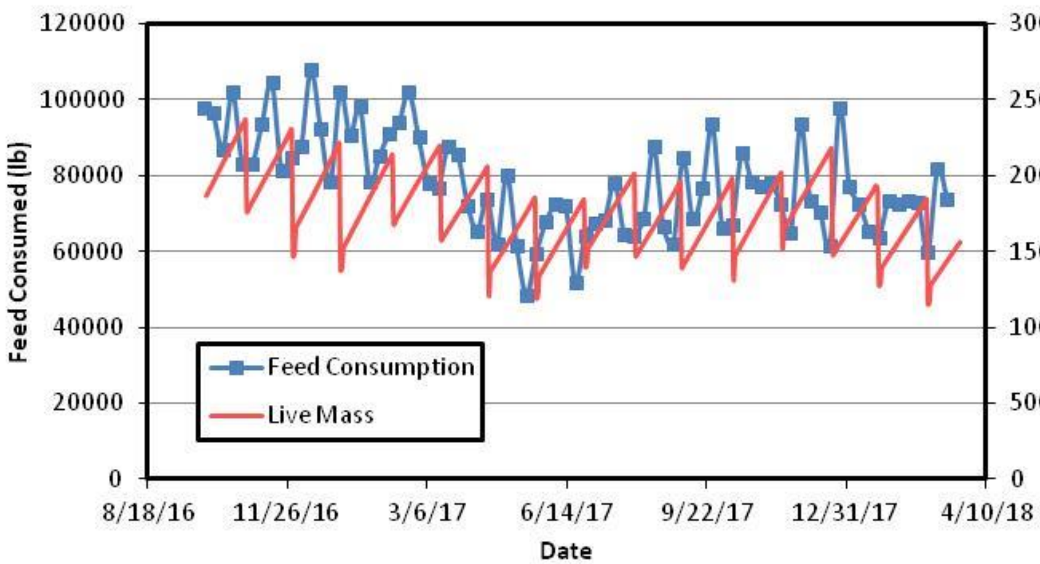

Figure 13. Comparison of biweekly feed consumption and daily barn total live mass.

Characteristics of the Separated Manure and Data Extrapolation

Nutrient Analysis and Removal of Abnormal Results

The liquid manure production data in July 2017 and August 2017 was excluded due to the malfunctioning of the conveyor system. The conveyor mechanism broke down and disrupted both the solid and liquid manure removal. For the liquid manure, more solids were drained into the collection pit, which increased the pumping, as well as changing the consistency of the liquid manure. The pressure logger had to be removed for maintenance, to allow for removal of solid buildup in the collection pit, causing a loss of data for approximately a month and a half. The liquid in the pit, shown in Figure 14, during this time visibly showed higher solid content compared with normal operation, that the liquid manure did not typically have identifiably solid characteristics to note. The altered consistency also skewed the nutrient contents in the liquid manure samples, which was excluded for consistency. By that same metric, six monthly samples were excluded because they were diluted by rain water, reducing the overall nutrient content. In comparison, nutrient data of solid manure was kept each month, because they were fairly consistent throughout. Measured nutrient and moisture contents of each monthly liquid sample are shown in Figure 15. Figure 16 shows the nutrient and moisture content values for the solid manure samples.

Figure 14. Appearance of liquid manure in collection pit during period of mechanical issues for the finishing barn, with an apparent higher solid content.

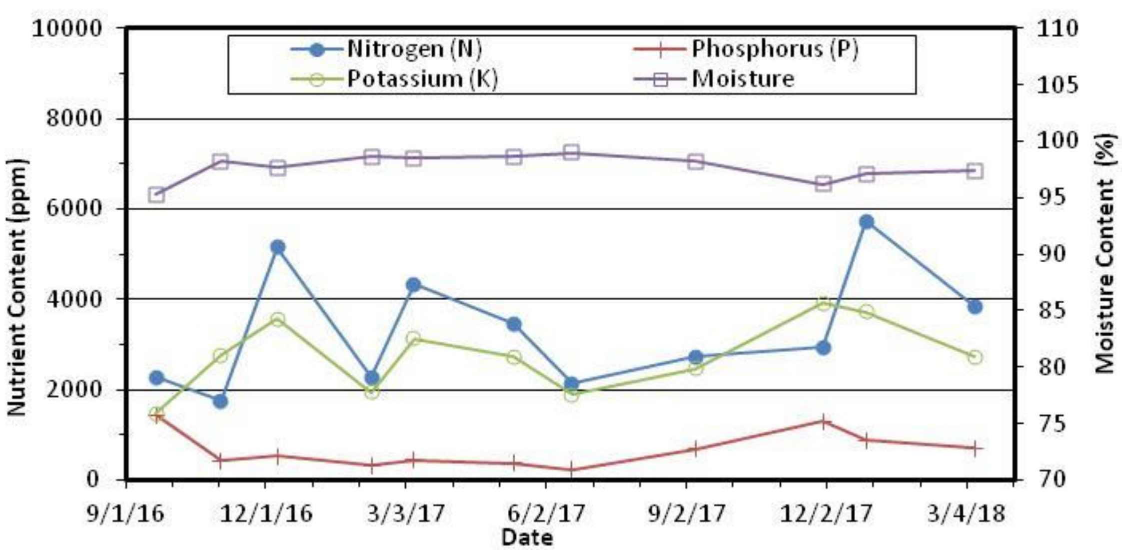

Figure 15. Monthly nutrient and moisture contents of liquid manure samples.

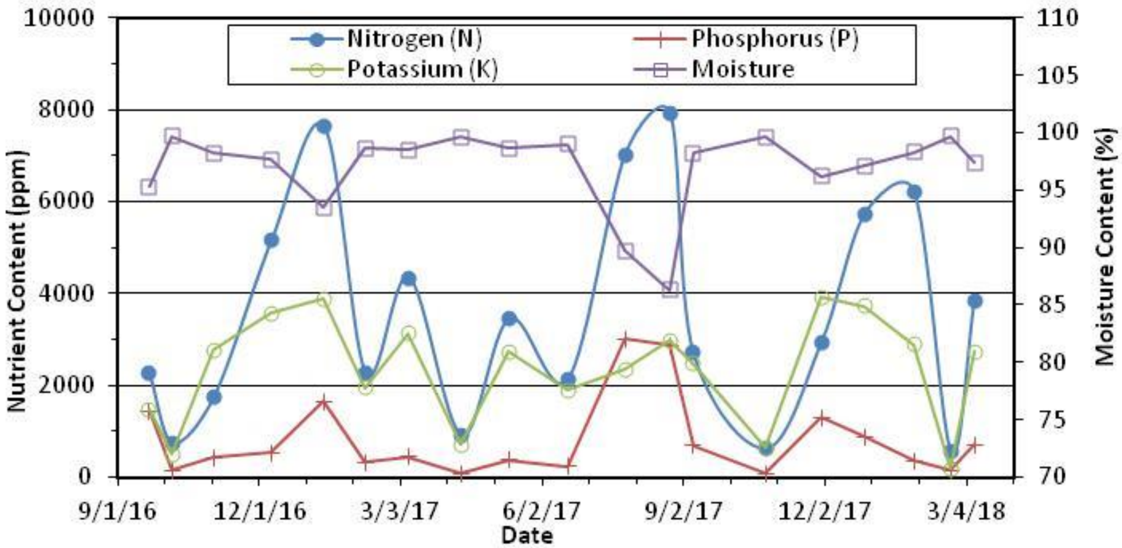

Figure 16. Monthly nutrient and moisture contents of solid manure samples.

Table 1 summarizes the average nutrient concentrations, and carbon and moisture contends for the solid and liquid samples. As expected, the solid stream had higher concentrations of all nutrients and carbon, because the liquid stream had higher moisture content. The average moisture content of the liquid manure was 97.7%, whereas the solid manure had 72.5% moisture content, indicating the solid manure was almost "stackable" ("stackable" quality manure generally has a total solids content of 25% or greater (Lorimor et. al. 2004). Solid manure also had on average five times the amount of nitrogen content, over twice the ammonium content, nearly nine times the phosphorous content, and two and a half times the amount of potassium with respect to the liquid manure. This indicates that the separation barn is achieving its primary purpose in separating these important nutrients from the liquid portion, which can be helpful for manure nutrient management and land application purposes.

Table 1. Summary of nutrient contents of the solid and liquid manure samples.

	Nitrogen (ppm)	Ammonium (ppm)	Phosphorous (ppm)	Potassium (ppm)	Carbon (%)	Moisture (%)
Liquid Manure	3,334	3,199	669	2,762	1.18	97.7
Solid Manure	15,864	6,763	5,890	7,020	13.2	72.5

<u>Nutrient Separation Efficiency</u>

While the two manure streams contained different nutrient contents, the measured production rates are critical to put these findings in greater context. The average daily liquid manure flow rate was 884.5 gallons, while the solid manure production rate was 299 gallons per day. Because there were quite a few data gaps in the manure production rates (Figures 8-11) and monthly liquid manure nutrient values (Figure 15), the nutrient separation efficiencies for the important manure nutrients were not calculated using monthly data, but only based on overall averages. Table 2 provides the calculated mass flows of the solids and nutrients of the liquid and solid streams, and the removal efficiency with respect to the liquid stream. Based on the overall average nutrient contents and production rates, the solid separation removed

61.7%, 41.7%, 74.8%, and 46.2% of nitrogen, ammonium, phosphorous, and potassium, respectively, from the total manure production. As well, the amount of total solid removal was 80.2% from the liquid manure production.

Table 2. Mass flows of manure nutrients in the solid and liquid streams.

	Nitrogen	Ammonium	Phosphorous	Potassium	Carbon	Total Solids
Liquid Manure (gal/day)	2.95	2.83	0.59	2.44	10.4	20.3
Solid Manure (gal/day)	4.74	2.02	1.76	2.10	39.5	82.2
Total Manure (gal/day)	7.69	4.85	2.35	4.54	49.9	102
Percent Removal by Solid Separation (%)	61.7%	41.7%	74.8%	46.2%	79.1%	80.2%

The solid-liquid separation barn was able to separate 62% of nitrogen and 75% of phosphorus from the total manure stream into the separated solid manure. The separated solids had moisture content of 72.5% (average of 19 monthly samples), which was “stackable” manure. It was also several times richer in manure nutrients (smaller volume and less effort to spread) and can be stored for longer time and be transported off farm (fields further away or sold as fertilizer) more economically, or allows for byproduct production such as composted manure. Solid-liquid manure separation allows for more flexible manure nutrient management plan. While the solid manure is likely to be the primary fertilizer used, due to its higher overall concentrations, the phosphorus-reduced separated liquid manure can be applied on fields as needed, allowing for necessary nitrogen content for crop growth to be attained with less risk of exceeding phosphorous content levels.

The nutrient analysis denotes how separation of solids and liquids in manure production could separate out certain nutrients (such as phosphorus) of the manure at the barn or source, without utilizing additional solid separation technologies such as screen and centrifugal separation systems. In general, the liquid manure contained lower nutrient concentrations, as a result of lower solids content. Comparing the two manure flows and manure nutrients within them, there is a strong correlation between the presence of dry matter and nutrient content. Analysis was focused on the total mass of each nutrient in the solid and liquid portions, to better characterize the manure management system (Saeys et al., 2005). This analysis is important to the liquid manure filtration processes, as attaining the higher moisture content would lead to less particulate and nutrients to filter, which favors potential water recycling, especially when the solid-liquid separation barn already extracted 80% of the solids in the solid manure stream.

In evaluating the nutrient separation rate calculated here, it is useful to compare the values to values from previously calculated estimations. Total solids content was reported as being 9.0% of the total manure stream in the literature (ASAE 2010). The separation finishing barn that was monitored in this research study averaged a total solid content of 8.7%, indicating a similar result. This consistency continued for nitrogen, which was reported as 0.7% of the total mass and was calculated in this research to be at 0.65%, ammonium, reported as 0.5% total mass and calculated at 0.41%, and phosphorous, which was reported as 0.21% total mass and calculated at 0.20%. The only key nutrient measured that the results were dissimilar for was potassium which was reported as 0.24% total mass and was calculated in this research as 0.38%. It is not currently known as to why the potassium levels differed as much as they did, particularly with the other concentrations being so similar, so it is important to note.

The results from this study are also compared to a previous study performed on a research finishing barn utilizing a similar scraper separation system for solid liquid separation. The barn was smaller, with two rooms instead of four, with a maximum capacity per room of 168 head and different gutter removal system for solid and liquid manure removal (von Bernuth et. al. 2005). The von Bernuth study had estimated solid stream moisture content at about 66%, where the findings in this research had a moisture content averaging 72.5%. As well, the von Bernuth study estimated a solid separation of 91.6% for organic C, 91.0% for phosphorous and 59.7% for potassium, compared to the separation efficiencies calculated for this study which were 80.2% for carbon, 74.9% for phosphorous, and 46.2% for potassium. The average solid stream: liquid stream flow ratio based on the von Bernuth results were 24.9%, while this research had the ratio at 19.3%. However, some results were relatively close, with the nitrogen content calculated being 67.4% compared to our findings at 61.7%, and the ammonium concentration being 39.1%, compared to 41.7% based on our findings. It should be noted that liquid manure quality was not reported in the von Bernuth study, and the nutrient concentration was reported via separation efficiency, rather than concentration in ppm, so it is unknown if the differences in nutrients in the solid stream had a corresponding effect on the liquid stream and what those calculated concentration were. Table 3 presents the data for easier.

Table 3. Nutrient separation by solid separation of two studies.

	Nitrogen (%)	Ammonium (%)	Phosphorous (%)	Potassium (%)	Carbon (%)
Von Bernuth Study	67.4%	39.1%	91.0%	59.7%	91.6%
Brown Study	61.7%	41.7%	74.9%	46.2%	80.2%

Correlations of Manure Production and Total Live Mass

Weekly manure productions rates were compared with total live mass present in the barn, Figures 17, and 18. Although there was not a strong linear correlation between live mass and the flow rates, manure production did show an upward trend with higher live mass. This slight upward trend was probably based on a combination of a multitude of factors, including the multiple growth cycles in the four finishing rooms (vs. all-in, all-out finishing operation), uneven distribution of solid manure when measuring height, high number of data abnormalities (rainfall dilution and scraper system malfunctioning), and other unknown factors. While feed consumption rate was tracked, records were not kept of water usage because the team chose to closely monitor the liquid manure flow using pressure loggers. Should the barn be an all-in, all-out operation, the minimum and maximum live mass would have been 60,000 lbs and 324,000 lbs, which provides a wider range of correlation analysis.

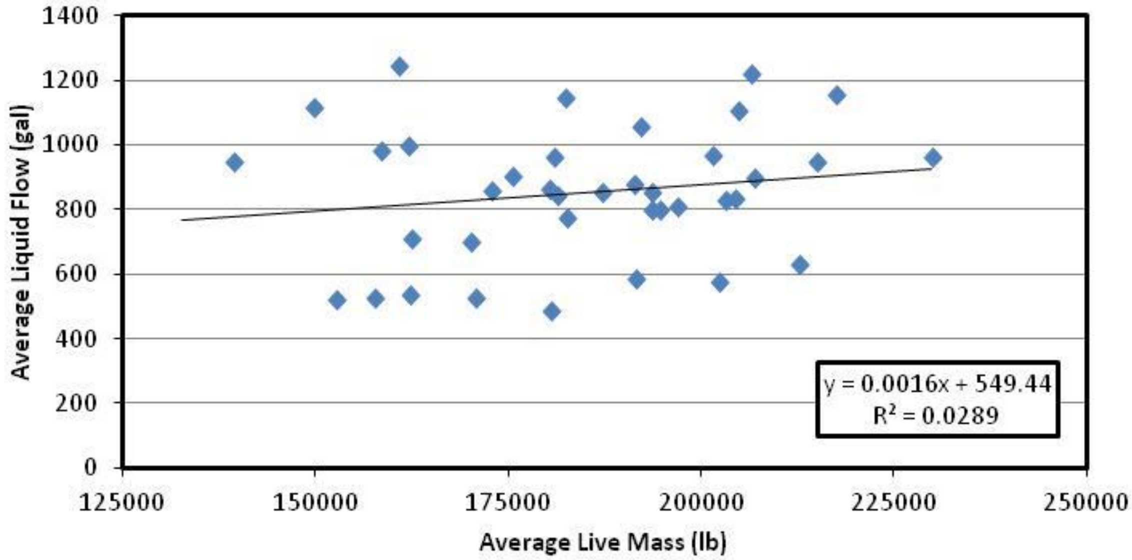

Figure 17. Correlation of liquid manure production and total live mass.

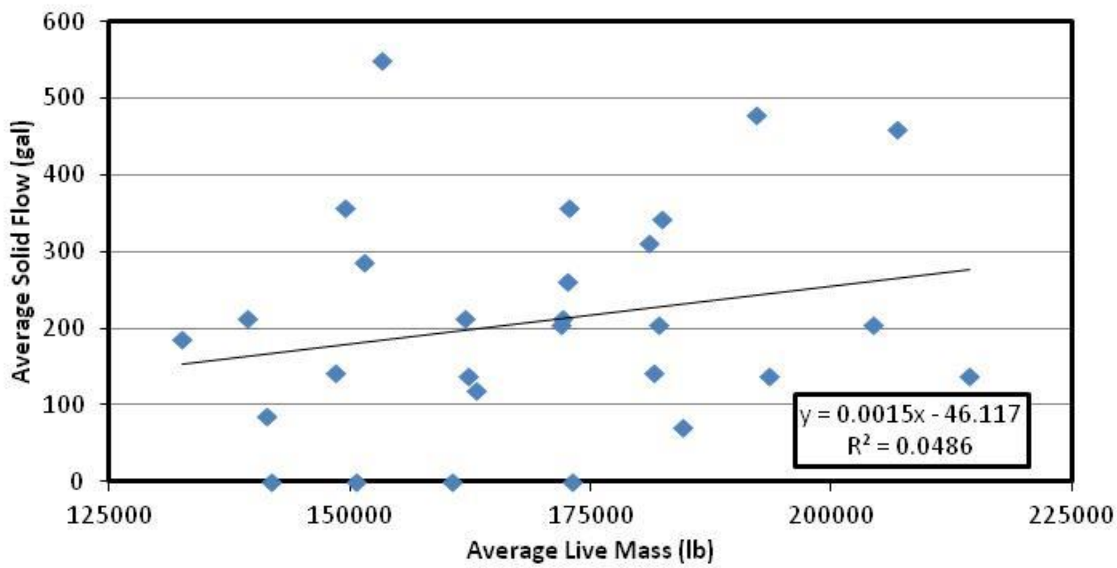

Figure 18. Correlation of solid manure production and total live mass.

2) *Identification of the minimal or different levels of pretreatment and filtration of the liquid manure, for practical fertilizer concentrate, transportation, and potential water recycling; and*

<u>Pretreatment of Liquid Manure</u>

<u>Pretreatment Involving Filtration</u>

Use of the metal screen filter proved to be a simple process for performing pretreatment, as the filter was reusable after a quick wash to remove large particles, and the screen filter opening was coarse enough to allow relatively quick filtration. A five gallon bucket of liquid manure could be filtered in 10 minutes. The speed of removal suggests and confirms that a commercial, larger scale vibrating screen process could be efficient for pretreatment of the liquid manure. The screened solid manure could then be added to the solid manure from the barn. In comparison, the fine filter paper was more difficult to obtain consistent flow. Depending on the solids content of the liquid manure, the first 250 ml of liquid manure could be filtered through the membranes in two minutes. However, a layer of fine solid formation would often form and lead to significantly lower flow rate over time. The slowed filtration speed for a 250 ml sample could range anywhere from 2 hours for the larger pore sized membranes, to having the filtration rate approaching zero for the more fine membranes. This result is likely a combination of the vacuum pressure produced by the hand pump being insufficient, along with membrane fouling with solid settling. Further testing indicated that using just the metal screen filter was enough to prevent over-pressurizing the crossflow filtration cell. Figure 19 shows photos of the setup for the pretreatment filters, as well as a photo showing the solid film accumulation on top of the pretreatment filter that caused flow blockage.

Figure 19. Pretreatment filter setup at beginning (left), and issues with solid film accumulation (right).

<u>Pretreatment Using Chemical Additions</u>

Initial testing with the filtration unit showed one major problem that occurred with the unfiltered manure cycling was foam formation in the liquid manure reservoir and a strong ammonia smell. Foam formation in manure filtration is a problem that has been noted in previous studies (Karakashev et al. 2008), and the ammonia smells could be exacerbated by a rise in temperature and nutrient content and pH changes. In monitoring of the liquid manure, the pH level was generally in the high 8 range during filtration, while the liquid manure when collected usually was in the high 7 to low 8 range. The cause of the foam formation is not entirely understood. Initial thoughts considered the possibility of heat produced by the hydraulic pump causing some reaction, as the temperature of the liquid in the basin seemed higher than at the start of testing (not recorded systematically). Another potential cause was the stagnation of the liquid manure in original flat bottom reservoir. No major foaming issue was observed in the new conical reservoir. Figure 20 shows an example of liquid manure foaming as observed in testing.

A pretreatment step was taken to reduce foaming by conducting pH adjustment on the manure. This process has been indicated to reduce flux in membranes used for manure filtration, up to a certain point at least (Masse et al. 2008). As suggested by the study, the liquid manure was adjusted to pH of 6.5. Figure 21 shows the average pH alteration of the liquid manure samples, comparing the pH before adjustment, prior to running the filtration unit, pH of the filtered sample, as well as the recycled liquid manure pH.

Figure 20. Example of foam formation in the flat bottom liquid manure reservoir.

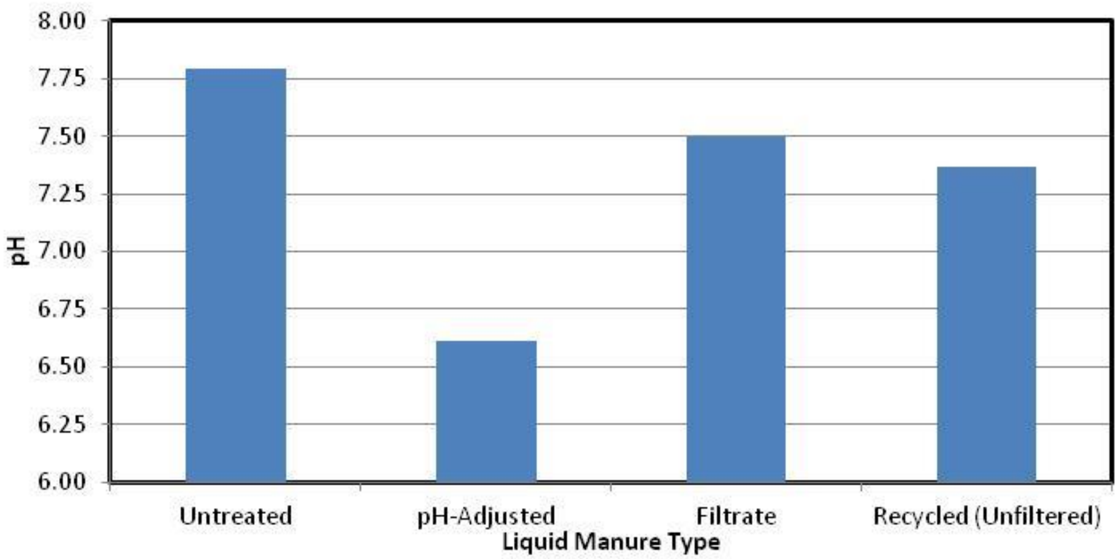

Figure 21. Average pH values for liquid manure at various points of filtration process.

Another pretreatment test was the addition of calcium carbonate to the liquid manure. Calcium carbonate, as an additive, is supposed to improve the efficacy of settling and separation of solid particles in the liquid manure. An article cited describing the use of calcium carbonate in this context mentions using 3 g/L of calcium carbonate, which equates to 57 g for a 5 gallon bucket (Agomoh 2012). To check that this ratio is the most effective available, a test was performed utilizing calcium carbonate in different ratios, allowing for a 24 hour settling time for samples with a calcium carbonate content of 0, 3, 6, and 9 g/L respectively. These samples were then put through a total volatile solids test to determine the effect on the solid content in the liquid manure. Table 4 shows the results of this testing. While the differences in solids content does not seem to be significant in comparison, the tests do seem to indicate that the solids content in the 3 g/L sample is the lowest and thus affirms the decision to utilize that ratio.

Table 4. Results of VSS/TSS testing for various concentrations of calcium carbonate.

Sample Concentration	Initial Mass (g)	Total Solid Mass Content (%)	Volatile Solid Content (%)
0 g/L $CaCO_3$	40.1	2.21%	43.7%
3 g/L $CaCO_3$	37.3	2.15%	42.4%
6 g/L $CaCO_3$	41.7	2.37%	47.7%
9 g/L $CaCO_3$	39.9	2.80%	55.9%

Filtration of Liquid Manure Using Crossflow Unit

Initial Microfiltration and Reverse Osmosis Tests

Figure 22 shows the average flow rates at 15 minute intervals of filtering distilled water, using the microfiltration and reverse osmosis membranes, where Figure 23 compares the same conditions for filtering the liquid manure. In general, the flow rate decreased with time, but varied between membranes and liquids. In particular, the microfiltration membrane had a drastic drop off in flow rate between the fifteen and thirty minute mark when treating distilled water, although even the minimum average flow rate was 5-10 times higher, whereas the alteration between average flow rates for the reverse osmosis membrane with distilled water was much less significant than expected. In comparison, the alteration in flow rates for filtering liquid manure showed a similar trend in general, although the overall flow rate was significantly higher for the microfiltration process, compared to reverse osmosis. The difference in flow rate from the microfiltration membranes between sample types was quite significant, with the minimum flow rate recorded with water was nearly triple the maximum recorded flow rate for the manure, whereas the difference in flow rates between distilled water and manure is negligible for the reverse osmosis membrane. Figure 24 demonstrates the use of the membranes can affect membrane quality over time. The photo on the left was a lightly used microfiltration membrane, photo on the right shows the end results of filtration for the day. The darkened colors represent the area where manure was filtered and show how flow rate over time tends to decrease, due to membrane clogging and increased flux.

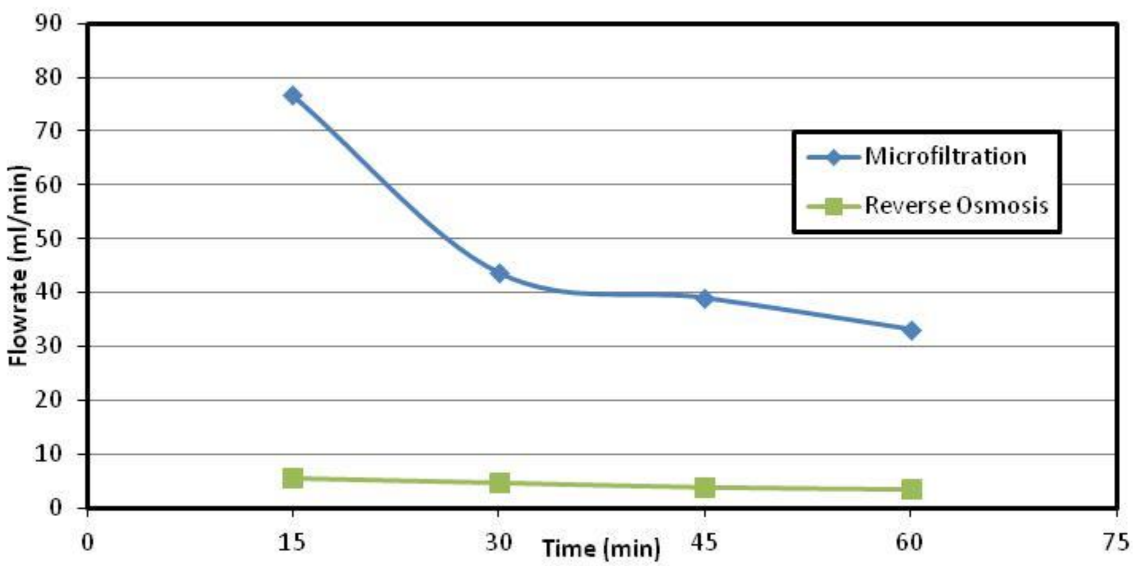

Figure 22. Average flow rates at fifteen minute intervals, for microfiltration and reverse osmosis treatments for distilled water.

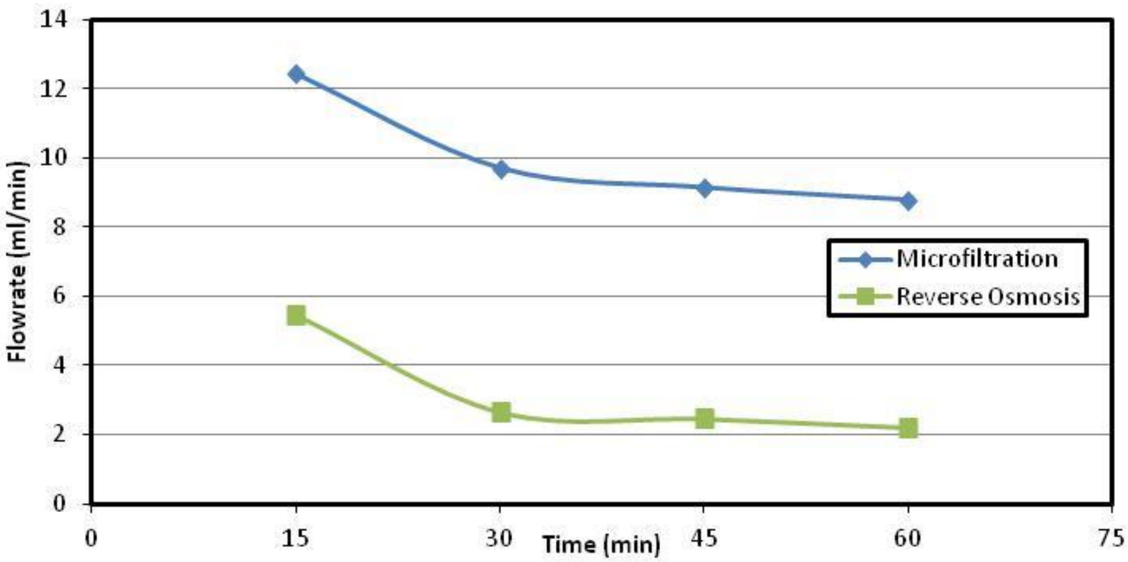

Figure 23. Average flow rates at fifteen minute intervals, for microfiltration and reverse osmosis treatments for liquid manure.

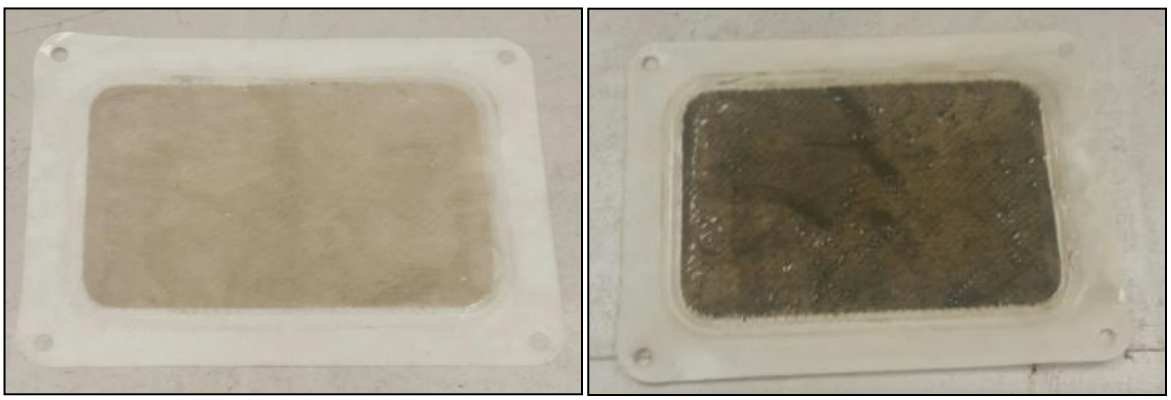

Figure 24. Microfiltration membrane before (left) and after (right) manure filtration in the Sepa crossflow cell.

Nutrient Contents of Filtered Manure

A total of 8 samples were filtered using the microfiltration of polyvinyl difluoride membrane and 11 samples filtered with reverse osmosis using the GE Osmonics SG TFC membrane. Figure 25 compares the average nutrient contents in the three liquid manure samples: unfiltered, and microfiltration and reverse osmosis filtrate. While the transition from unfiltered to reverse osmosis filtered demonstrated some decrease in nutrient contents in several categories, the results did not support the potential of water recycling. The company, which supplied the filtration unit and filters, suggested that the raise in nutrient concentration after the microfiltration was because the membrane was not rated for removal of dissolved nutrients and because small sample numbers amplified lack of difference. In comparison, they estimated the reverse osmosis should result in a rejection rate for the nutrients nearing 80%, which did not represent the average nutrient removal rates by the reverse osmosis results of this research.

On average, the removal of nutrients and solids from the unfiltered manure to the reverse osmosis filtrate was 31.6%, with a range of 21.1% removal of total suspended solids, to 47.0%

for potassium. Although factoring in the RO membrane was used on the microfiltered filtrate, the average removal increased to 33.8%, with a range of 23.9% removal of total suspended solids to 51.1% removal of ammonium.

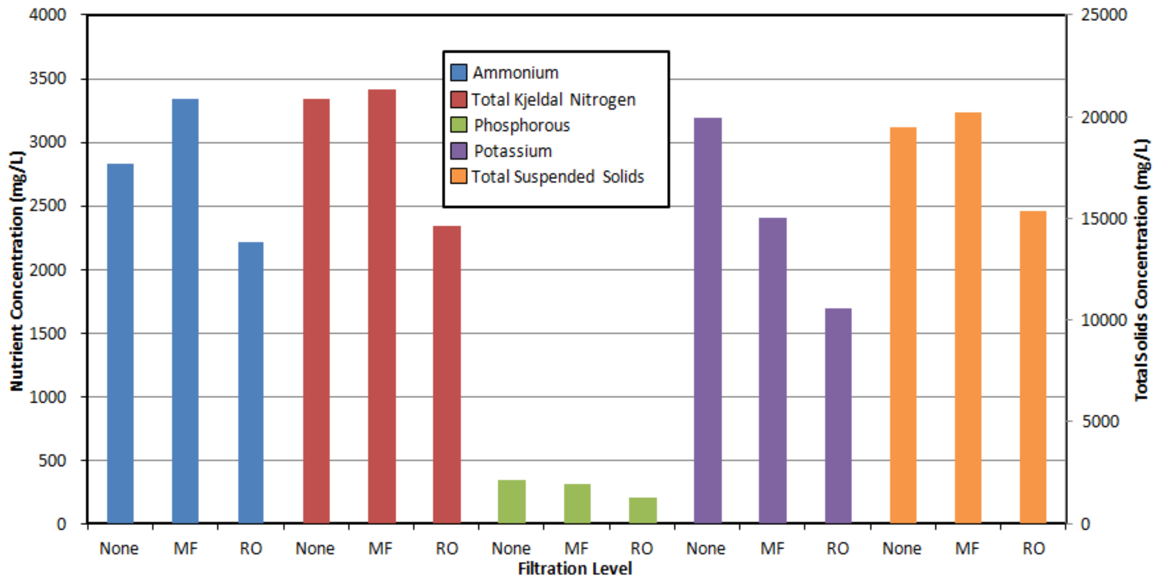

Figure 25. Concentrations of measured nutrients and solids in liquid manure stream, separated by filtration levels.

<u>Results of Additional Membrane Filtration</u>

Figure 26 depicts the average flow rates of filtering distilled water before treating manure, filtering liquid manure, and the flow rate of filtering distilled water after manure filtration for each membrane for the April samples. It is important to note that the filtration rates, particularly for the SW30XLE reverse osmosis membrane, is based off of one full filtration cycle. As a result, the flow rate calculations may be skewed due to the membrane not being primed fully, so flow rate for the distilled water before manure may be lower than expected. As well, they only represent one filtration cycle for a completely untarnished membrane, so the filtration rates also are likely higher than expected.

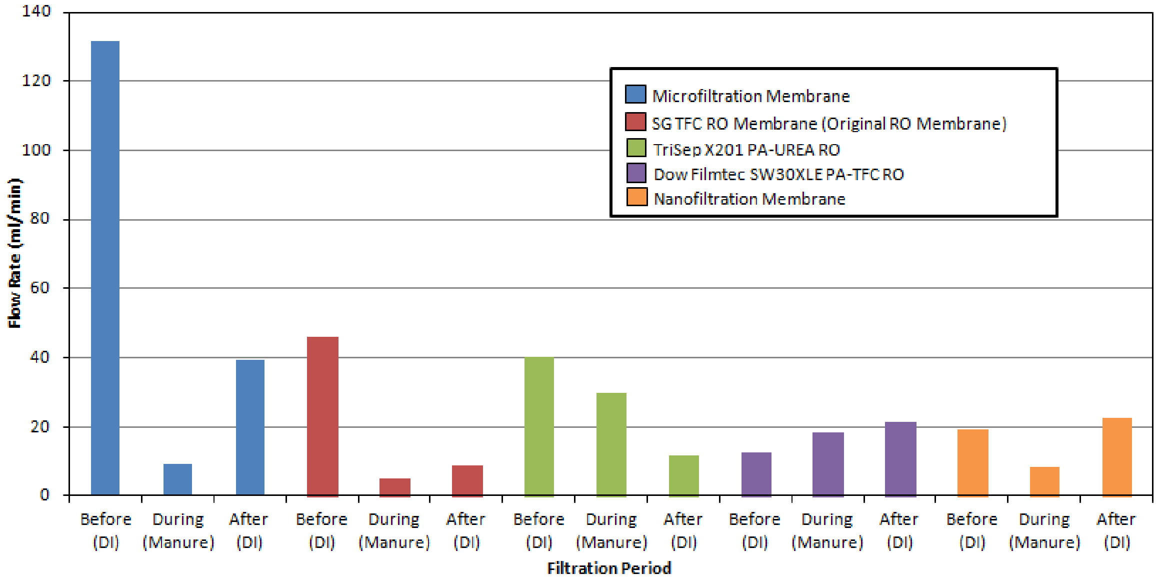

Figure 26. Comparison of flow rates before, during, and after manure filtration, separated by membrane used.

Table 5 lists the nutrient contents of the untreated liquid manure, and filtrate samples from different types of membrane filters. The data indicate that the nanofiltration resulted in generally lower nutrient contents, than all of the reverse osmosis filtration. Table 6 shows the comparison of the highest and lowest nutrient concentrations recorded, the filtration level that nutrient content was obtained with, and the percent difference. Again, the nanofiltration and reverse osmosis filtration were conducted after the microfiltration treatment. The results indicated that the nanofiltration membrane was obtaining a better nutrient removal than all of the reverse osmosis filtration, which would not be as expected given that the reverse osmosis membranes were listed with higher rejection rate. The rate of rejection suggests that the type of reverse osmosis membrane used was not a significant factor to the issues experienced, and the lower than expected rejection rates lies in some other issue.

Table 5. Nutrient concentrations of the untreated manure and filtrate samples from different types of membrane filters.

	Unfiltered	Microfiltration	GE SG RO	Nanofiltration	TriSep X201	SW30 XLE
Ammonium (ppm)	4,563	3,971	2,841	2,742	3,817	3,550
TKN (ppm)	4,761	4,184	2,950	2,844	4,106	3,707
Phosphorous (ppm)	513	415	277	252	391	351
Potassium (ppm)	3,547	3,010	2,131	1,994	2,801	2,597
Total Dissolved Solids (ppm)	23,168	21,248	17,600	16,960	20,864	20,416

Table 6. Comparison of highest and lowest nutrient concentrations and percent change.

	Highest Nutrient Content (ppm)	Filtration Level (High)	Lowest Nutrient Content (ppm)	Filtration Level (Low)	% Difference
Ammonium	4,563	Unfiltered	2,742	Nanofiltration	39.9%
TKN	4,761	Unfiltered	2,844	Nanofiltration	40.3%
Phosphorous	513	Unfiltered	252	Nanofiltration	50.9%
Potassium	3,547	Unfiltered	1,994	Nanofiltration	43.8%
Total Dissolved Solids	23,168	Unfiltered	16,960	Nanofiltration	26.8%

Performance of Filtration Based on Salt Solution

Figure 27 shows the resulting flow rate and the conductivity during each interval, as well as the conductivity of the recycled salt solution. The results indicate two major points of interest. The lower than expected reverse osmosis rejection rate suggests the crossflow unit was not performing as expected, even if filtration was occurring at some level. The second point of interest is that, the salt concentration (conductivity) decreased over time. The change in conductivity indicates that the efficacy of filtration increased as time went on, while the flow rate decreased. The change may show that the blockage of the membrane by the particles in the solution improves the filtration rate, while the rejection rate was still relatively low.

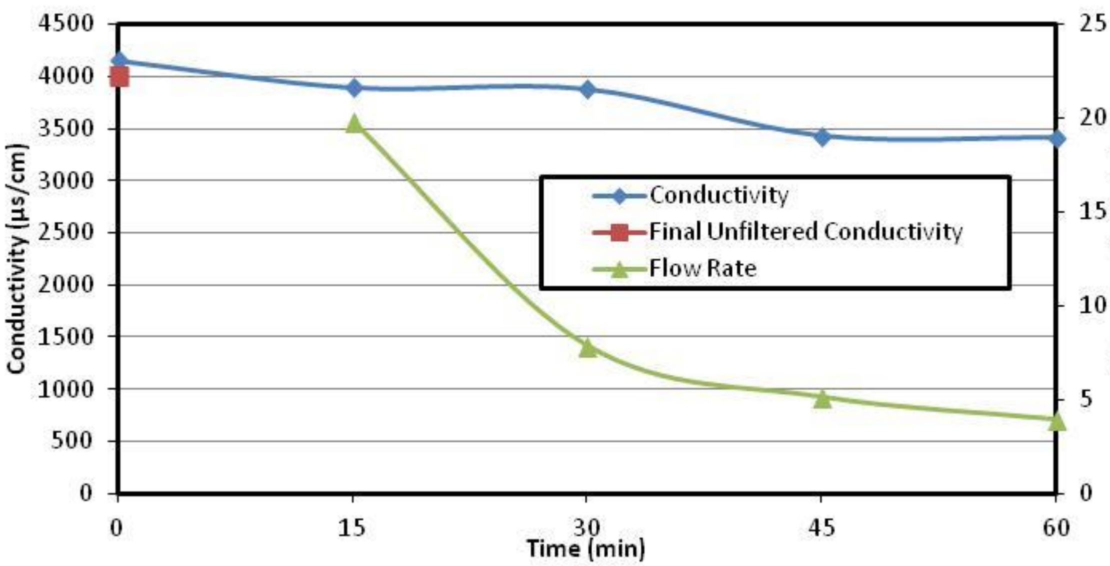

Figure 27. Conductivity and flow rate over the course of an hour of filtering salt solution with reverse osmosis membrane.

In trying to determine the source of the unidentified leakage and other issues, we relied on the crossflow unit company (Sterlitech) who also supplied the membranes. One point immediately tested in doing the conductivity tests was the O-rings used in the cell. The O-rings were replaced with new ones before conducting the April tests, and the low performance remained, suggesting the O-rings were not the source of this problem. Other suggested causes included possible damage to the membrane during testing or improper conditioning of the membrane before testing, but membranes were checked after every test and replaced as needed.

After further discussion with Sterlitech, a couple of definitive points were reached indicating some likely causes of issues to be noted for future research. The first problem determined was that the cell was not being properly pressurized, due to a miscommunication in applying the system. The given pressure range of operation for the membrane was utilized as the base pressure for the cell, but the pressure is rather supposed to represent the optimal pressure of the flow through the membrane. This misunderstanding did result in the cell being under pressurized, where it is supposed to be set at a starting pressure approaching 1000 psi. This may have contributed to additional leakage due to the lack of pressure allowing for the liquid to seep past the O-rings. The other major finding was that there was indication that the membrane was being damaged during operation. Specifically, it appeared that the permeate carrier and the spacer used during operation may had slight overlap with the inner O-ring during filtration while pressurization. This seems to have resulted in damage to the membrane around the O-ring site, creating "micro-ruptures" allowing for solid particles to more easily pass through the membrane. The possible small openings would also explain why there was some level of filtration, as sections of the membrane would still be operating as intended. The damage, being as small as it was initially, was unnoticed during testing, being thought to just be a normal byproduct of operation at high pressures, and also likely contributed to a shorter lifespan for the membranes used, as larger tears tended to occur in the O-ring site as well. The border of the carrier and spacer were trimmed at points, to try to avoid overlap, but the issue persisted, so it is still unknown if it could have also resulted from factors like the edges of the components shifting and causing damage. Determining a practical method of evaluating membrane health, ideally both in between and during operation would likely be an effective option for avoiding similar issues in the future. While the issues experienced with the filtration membranes possibly being, the economic analysis was completed utilizing the results obtained in the filtration testing, to best meet the project objectives.

3) *Cost implications and returns of the barn, storage systems, and different levels of nutrient and water recycling.*

Economic Analysis

Barn and storage shed

Major economic factors to consider include the construction and annual operating costs associated with the separation barn and storage shed, as compared with the deep-pit barn. The initial costs primarily account for construction and labor costs with building the finishing barn, scraper and controller, conveyor system, liquid manure collection pit and pump, and manure storage shed. The farmer kept track of the construction costs for the finishing barn independently of the costs of the manure storage shed. The costs were prices as is in 2010, at $323,000, with individual components and labor cost included in Table 7. The total construction cost for the finishing barn, including the manure storage shed, was $323,000. Comparing with typical deep-pit barn construction, this price is 17% higher (compared with the upper range), the deep-pit barn was $175 to $230 per pig space in 2011 (Farm Journal's Pork, 2011).

Part of the reasons were that the solid-liquid separation barn was a single, smaller (compared with a quad building which holds 4000-4800 pigs), and custom-designed and custom-constructed barn. Should there be more of similar barns built in the region, the overall construction costs are expected to be lower and closer to the deep-pit barn. In terms of carbon footprint of the separation barn, it did require a slightly larger center workroom for housing the conveyor system and ventilation fans, and a small basement to access the gutter, scraper system, and liquid manure channel. The size of the finishing barn is comparable to the deep-pit barn. However, an additional manure storage shed outside of the finishing barn is required, while the deep pit barn stores all the manure for one-year. The ventilation needs and building materials are similar when comparing the separation and deep-pit barns.

The annual maintenance costs are estimated and reported in Table 8. The farm did not record labor costs, as the repairs were performed on-site by farm staff. It is estimated that the labor costs would be 50% more of the parts, that the total maintenance with labor are projected to be $3,500. The costs are also based on the amount spent on replacement parts through a seven year period in which the barn has been operating. The electricity cost estimates are based off of the yearly cost estimated for running the automated scrapers and conveyor system. The estimate is based on the rated output of seven, 2-horsepower motors, one for each room in use for the scraper system, and three for the conveyor system. The scraper was run based on the feed auger system used with the barn, set to follow feed delivery rate, with an average daily operation rate of six times per room per day, for four minutes per scraper cycle. Meanwhile, the conveyor system also averaged six operations per day, with fifteen minute cycles of operation. This equates to each scraper operating for 24 minutes a day, and the conveyor operating for 90 minutes each day, with three motors. This equals out to 366 minutes of operation for 2 horsepower motors each day, which leads to an electrical need of 9.10 kWh/day, with an estimated cost per day of 90.61 cents cost for daily operation. Extrapolating this out to a yearly cost, it ends up being $330.73 a year, using 3.321 MWh each year. Again, these costs are based on the given average Missouri commercial electricity cost of 9.96 cents/kWh, so those costs may fluctuate depending on area electrical cost.

Table 7. Initial costs for finishing barn construction.

Construction Needs	Total Cost	Cost per Pig (1,200 head)
Finishing Barn (80 x 132 feet)	$280,000	$233.33
Building	$188,000	$156.67
Concrete	$60,000	$50.00
Equipment	$32,000	$26.67
Conveyor System	$11,000	$9.17
Manure Storage Shed (25 x 75 feet)	$32,000	$26.67
Total Cost	**$323,000**	**$269**

Table 8. Annual Cost for finishing barn maintenance.

Maintenance Items	Yearly Cost	Cost per Pig (1,200 head)
Motor Replacements	$228.14	$0.19
Link Chain for Conveyor	$457.14	$0.38
Cable Replacements, 1000ft/year	$600.00	$0.50
Pulley Replacements, 2 sets/year	$57.14	$0.05
Electricity for Scraper and Conveyor Systems	$330.73	$0.28
Total Cost	**$1,673**	**$1.39**

Electrical Consumption for Filtration of Liquid Manure

Another factor to consider when evaluating the efficiency of the filtration process is the operating and energy costs of the membrane filtration cell. The primary issue is the fact that the unit utilized was a bench-scale model, which is not representative of the actual costs of commercial scale filtration units. It is likely that the energy consumption decreases with the larger scale and commercial units. Obviously, with only the laboratory research unit being conducted here, it is impossible to test if this is the case. The energy consumption rates for the cell were evaluated and presented for discussion. The SEPA filtration hydracell pump had a power output of 1.32 horsepower, which allowed to an evaluation of power consumption based on average flow rate. Table 9 summarizes the estimated power consumption (kWh/liter), flow rates for both the microfiltration and reverse osmosis membranes, for both distilled water and liquid manure. In addition, the cost per liter of filtrate is also estimated, based on the power consumption estimated being converted with the most recently available cost of electricity per kilowatt-hour, which currently is at 9.96 cents/kWh.

Table 9. Comparison of filter flow rate and energy consumption.

Filter Type/Fluid Filtered	Flow Rate (mL/minute)	Pressure (psi)	Power Consumption (kilowatt-hours/liter)	Average Cost per Liter (cents)
Microfiltration (DI water)	70.29	240	0.23	2.33
Microfiltration (liquid manure)	10.04	240	1.63	16.28
SG TCF RO (DI water)	14.51	360	1.13	11.27
SG TCF RO (liquid manure)	3.52	360	4.66	46.44

Ultimately, water recycling was not a feasible end result given the parameters in which this study was conducted. While the issues with the reverse osmosis membrane not filtering the liquid manure at an expected and satisfactory level were the most apparent issues experienced, and may not be representative of the actual potential for filtration of the manure, the other side of this issue lies in the discrepancy between cost and liquid output obtained from running the system. The average total operation time for a reverse osmosis membrane used in this experiment was 18.6 hours, which when utilizing the average flow rate for liquid manure found in testing of 3.52 mL/min equates to approximately 4 liters of filtered manure over the life of the membrane. Reverse osmosis membranes purchased in the study cost around $50 each, although this cost is due to buying precut, five-count groups of membranes, and the cost would likely be lower via purchasing membranes in sheet bulk and cutting them individually, but this would have been too costly for the scope of this research. The cause for changing membranes typically involved some degree of rupturing of the membrane itself, rather than complete membrane blockage. In theory, the lifespan of the membranes used could be much longer if rupturing could be reliably avoided, but membranes were stored and tested following the manufacturers specifications, so it is not known at this point how better maintenance could be done. One potential possibility that could be looked into in the future is whether the length time that the membrane has been utilized (meaning days since initial use, rather than actual time of operation) could alter the likelihood of rupturing. The membranes had to be kept wet after initial use, so there may be some possibility that longer running times over a shorter number of days would reduce membrane degradation. In contrast, however, due to lower than expected nutrient filtration, it is likely that fouling would be much more pronounced given ideal operation parameters, which should also be considered. Ultimately, while water recycling is able to be more effective in larger-scale operations, it proved to not be efficient in a cost-to-flow comparison for the bench-scale model used here.

Based on the bench-scale crossflow filtration unit, the active membrane filter area was 5.91 inch x 3.94 inch (15 cm x 10 cm), or 23.3 inch^2 (0.015 m^2) and had an average reverse osmosis flow rate 3.52 mL/min. Assuming a linear relationship between surface area and flow rate, a flow rate of 237.3 ml/min could be achieved by 1 m^2 of membrane filter. The average liquid manure produced in this barn was 885 gallons, which equates to 3,350,000 milliliters a day. Thus for a day's worth of liquid manure to be filtered in a day (24 hr operation), it would require 91.5 ft^2 (8.5 m^2) of membrane filter without considering fouling and down time for maintenance such as filter regeneration. However, a larger farm-scale reverse osmosis filtration system would incorporate a much larger surface area, and more resolute monitoring of operating pressure and flow rate, perhaps with multiple subunits to allow for better maintenance and coordination of the filtration process, which also likely result in higher flow rate and better nutrient rejection efficiency. The bench-top filtration unit was probably undersized for this research (flow rate rated as 7-70 ml/min), which our flow rate did not meet reliably, as indicated by the average flow rate of 3.52 ml/min. There were very high dissolved nutrients in the pre-filtered liquid manure because no dilution water added and the barn operation was very efficient in reducing water waste. As indicated by the tests comparing flow rates measured over the course of an hour, membrane filtration tends to slow down more over time, due to membrane clogging and increases in flux causing a higher rejection rate. Heavy membrane fouling likely would be experienced with a larger filtration device, unless the filtration area was significantly increased, which would result in even higher capital costs. The filtration process required close monitoring of the membrane integrity and effluent quality to ensure that rupturing has not occurred, again suggesting the unit was not appropriate for the high nutrient liquid manure.

Nutrient removal challenge was compounded by the nutrient separation that already happened in the solid-liquid separation barn. In particular, the average nutrient removal rate was 61.7% removal for nitrogen, 41.7% for ammonium, 74.9% for phosphorous and 46.2% for potassium. The average nutrient removal rate for the filtration process as a whole, going through the reverse osmosis was 29.8% removal for nitrogen, 39.5% for phosphorous and 47.0% for potassium of the already separated liquid manure. Based on the separation efficiency, it is estimated that the remaining nutrients in the liquid manure contain 26.9% of the total nitrogen produced, 45.5% of total ammonium, 15.2% of phosphorous, and 28.5% of potassium. Table 10 is a table comparing the estimated nutrient separation rates calculated via the barn and the membrane filtration. Based on these average results, extrapolated for a full year, it is estimated that the full filtration would result in an annual production rate of 756 gallons of nitrogen, 807 gallons of ammonium, 131 gallons of phosphorous, and 471 gallons of potassium in the liquid stream.

Table 10. Nutrient removal via separation and filtration.

	Nitrogen	Ammonium	Phosphorous	Potassium
Daily Total Nutrient Flow (gal/day)	7.7	4.9	2.4	4.5
Daily Liquid Stream Mass (gal/day)	3.0	2.8	0.6	2.4
Percent Removal from Liquid Stream (%)	61.7	41.7	74.9	46.2
Daily Filtered Liquid Stream (gal/day)	2.1	2.2	0.4	1.3
Percent Removal from Filtered Stream (%)	73.1	54.5	84.8	71.5

Given the daily average 885 gallons of liquid manure needing to be filtered, and assuming both microfiltration and reverse osmosis are need in the process, power consumption was estimated to be 21,112 BTU/gallon (5,884.76 kJ/liter) and 60,216 BTU/gallon (16,785 kJ/liter) needed for microfiltration and reverse osmosis, respectively. This energy cost equates to a total energy use per day of 71.99 MBTU (75.95 GJ), or 26.28 GBTU (27.72 TJ) per year, which based on the most current commercial electricity cost for Missouri, would be greater than $700,000 per year, which is not feasible for the nutrient/water recycling purposes. However, this calculation is obviously not representative of what a farm-scale would cost because of more efficient and more accurate operation, but does serve to indicate nutrient extraction could be costly and that a small scale operation should not be extrapolated to farm-scale filtration system.

The laboratory filtration experiment underestimated the difficulties and complexity of the nutrient separation. Only a half-time graduate student was budgeted at 18-months to collect the field measurements with various barn data gaps, intensive data preparation and analysis, and difficult liquid manure reverse osmosis process. The experiment was then extended to about 2-years to collect more field data, and further improve and investigate the liquid manure filtration, When the team reached out to the Canadian researcher as planned, for technical support on the reverse osmosis, the researcher had retired and did not respond to our questions.

The fact that most of the monthly reverse osmosis filtration showed only marginal (<30%) nutrient removal, the filtration unit probably had a significant leakage or other technical issues. In addition, the filtration unit was very small, it is not practical to estimate the costs and maintenance implications of the commercial scale reverse osmosis process. Although the laboratory scale filtration tests did not yield desirable nutrient separation, the results did suggest it is very time consuming and energy intensive to conduct reverse osmosis on liquid manure, most likely due to the very high solid contents and dissolved nutrients, and large capital cost needed to start with high surface areas of membrane filters to more efficiently process (reverse osmosis) the liquid manure.

Air Quality Data

The gas concentration measurement data included in this research was meant to be qualitative indicator of the general air quality of the solid-liquid separation finishing barn. Only grab sampling and simple chemical tube measurements of the ammonia and hydrogen sulfide were conducted. Although not originally included in the research plan, the air quality indicator could be an important factor to consider when evaluating the overall performance of the solid-liquid separation barn.

Ammonia Concentrations

Concentrations of ammonia at the barn exhausts ranged from 0.26 to 6.0 ppm, with the average wall fan exhaust concentration being 1.30 ppm, while the average pit fan exhaust concentration was 1.91 ppm. It is notable that ammonia concentrations only exceeded 3.0 ppm for either fan for one month, being March 2017. Excluding that month, the averages instead are 1.18 ppm for the wall fan and 1.65 ppm for the pit fan. In a similar study performed previously, evaluating a similarly designed scraper separation system for a university barn (von Bernuth et. al. 2005), a similar range of concentration was found. The weekly average concentrations measured ranged between 0.82 ppm and 6.17 ppm, with the maximum concentration not exceeding 7.5 ppm. The ammonia concentrations of this study are lower than those measured in deep pit barns, which averaged over 15 ppm during winter months (which is when the ammonia content tended to be highest) as seen in the literature (Lim et al., 2011).

Performance and the number of fans running at any particular time could vary, often with the lower fan count leading to higher concentrations._Air quality could also be affected by the number and size of animals, manure management, time of day, and season. In addition, other improvements were made to measurements, particularly measuring all fans in the pit exchange portion of the barn separately in scenarios where multiple fans were running concurrently. Figure 28 depicts average ammonia concentration each month, except in October 2016, where the air quality was not measured. One important note is the ammonia and hydrogen sulfide concentrations were taken using Dräger tubes. Measurement of the Ammonia tube was not recommended to be taken when the ambient temperatures was 50°F (10°C) and below. Although the barn exhaust temperatures were always higher than 50°F, the measurements were taken from outside of the barn for biosecurity reasons. This might have exposed the Dräger tubes to ambient temperature, which were at times lower than 50°F and could have affected the measurement accuracy.

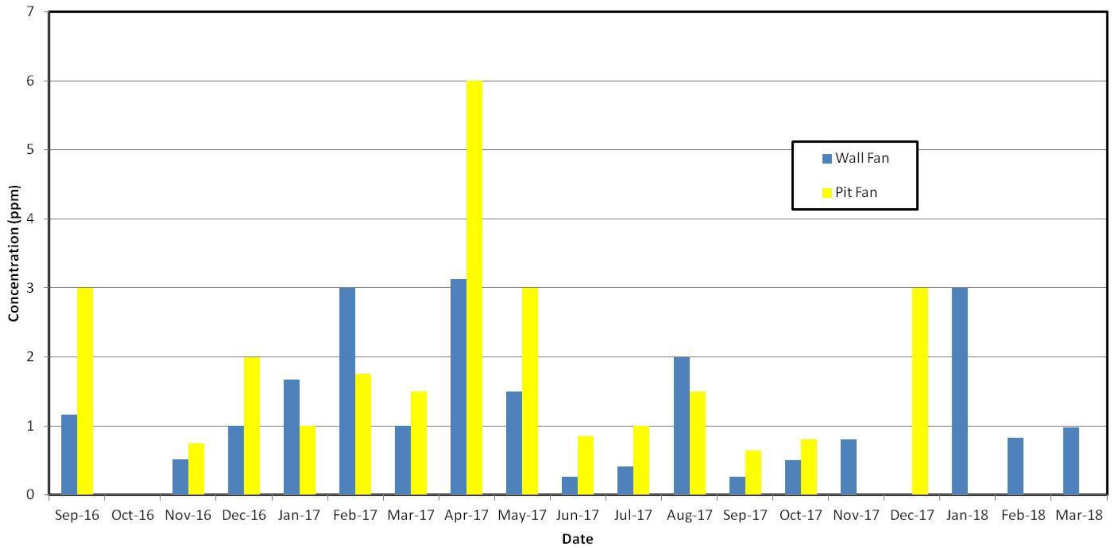

Figure 28. Monthly average ammonia concentrations measured at both wall and pit fans.

Hydrogen Sulfide Concentrations

For hydrogen sulfide, the Dräger tube never detected measurable concentration (below detection level of 0.2 ppm). A test was performed using hydrogen sulfide calibration gas (1.7 ppm) with the same air gas tubes, and accurate levels were detected. Alternative measures were taken using a Jerome meter as mentioned prior. Figure 29 shows the average hydrogen sulfide concentrations measured using Jerome meter. Average wall fan exhaust concentration was 0.11 ppm, while the average pit fan exhaust concentration was 0.10 ppm. These findings, combined with the inefficacy of the gas tubes obtaining detection align with previous results for scraper barn air quality (von Bernuth et. al. 2005). Hydrogen sulfide levels were not in the detectable range for either study when utilizing gas tubes (0.5 ppm for the von Bernuth study) and an average air quality around 0.1 ppm would be consistent with this. In comparison, a previous study found the average hydrogen sulfide concentration in exhaust from a standard deep-pit barn was 0.42 ppm (Ni et. al. 2000), which would have been detectible with the gas tubes utilized in our testing. Lower concentrations of hydrogen sulfide are expected in the solid-liquid separation barn because it has much lower amount and shorter time period of manure accumulation, when compared with the deep-pit barns.

Figure 30 compares the calibration checks of hydrogen sulfide levels (measured in lab), before and after measurements at the farm. The tests indicate, after performing a regeneration cycle as suggested by the manufacturer, that the measured hydrogen sulfide tended to decrease after several field measurements. As well, the measured span gas concentration was lower than the certified concentration, while the span check results were relatively consistent. As for the zero air, concentrations measured were more consistent and not affected by the field measurements. No adjustment was made to the Jerome meter readings based on the zero and span calibration checks because of several reasons. First being the drift noticed before and after the field measurements, and second being a lack of consistent and more thorough calibration checks and even calibration to the Jerome meter. Air quality measurement was not originally included in this research. In addition, the Jerome measurements were started late in the research and with relatively small sample size. Even when a correction factor of 3-4 times was applied to adjust the Jerome measurements, the average hydrogen sulfide concentrations would still be lower than 0.5 ppm. The hydrogen sulfide levels at this finishing barn were not of any immediate concern in terms of air quality issue, relative to the deep-pit barns.

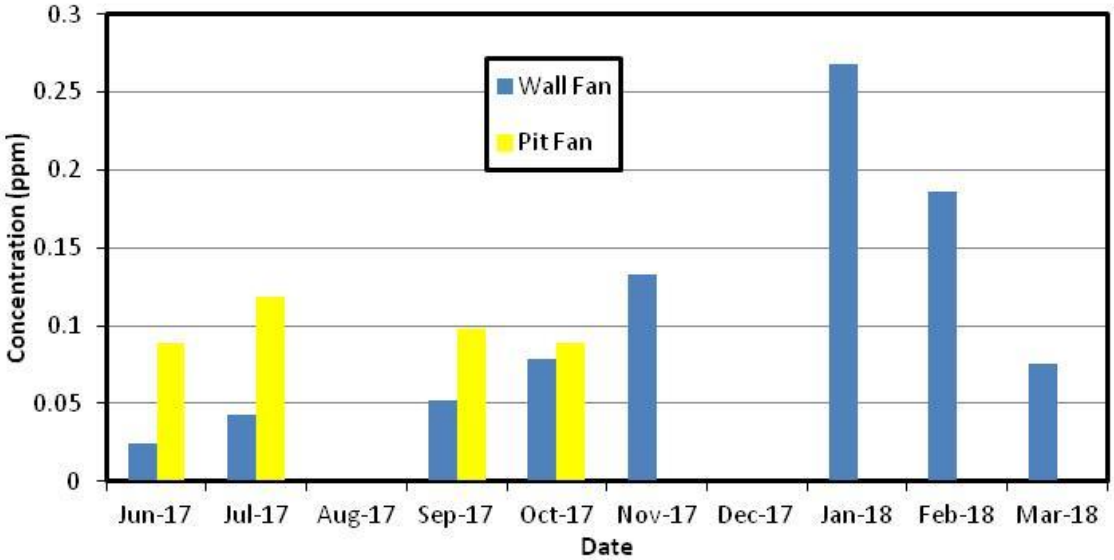

Figure 29. Monthly average hydrogen sulfide concentrations for wall and pit fans, measured with Jerome meter.

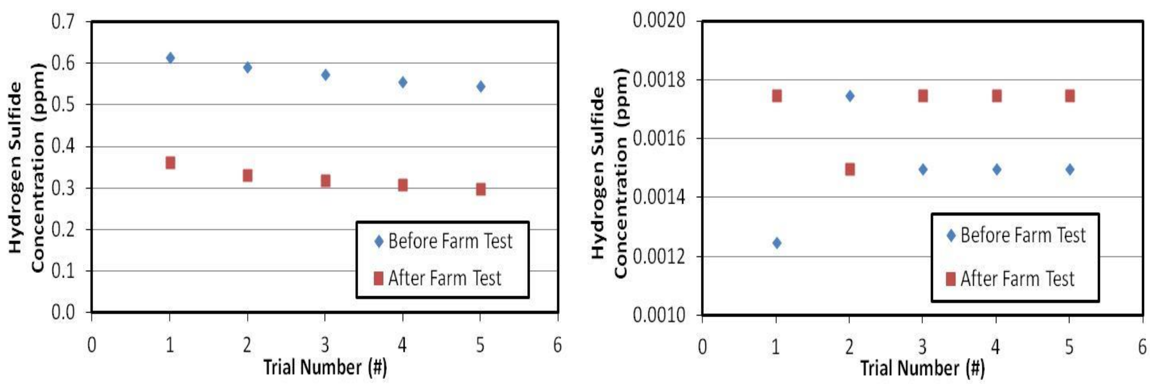

Figure 30. Comparison of the average hydrogen sulfide concentration before and after field measurements at the farm. The left shows measurements of a span gas of 1.7 ppm, where the right shows the zero air checks.

Conclusions and Discussion

Over the course of the period from August 2016 to April 2018, this study monitored the manure production of a commercial finishing barn utilizing a solid-liquid separation scraper system. The various factors contributing to or resulting from the production for the two manure streams provided a wide range of results to interpret. Overall, we can conclude that the final results obtained from monitoring the total manure production rate, air quality exiting the barn fans, and the pig growth rates made sense relative to other comparative sources. Nutrient separation for nitrogen and ammonium to the solid manure was very similar to what was reported in a previous study on a similarly designed finishing barn. The fraction of concentrations of potassium and phosphorous in the solid manure was lower in this study compared to that previous study, while the moisture content was 6% higher observed in this research. The overall results provide a solid manure that would be defined as “stackable”, so the variance between the two tests does not appear have a large impact on a lot of the fundamental characteristics of the manure produced, instead more demonstrating some level of variance that may exist for this separation technique. Overall, the results indicate that the barn design can attain some valuable results from separating the solid and liquid streams, including an 80% total solids removal, and nearly 75% removal of phosphorous. Operational costs for the scraper system after installment are estimated under $2,000 a year, with electrical demand being 3.3 MWh/year. Air quality measurements from the barn in particular was quite low in comparison to expected air quality measurements for a standard deep-pit barn; ammonia concentration averages less than 2 ppm compared to 15 ppm expected otherwise.

Regarding the implementation of the membrane filtration component to the research, the results found a mixture of problems and useful findings. Utilization of fine metal filter prior to filtration proved to be extremely effective. Metal filtering allowed for quick filtering of remaining coarse particles in a liquid stream with flow through being nearly instantaneous. Sometimes, the metal filter pores would clog and required a quick rinsing period. pH adjustment seemed to help reduce issues of foaming, but the randomness of the problem made it hard to come to a conclusion on a foam reduction solution, and it was difficult to determine if the adjustment improved other qualities of the effluent due to the tendency for the pH to increase during operation time. Calcium carbonate addition did not seem to make a major impact on filtrate quality, although this may be a result of the high moisture content, combined with the screen filtering afterwards removing larger particles anyway. As a result, some use may be found in cases where solids content is higher than normal. Overall, the filtration efficiency was not as effective as hoped, with the microfiltration membrane not being restrictive enough for nutrient removal and the reverse osmosis membrane having a slower than expected flow rate, noticeable fouling on the membrane itself, and a nutrient rejection rate averaging around 30% rather than the expected 80%. However, given the low rejection, combined with the tests with additional membranes showing a higher rejection rate for nanofiltration, which has a greater pore size; it is likely that the reverse osmosis results are not indicative of the full potential of liquid manure filtration. Further testing has seemed to indicate leakage in the filtration unit, potentially through damage to the membrane during filtration. As a result, determining and maintaining healthy system pressure and liquid flow rate may be imperative for preserving membrane quality to arrive at a higher rejection rate.

Considering the issue was consistent across different reverse osmosis membranes, future research may want to look into application of a larger-scale crossflow system to see if nutrient removal and flow rates can be improved significantly. Even without the desired removal rates, however, the addition of membrane filtration was enough to improve nutrient removal of the four major monitored nutrients to all over 50% removal from the liquid stream, with three of the four at 70% removal or greater. These findings proves the value of incorporation of separation techniques, whether they be used on a microscopic scale or a macroscopic one, in being able to control nutrient and solids concentrations. The primary goals for future research need to be improving manure filtrate flow rate, obtaining a greater level of filtration for the solids in the liquid stream, and determining the cost of installation and upkeep for a filtration unit that can operate at the level of a farm operation, as extrapolating the costs off of bench-scale model does not seem remotely indicative of the true cost, due to improved efficiency and power.

Acknowledgement

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