A NOVEL TREATMENT SYSTEM TO REMOVE PHOSPHORUS FROM LIQUID MANURE

C. D. Church, A. N. Hristov, R. B. Bryant, P. J. A. Kleinman, S. K. Fishel

ABSTRACT. *Lowering the phosphorus (P) content of animal manure is one approach of addressing concerns over surplus P accumulation in soils resulting from land application of animal manure. We sought to develop a treatment system for liquid manures that conserves manure nitrogen (N) while removing most of the manure P. Initial evaluation of a treatment system involving manure solid separation and precipitation of dissolved P with an alkaline salt ($Ca(OH)_2$) resulted in poor liquid/solid separation and poor dissolved P removal and created conditions promoting ammonia-N (NH_3-N) volatilization. As a result, we developed a three-stage system with iterative solid removal and acid salt (ferric sulfate – $Fe_2(SO_4)_3$) sorption of dissolved P: (1) removal of bulk and intermediate sized solids (>25 μm); (2) chemical treatment to convert dissolved P; and (3) final removal of fine solids and chemically sorbed P. When tested on manure slurries from 150 and 2700 cow dairies, 96% to 99% aqua regia extractable P was removed along with 92% to 94% of the solids, resulting in liquid manure filtrates with N:P ratios greater than 19:1. While costs of treatment were roughly \$38 kg^{-1} P removed, equivalent to \$750 cow^{-1} yr^{-1}, we anticipate that refinement of the process and beneficial uses of the solid materials (bedding, compost, etc.) will improve cost-efficacy considerably.*

Keywords. *Chemical precipitation, Manure, Nitrogen, Phosphorus, Solid separation, Treatment systems.*

Managing manure phosphorus (P) has become a priority concern of livestock operations, in part due to nutrient management implications with land application of manure. Concentrated livestock production occurs in many regions of the country and is associated with regional and farm-scale accumulations of P due to the nature of feed nutrients and metabolism by the animal, with manure P typically containing more than two-thirds of consumed feed P (Hristov et al., 2006). These accumulations have, over time, created a legacy of P sources that can enrich runoff water and contribute to downstream eutrophication (Daroub et al., 2009; Sharpley et al., 2013), the most pervasive water quality problem in the United States, which accounts for about 66% of the impaired conditions of U.S. rivers (Carpenter et al., 1998). Compounding the legacy effect of regional and farm P accumulations is the imperfect ratio of N and P in most livestock manures when used as a fertilizer source. Ideally, to meet crop demand, N:P ratios should be around 6:1, and indeed typical dairy manure is near this ratio, but greater than 50% of the nitrogen in manure is lost through volatilization immediately after application. This results in excess application of P to agricultural soils when manures are applied to meet crop N demand (Sharpley et al., 1994). Few options are available to efficiently move manure P from areas of surfeit to areas of deficit and few options exist to adjust manure nutrient ratios to better fit crop demand (Sharpley et al., 1994; Kleinman et al., 2012).

A variety of approaches have been proposed to treat animal manures to reduce their potential for adverse environmental impact. Most successful has been the use of aluminum (Al), iron (Fe), and calcium (Ca) salts as manure amendments to reduce the solubility of P, thereby decreasing the potential of manure to enrich dissolved P in runoff water (Moore and Miller, 1994; Smith et al., 2004; Irshad et al., 2012). The application of alum ($Al_2(SO_4)_3$) to poultry litter has also been shown to improve the conservation of NH_4-N in manure due to the weak acidic properties of alum (Moore et al., 2000). However, amending manures to reduce manure P solubility does not

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The authors are **Clinton D. Church,** Environmental Chemist, USDA-ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania; **Alexander N. Hristov,** Professor, Pennsylvania State University, College of Agricultural Sciences, University Park, Pennsylvania; **Ray B. Bryant**, Soil Scientist, **Peter J.A. Kleinman**, Soil Scientist and Research Leader, **Sarah K. Fishel**, Biological Science Technician, USDA-ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania. **Corresponding author:** Clinton D. Church, USDA-ARS Pasture Systems and Watershed Management Research Unit, 3702 Curtin Rd, University Park, PA 16802; phone 814-863-8760; e-mail: clinton.church@ars.usda.gov.

in large part change the N:P ratio in manures and does not address the accumulation of P on farms. To achieve that objective, removal of P is necessary while conserving sufficient N to create an N:P ratio more favorable to crop production.

Although P removal options are abundant in municipal wastewater treatment systems, few options exist for livestock manure. In South Carolina, a two-stage system was developed for permanent installation on swine production facilities (Vanotti et al., 2005, 2010). While there are different configurations of this system in use, it generally employs a nitrification bioreactor followed by P precipitation induced by the addition of $Ca(OH)_2$. Approximately 83% of manure N and 95% of manure P are removed by this process. Manure solids and Ca-P are exported for end uses in compost or low-solubility fertilizer. Treated effluents with a N:P ratio of approximately 10:1 are left on farm where it is generally used in fertigation. The sequence of treatment steps in the South Carolina system was designed to reduce carbonate and ammonium buffers with nitrification prior to P precipitation so that NH_3-N would not be driven off by the alkalinity of the $Ca(OH)_2$ in the P precipitation step (Vanotti et al., 2005).

In Louisiana, Davis (2011) developed a two-step system for treating clarified (passed through a coarse sand separator to remove sand and large particles, and then allowed to settle in a storage sump) dairy parlor wastewater utilizing Ca-P precipitation [$Ca(OH)_2$ addition] followed by biological conversion of ammonia (NH_3-N) to nitrite (NO_2^--N) and nitrate (NO_3^--N). Clarified dairy parlor wastewater was first raised to pH > 10 by the addition of a 30% solution of $Ca(OH)_2$ and hydroxyapatite precipitates were allowed to settle in a conical clarifier where they were collected from the bottom periodically. The pH of the effluent water was lowered to between 8 and 9 (using sulfuric acid monosodium and disodium salts) and introduced into the N bioreactor (a hanging basket trickling filter using rice hulls as a growth medium) in batch mode. This system was shown to remove 99% P from clarified dairy parlor wastewater. However, 53% of the total N in the parlor wastewater was lost to the atmosphere by NH_3 volatilization during the P precipitation step due to the high pH (pH > 10) associated with $Ca(OH)_2$ addition, and the open nature of the mixing and precipitation tanks. Of the 47% NH_3-N still remaining in the liquid, 50% was biologically converted to NO_2^--N and NO_3^--N over a five-day period in biological reactors, equivalent to 25% of the total N in the clarified dairy parlor wastewater.

While testing of the Louisiana system was only carried out with a parlor wastewater with very low solids content, the potentially portable nature of the P precipitation stage of the system and the high nutrient removal efficiencies showed potential for use on multiple operations. This would be of particular benefit to areas with high numbers of small livestock operations without the resources to invest in a single, dedicated nutrient removal system. Such conditions are common in many areas of the Chesapeake Bay watershed, where a priority has been placed upon improving nutrient management on small livestock operations in sub-watersheds with an excess of manure P (Kleinman et al., 2012). Preventing the N loss however, would require a closed P precipitation system and a gaseous treatment stage that captures NH_3-N if developed into a full-scale process.

We sought to develop a prototype treatment system for liquid manures that conserves or captures the manure nitrogen (N) content while removing most of the manure P content. Focusing upon dairy manure for initial testing of the system, our specific goals were to: (1) remove sufficient P from dairy manure slurry to achieve a N:P ratio of at least 8:1, and (2) concentrate the P into a solid, stackable form for transport off the farm. In addition, the prototype system would provide sizing parameters for building a full-scale system that could treat at least 38 m^3 in one day (equivalent to 26 L min^{-1}, or approximately 10 times the volume produced by a 100 cow dairy in one 24 h day) while being sufficiently compact and light to be mounted on trailers for transport to multiple small (100-150 cow) dairies.

MATERIALS AND METHODS

Our approach was to design and evaluate components of sequential manure filtration systems, including liquid-solid separation, chemical treatment, and supplemental stages. To do this, we first adapted the Louisiana system of Davis (2011) to include an initial, two-stage liquid-solid separation step (using the auger press and fiber filter, described below) because we intended the system to treat dairy slurries as opposed to clarified wastewaters. Then, we tested various alternative liquid-solid separation technologies in designing the final MAPHEX (MAnure PHosphorus EXtraction) System configuration. A combination of adaptive field-scale and bench-top experiments was employed, conducting a mass balance of P and N in both manure liquids and solids during the filtration process.

STUDY AREA

The study was carried out in central Pennsylvania, part of the Chesapeake Bay Watershed and an area with intense focus on developing alternative treatment systems for manure (Kleinman et al., 2012). Manure from the dairy sector was estimated in 2010 to account for 20% of all manure phosphorus and 24% of all manure nitrogen in the Chesapeake Bay Watershed (Brosch, 2010). The majority of dairy farms in the study area tend to be small (<100 head/farm), although an increasing number of larger operations (>1000 head/farm) can now be found. Manure storage is increasingly found on smaller dairy farms and is a constant feature on large operations. The liquid nature of most stored dairy manure reduces its potential for off-farm transport and therefore was the impetus for developing treatment options to manipulate manure solids and nutrients.

LIQUID-SOLID SEPARATION TECHNOLOGIES

a) Auger Press

The auger press tested (Manure Monster, Neptune Enterprises, Richland Center, Wis.) was selected because of its wide use in the dairy industry where it is effective at removing bulk solids from manure slurries, leaving dry stackable solids. The system tested in the current project is capable of maintaining a 47 L min^{-1} flow rate. Commonly, solid rejects from this auger press are retained by dairies to be composted and dried, and ultimately recycled for bedding material.

b) Fiber Filter

The fiber filter tested (Model FF-6, Vincent Corporation, Tampa, Fla.) is a screw press with a differential screw pitch that incorporates a flushing cycle for screen clearing. The fiber filter was selected for the current study because of its capability in removing fibrous particles >42 μm diameter, and therefore potential as a secondary liquid-solid separation step following bulk solid removal. The fiber filter is typically used in vegetative and fruit juice industries and is capable of maintaining an 88 L min^{-1} flow rate.

c) Decanter Centrifuge

The decanter centrifuge tested (Bird 12x30, Andritz AG, Graz, Austria) is currently used for liquid-solid separation in a broad array of industrial applications (from manure management to mining). The decanter centrifuge was chosen for the current study due to its demonstrated ability to remove both bulk and medium sized particles (>25 μm diameter) from dairy manure while maintaining a 38 L min^{-1} flow rate. This machine incorporates an internal auger to move solids to one end of the centrifuge bowl where they are discharged. Liquids flow out the other end of the bowl where they are discharged by gravity.

d) Membrane Filter

The membrane filter tested (Model FMX-B, BKT Incorporated, Anaheim, Calif.) is capable of removing fine particles (0.02-25 μm) and is designed to operate at a 44 L min^{-1} flow rate (manufacturer specifications, BKT Incorporated). This type of filter has previously been shown to be effective at removing solids from anaerobically digested poultry manures as well as wastewater treatment. It features rapidly rotating circular filtration membranes to continually clear the filter pores.

e) AutoVac®

The AutoVac® tested (Model AV220, ALAR Engineering Corporation, Mokena, Ill.) is a vacuum filtration system that uses a diatomaceous earth cake as a filter. The AutoVac® is currently used in a number of industrial applications to remove fine particles (0.5-40 μm). The AutoVac® tested features a vacuum pulled on a slowly rotating 0.61 m diameter by 0.61 m long drum with a surface area of 0.03 m^2 in a shallow tank and is capable of maintaining a 9.5 l min^{-1} flow rate. A diatomaceous earth slurry is introduced to the tank where it builds up a layer of diatomaceous earth on the drum as it rotates, and subsequently serves as a filter for the waste slurry. Dairy manure slurry is then pumped into the tank and liquids are drawn to the interior of the drum, leaving solids on the drums surface that are continually removed by a steel knife as the drum rotates, exposing a fresh filtration surface. Despite its slow rate of filtration, the AutoVac® was selected for the current study due to its unique ability to remove plugged filter material, and its availability in a large range of configurations that could ultimately accommodate higher flow rates than the unit tested.

f) Ancillary Components

Various ancillary components were also employed and included:

1) electrical trash pumps (pump outlet: 7.62 cm for raw manures and 5.1 cm for all other liquids) to provide inputs to the major components of the system;
2) tanks (1.9 m^3) to contain effluents and for chemical treatment (mixing performed by rapid recirculation);
3) a 40-kW diesel generator; and,
4) hoses and valves (10.2-cm pinch valve to prevent plugging with raw manures, 5.1-cm ball valves for all other liquids) fitted to the major components for flow control.
5) two 7.6- × 2.4-m gooseneck trailers.

g) Assembly of Manure Treatment System Components

Prototype components for liquid-solid separation and chemical treatment steps were assembled and mounted on trailers at the USDA-ARS Pasture Systems and Watershed Management Research Unit watershed field station (Klingerstown, Pa.) and tested at either Pennsylvania State University's Larson Agronomy Farm (Pennsylvania Furnace, Pa.) or at commercial dairy operations.

MANURES TESTED

Dairy manures were obtained from three commercial farms. Due to the number of treatment technologies evaluated at various scales (from laboratory to field), testing was carried out over a nine-month period (March-November 2013). In order to use fresh manure, it was not possible to evaluate all technologies with identical manure sources.

150-Cow Dairy

Manure slurry was obtained from a dairy farm with 150 lactating Holstein dairy cows (*Bos taurus*) housed in a free stall barn. Dairy manure was scraped daily into a holding pit and water was added once per week to the pit to transfer manure to an above-ground slurry holding tank. Manure from the open slurry holding tank was agitated for approximately 24 h, then was transferred to a 8.800 L recirculating tanker (two dates, 19 March and 10 November 2013) and used as the source for testing the modified Louisiana system and for final field testing of the MAPHEX System.

1500-Cow Dairy

Centrifuge effluents for laboratory chemical optimization tests were collected (19 June 2013) from a dairy with an operating centrifuge for liquid-solid separation. This dairy had 1500 lactating Holstein dairy cows housed in a free stall barn. Dairy manure was scraped into a holding pit, where water was added, and manure was transferred continually to a sand separator, with its effluents being fed to a decanter centrifuge capable of removing particles >25 μm diameter while maintaining a 154 L min^{-1} flow rate (DeLaval, Tumba, Sweden).

2700-Cow Dairy

The largest dairy from which we used manure had approximately 2700 lactating Holstein dairy cows housed in free stall barns. Manure from the barns was scraped into a holding pit, where water was added, and was transferred continually to an above ground open holding tank, where it was circulated continually through a screw press for liquid-solid separation. Manure from the holding tank was pumped directly into the MAPHEX system for testing on 18 November 2013. One major chemical difference in this dairy's manure treatment compared to the other two dairies is that they amend their manure with lime for bacterial control, resulting in a manure slurry that was intended to have an elevated pH.

SAMPLE COLLECTION/PRESERVATION AND LABORATORY ANALYSIS

Sample Collection and Preservation

Samples were taken of the raw dairy manure slurry, and of effluents and solid rejects from the liquid-solid separation steps to test for solids content and P and N concentrations (discussed later). Raw manure slurry samples (5) were collected from a well-stirred tank or open holding pit (44-1000 m^3) which served as the source for the treatment, while effluent samples were collected from a well-stirred tank (essentially a large-scale churn splitter, USGS 1998) that homogenized the entire production (0.88-1.32 m^3) of the previous step. Additionally, during the testing of the MAPHEX System, a large sample (88 L) was also collected of the chemically treated centrifuge effluent from each farm, and was sent to BKT, Inc. (Anaheim, Calif.) for testing in the membrane filter unit. Solid reject samples (3) were collected from a well-mixed bin that contained the entire production from the previous step. All samples were stored at 4°C until analyzed or used in laboratory-scale testing.

Aqua Regia Extractable P Determination

Samples were subjected to aqua regia (25% HNO_3, 75% HCl) extractable P and Ca (ARP and ARCa), water extractable P (WEP), and Kjeldahl digest N (TKN) analysis. Briefly, for ARP and ARCa, manure slurries and solids were extracted with aqua regia following a modified EPA Standard Method 3050B (Kimbrough and Wakakuwa, 1989). Solids were oven dried at 110° C for 16 h to determine solids content, but were digested wet, such that the sample size contained 0.5 g of solid material. These samples were then digested with 5 ml aqua regia at 95°C for 1.5 h, and then 2.5 mL H_2O_2 was added and the samples were digested for an additional 30 min at 95°C. The final effluents from the AutoVac® and membrane filter were treated as water samples. Briefly, 10 mL of sample was digested for 1.5 h at 95°C with 2.5 mL aqua regia, and then 2.5 mL H_2O_2 was added and the samples were digested for an additional 30 min at 95°C. Following dilution to final volumes and filtration (Whatman 1), P analysis was then performed on all extracts using an inductively coupled optical emission spectrophotometer (ICP-OES, Varian).

Water Extractable P Determination

Water extractable P was determined by the method of Kleinman et al. (2007). Briefly, based on the solids content, sufficient sample of manure slurry to contain 2.0 g solids was shaken with enough distilled water to make a final weight of 202 g on an end-over-end shaker at 15 rpm for 1 h. The final effluent from the AutoVac® was treated as a water sample. Samples were centrifuged (34,000 g_0) and filtered (0.45 µm), and analysis was then performed on all extracts using an inductively coupled optical emission spectrophotometer (ICP-OES, Varian).

Kjeldahl Digest N Determination

Samples were also extracted for Total Kjeldahl N (TKN) determination (Gallaher et al., 1976; Peters, 2003). Briefly, an amount of sample equivalent to 0.5 g solids material was weighed into digestion tubes, 3.5 g K_2SO_4, 0.4 g $CuSO_4$, and 7 mL of concentrated sulfuric acid were added. The sample was then digested at 375°C for 2 h. Following dilution to final volumes and filtration (Whatman 1), N analysis was then performed by Quick Chem Method 10-107-06-2-H (Lachat Instruments, 2003).

DATA ANALYSIS

Nutrient removal efficiencies were determined from a mass balance approach comparing influent loads with observed loads in effluent liquids and solid rejects at each step of the manure treatment process.

RESULTS AND DISCUSSION

We first evaluated the potential to adapt the Louisiana System proposed by Davis (2011) to achieve our P removal, N conservation, and flow requirement goals with liquid dairy manures. When the modified Louisiana System failed to precipitate P due to the high solids content of commercial dairy slurries, we designed a new system based upon sorption chemistry rather than precipitation of P by $Ca(OH)_2$.

DEVELOPMENT AND TESTING OF A MODIFIED LOUISIANA PROTOTYPE TREATMENT SYSTEM

The original Louisiana System was designed to treat clarified manure liquors from a settling pond, and thus did not include Step 1 shown in figure 1. To treat raw manures, our conceptual design of a modified Louisiana System consisted of: 1) an initial, two-stage liquid-solid separation step to remove solids prior to chemical treatment; and 2) chemical treatment with $Ca(OH)_2$ (fig. 1). We chose to assemble the components of the liquid-solid separation step and test the chemical treatment in the laboratory to determine amounts of $Ca(OH)_2$ needed and particulate settling velocities, which would be critical in designing the cone-bottomed clarifier.

a) Design and Testing of Liquid-Solid Separation

The initial liquid-solid separation was designed to be carried out in two stages, removing the bulk solids from dairy manure with an auger press, and then removing the medium-sized particles (>42 µm) with a fiber filter. This

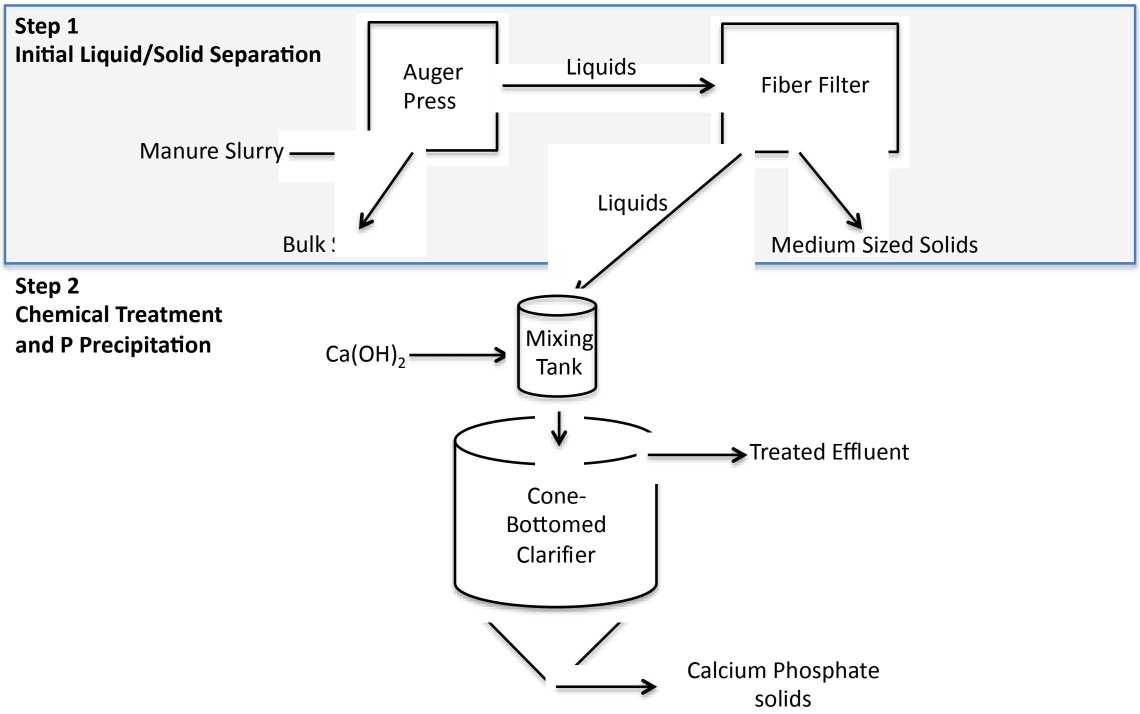

Figure 1. Conceptual flow chart of a Modified Louisiana (Davis, 2011) manure filtration system.

sequence of solids separation was intended to remove bulk solids with the auger press, leaving behind a source of material that could be used as bedding. Alternatively, the bulk solids from the auger press could be combined with the fiber filter solids and possibly sold as fertilizer after composting.

The combination of auger press and fiber filter was readily adapted to fit on one 7.6- × 2.4-m gooseneck trailer along with ancillary pumps and electrical generator. While both the auger press and the fiber filter were effective in removing P from the raw dairy manure (table 1), only the auger press produced a solids reject that could serve as a stackable solid and would have potential to serve as bedding or to be removed from the farm. The solids from the auger press comprised approximately 1/10th of the total volume of raw manure and had a solids content of 33%. Compared with the solids from the fiber filter, solids from the auger press contained relatively low concentrations of P (468-699 mg kg^{-1}). In contrast, the reject solids from the fiber filter were of the consistency of applesauce, with a solids content of roughly 10%, comprising approximately one-third of the total volume of influent from the auger press. Since one of our goals was to design a system that could treat at least 38 m^3 manure d^{-1}, the fiber filter would leave more than 14 m^3 of slurry that would be problematic to further de-water to put it into a compact compostable or transportable form.

Table 1. P removal within the liquid-solid separations step of the Modified Louisiana System.

Manure/Effluent (150-cow dairy)	Solids (%, by weight)	Aqua Regia Extractable P (mg kg^{-1})	Aqua Regia Extractable P Removed (mass basis,%)
Raw manure	7.4	402.1	0
Auger press effluent	5.7	415.7	14
Fiber filter effluent	4.6	365.5	28

b) Design and Testing of the Chemical Treatment

After the initial liquid-solid separation step described above, effluents from the fiber filter were to be subjected to chemical treatment by $Ca(OH)_2$ to coagulate the remaining particles and to remove dissolved P (primarily orthophosphate) into a solid calcium phosphate form. It was anticipated that the calcium phosphate would be periodically removed from the bottom of the tank, dried, and stored for use as a high-value phosphorus fertilizer.

The Louisiana System reported by Davis (2011) delivered 21 g of industrial grade hydrated lime (mixed in a lime/water slurry) per liter of clarified dairy parlor wastewater. We tested various concentrations (5-420 g L^{-1}) of $Ca(OH)_2$ amendment in the laboratory in order to appropriately design the cone-bottomed clarifier. Due to the high solids content of the filtrate after the liquid-solids separation step (table 1), treatment with $Ca(OH)_2$ failed to separate solids and P by gravity alone. Rather, the particles formed flocculates that remained in suspension for at least 40 days, at which time they were discarded. We also tested treatment of the fiber filter effluent with $Al_2(SO_4)_3$ in various concentrations (5-420 g L^{-1}). The results of this testing similarly failed, producing a suspended gel that would not separate into liquid and solid phases. Further testing suggested that failure of $Ca(OH)_2$ and $Al_2(SO_4)_3$ treatments was due to both the size and quantity of particles retained in the fiber filter effluent. Indeed, bench-top filtration of the fiber filter effluent to remove particles >30 µm resulted in successful precipitation by both chemical treatments. Given these failures, we concluded that a completely new design, using different liquid-solid separation mechanisms while testing different P

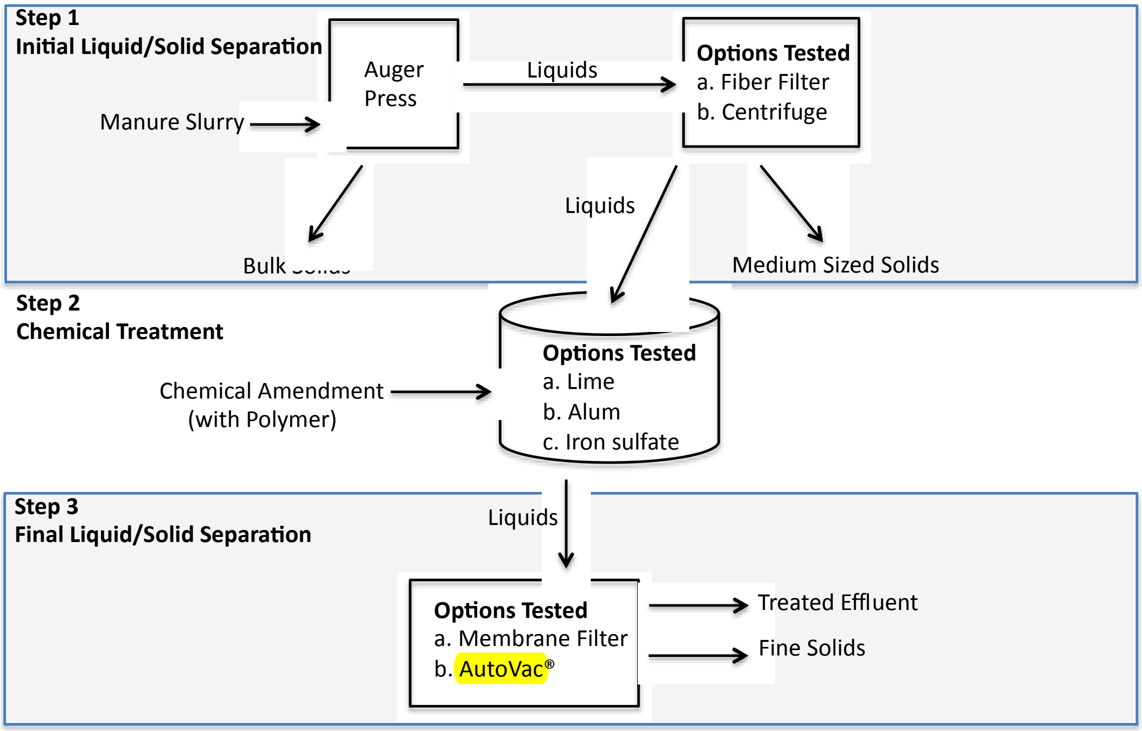

Figure 2. Flow chart showing options tested in designing MAPHEX system.

removal chemistries would be necessary to accomplish all the goals of the project.

Development and Testing of the Manure Phosphorus Extraction (MAPHEX) System

Following the failure of the Modified Louisiana System during testing, we explored a number of options to design the MAPHEX System, which consisted of: 1) an initial two-stage liquid-solid separation step; 2) chemical treatment; and 3) a final liquid-solid separation step (fig. 2).

a) Development of the Initial Liquid-Solid Separation

As in the Modified Louisiana System, the initial liquid-solid separation of the MAPHEX System was designed to occur in two stages: the first to remove the bulk solids; the second to remove intermediate solids (>25-40 µm). Since the auger press used in the Modified Louisiana System worked well to perform bulk solids removal, it was retained as the first stage for both options tested. However, we investigated two second-stage liquid-solid separation options to prepare the manure effluent for further treatment: a) the fiber filter used in the modified Louisiana system; and; b) the decanter centrifuge.

b) Chemical Treatment

Three options for chemical treatment were tested to coagulate the particles and to transform dissolved P (primarily orthophosphate) into a solid form prior to the final liquid solid-separation step. Five gallons of each of the liquid effluents from each of the liquid-solid separation options evaluated above were subjected to batch experiments to select a chemical treatment. For all batch experiments, a small amount (0.21 g L^{-1}) of an anionic polymer (Praestol® 2504, Ashland Deutschland GmbH, Krefeld, Germany) was added for coagulation. In separate tests, ferric sulfate, aluminum sulfate and calcium hydroxide were added at various rates (2.0-10 g L^{-1}), with the intent to convert P from solution to solid phase. While as much as a 700:1 ratio of N:P (much higher than our goal) was achievable at the higher chemical rates tested, optimal values (and chemicals used) were determined based upon flow rates through a benchtop AutoVac® unit, cost of amendments, and potential toxicity issues to plants (if Al were used and the resulting solids ended up in a low pH environment), without regard to P removal efficiencies. Fiber filter effluent for bench-top tests came from our testing of the Modified Louisiana System (above), while centrifuge effluents for bench-top tests were collected (19 June 2013) from the 1500-cow dairy, since it had an operating centrifuge for liquid-solid separation.

c) Final Liquid-Solid Separation

For the final liquid-solid separation we tested a membrane filter which removed particles larger than 0.02 µm (BKT, Anaheim, Calif.), and a vacuum filtration system that uses a diatomaceous earth filter (AutoVac®, ALAR Engineering Corporation, Mokena, Ill.), with the objective of removing remaining fine solids (<0.25 µm diameter) along with sorbed P from the chemical treatment step.

Design of the MAPHEX System

Initial Liquid-Solid Separation

We chose to use two stages for the initial liquid-solid separation step so that the bulk solids, which are low in P relative to the other two solids generated by the system, could be left behind on the farm to be composted and used as bedding material. For farms that do not use the compost for bedding, the bulk solids could be blended with the other solids from the system and sold as fertilizer after composting. Alternatively, the auger press could be eliminated from the system for those farms that would not utilize the bulk solids, so long as the remaining component was sized sufficiently to handle the added solids content while still removing solids >30 µm.

Due to its satisfactory performance, the auger press used in the Modified Louisiana System was retained as a first stage of the initial liquid-solid separation. For the second stage of the liquid solid separation step, the fiber filter was not retained because of the anticipated difficulty in dewatering the solids reject, and because, as tested, it did not remove all particles >30 µm. Changing filter screens could have solved the latter problem, but would have produced an even greater quantity of reject. Instead, we chose to use a decanter centrifuge after collecting and testing solids and effluent from a dairy farm with an operating sand separator and centrifuge. These solids were of a stackable consistency (approximately 30% solids), and the effluent was subjected to further chemical optimization tests.

b) Chemical Treatment Tests

Various chemical treatment tests for ease of flow through a benchtop AutoVac® unit were performed as indicated above on the effluents from the centrifuge samples collected from the operating dairy farm in conjunction with experts from Alar Engineering and samples were obtained for ARP and TKN analyses. The findings showed nearly equal results for $Al_2(SO_4)_3$ and $Fe_2(SO_4)_3$ in regards to both flow through the benchtop AutoVac®, ARP, and TKN, with N:P ratios as high as 700:1. We chose to use 3.0 g L^{-1} $Fe_2(SO_4)_3$ in the MAPHEX System however, so as to mitigate potential effects of aluminum toxicity to plants in the final solids in case they were at some point subjected to low pH values. Furthermore, we found that while theoretically the addition of $Fe_2(SO_4)_3$ could result in a measurable pH change, the amount added was not great enough to make an measurable change in the manures tested, presumably due to their large buffering capacity.

c) Final Liquid-Solid Separation

We had two potential choices for the final liquid-solid separation step, a membrane filter, and an AutoVac® unit. Initial tests of the membrane filter had indicated a promising N:P ratio of 20:1 even without chemical treatment, so a large sample of ferric sulfate treated centrifuge effluent from both farms used in the MAPHEX System testing was sent to BKT Inc. (Anaheim, Calif.) for further testing on their membrane filter system. While the membrane filter was able to lower the ARP to below 11 mg L^{-1} and to give N:P ratios of 433:1 and 130:1 for the two farms, respectively, the physical nature of the solids reject had an even higher water content (94%) than the fiber filter (90%), and would leave approximately one third of the total volume treated difficult to dewater. Therefore, the AutoVac® was chosen for the final liquid-solid separation step.

TESTING AND PERFORMANCE OF THE MAPHEX SYSTEM

Following the evaluation of options for the filtration and chemical treatment steps, we identified the most suitable components for the MAPHEX system (fig. 3). A complete prototype of the final MAPHEX System was constructed on two 7.62 × 2.4 m gooseneck trailers that could be towed behind a 1T truck. The MAPHEX System was then tested on manures from two commercial dairy farms in November 2013, one was a 150 cow dairy operation and the other a 2700 cow dairy. As noted, one major difference in how these dairies handled their manures was that the larger dairy added $Ca(OH)_2$ at several stages of their manure handling to inhibit bacterial growth, whereas the smaller dairy did not.

Overall results showed that the pilot-scale system was able to filter 17.6 L min^{-1} of fresh dairy manure at the smaller dairy and 6.6 L min^{-1} at the larger dairy, with the difference likely being attributed to the $Ca(OH)_2$ addition by the larger dairy. As mentioned, this manure was intended to have an elevated pH but in practice did not (pH = 7.64 as compared 7.67 in the non-amended manure). Aqua regia extractable Ca in the amended manure was considerably higher, however (6467 mg L^{-1} as compared to 1470 mg L^{-1}). This additional Ca likely formed very small precipitates with P and other constituents in the manure that partially plugged the diatomaceous earth filter in the AutoVac®, resulting in the lower flow rate. Therefore, in practice, dairy manure management will likely be a critical parameter when upscaling the MAPHEX System design.

In terms of P and solids removal, testing on the two farms showed a 98% removal of water extractable P from the two manures, and a 96% and 99% removal of ARP from the 150- and 2700-cow dairy manures, respectively, while all P-rich solids were dry and stackable, suitable for blending and composting (table 2). Furthermore, with TKN values in the final effluent being 357.9 and 385.8 mg kg^{-1} for the 150- and 2700-cow dairy, respectively, greater than 90% of the total N was retained and the N:P ratios achieved were 19:1 and 65:1.

ALTERNATIVE OPTIONS TESTED

In an attempt to reduce costs of operation, we also tested alternatives in both the configuration of the MAPHEX System, and in the chemistry used for treatment.

Four-Machine Configuration

As an alternative to the single-stage final liquid-solid separation step, we tested using the membrane filter and the AutoVac® unit together in a two-stage configuration. In this configuration, centrifuge effluents would be treated chemically and then serve as influents to the membrane filter. The slurry-like reject from the membrane filter (roughly 33% of the total volume) would then be fed to the AutoVac® unit, while the effluent from the membrane filter would have a relatively low P concentration with an N:P ratio greater than 8:1. It was anticipated that this might reduce costs since only 33% of the total volume would need to be treated by the AutoVac®, eliminating the need for a larger unit, as well as reducing the daily operating costs of the diatomaceous earth used for the filter.

Table 2. P removal in effluent of steps/stages of MAPHEX System.

Manure/Effluent (150-cow dairy)	Solids (%)	Water Extractable P (mg kg^{-1})	Aqua Regia Extractable P (mg kg^{-1})	Aqua Regia Extractable P Removed (%)[a]
Raw manure	7.5	171.5	482.2	0
Auger press effluent	5.8	126.7	494.8	14
Centrifuge effluent	3.8	64.8	277.3	46
AutoVac® effluent	0.6	3.2[b]	18.4	36

Manure/Effluent (2700-cow dairy)	Solids (%)	Water Extractable P (mg kg^{-1})	Aqua Regia Extractable P (mg kg^{-1})	Aqua Regia Extractable P Removed (%)[a]
Raw manure	7.9	185.4	435.7	0
Auger press effluent	7.6	187.8	430.1	15
Centrifuge effluent	4.0	130.5	317.5	44
AutoVac® effluent	0.5	4.6[b]	5.9	40

[a] Mass Basis.% of Raw Manure.

[b] Total Dissolved P: 0.45 µm membrane filter.

As anticipated, the results of testing the four-machine configuration showed that the effluent of the membrane filter was relatively low in P (76.2 mg kg^{-1}) and had an acceptable N:P ratio of 20:1. However, the slurry-like solids reject from the membrane filter required 1:1 dilution by water before it could be effectively filtered by the AutoVac®. Therefore, this configuration is not likely viable due to the need for large quantities of dilution water and the need for our projected system to be mobile, but might be an option if it were built as a stand-alone system.

Acid Mine Drainage Residual (AMDR) substitution for $Fe_2(SO_4)_3$

Acid mine drainage residual was obtained from Hedin Environmental (Pittsburgh, Pa.) and is a material derived from the environmental remediation of abandoned coal mine drainage. Impaired mine water is diverted into shallow ponds, where it is allowed to oxidize and the water either drains or evaporates. The residual left behind is a fine-grained yellowish-brown cake composed primarily of mixed iron oxides. Once dried, this cake was finely ground and used directly as a substitute for $Fe_2(SO_4)_3$ in the chemical treatment tank (3.0 g L^{-1}). In lieu of batch treatment in the chemical treatment tank, we also tried incorporating iron oxide into the diatomaceous earth pack (567 g) of the AutoVac® unit to promote P sorption as filtrate passed through the diatomaceous earth pack. The latter option, if effective, would also simplify the system somewhat, through the elimination of the chemical treatment tank.

The results of substituting the AMDR for $Fe_2(SO_4)_3$ in the chemical treatment tank showed that it was nearly as effective at removing P, with a final effluent concentration of 21.6 mg kg^{-1} compared to 18.4 mg kg^{-1}, with an N:P ratio of 232:1, and would likely serve to reduce the costs of treatment. However, the results of mixing the AMDR into

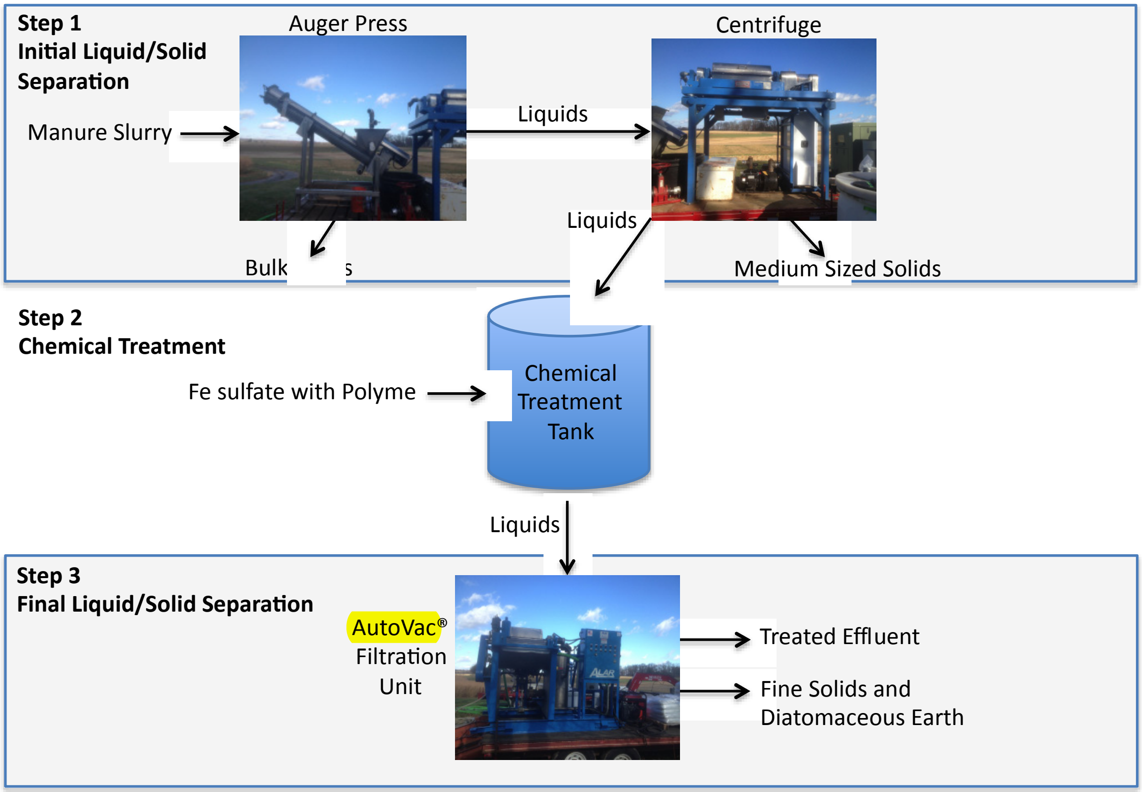

Figure 3. The MAPHEX System, showing two-stage, liquid-solid separation step, chemical treatment, and final liquid-solid separation steps.

the diatomaceous earth filter pack were not as promising (fig. 4). While P removal was good early in the experiment, resulting in an even lower effluent P concentration compared to the final effluent concentration gained by mixing the same amount (based on treating 189 kg of centrifuge effluent) of AMDR with the centrifuge effluent in the chemical treatment tank, the P removal efficiency rapidly and continually declined, likely due to rapid filling of sorption sites. Therefore, this method of chemical treatment is not likely to be viable.

CONCLUSIONS

Our two tests indicated that in terms of flow, the prototype system built was able to process manure at 66% of the target rate of 38 m^3 day^{-1} (26.4 L min^{-1}) at the small dairy and 25% of the target rate at the large dairy. However, even with the lower flow rate, the system tested could easily be scaled up to handle 38 m^3 day^{-1} (26.4 L min^{-1}) and still be a mobile system. This would require only increasing the size of the AutoVac® tested since the auger press and decanter centrifuge were capable of 47 and 38 L min^{-1} flow rates, respectively. Incorporating a larger AutoVac® would still result in a system of sufficiently small size to fit on two 7.6- × 2.4-m gooseneck trailers and could service the needs of ten 100-cow dairies. This would require a storage tank on each farm to sufficiently hold 10 days' worth of manure while the system was servicing other farms. It is also likely that cleaning or disinfection of the system would be necessary between farms if the system were operated as a mobile unit. Alternatively, the same size system could be operated in place to handle the needs of a 1,000-cow dairy if operated on a 24 h basis. The system could be scaled even larger, but a system larger than one capable of 82 m^3 day^{-1} (which could handle the needs of 21 100-cow dairies or one 2100-cow dairy) would likely not be mobile.

Estimated capital cost of a mobile full-scale system capable of treating 38 m^3 day^{-1} at the lower flow rate observed is $291,000. This capital cost includes: 1) auger press ($35,000); 2) decanter centrifuge ($100,000); 3) AutoVac® Model AV360 ($100,000); 4) 40-kW diesel generator ($35,000); 5) two gooseneck trailers ($13,000); 6) electrical trash pumps ($5,000); 7) chemical treatment tanks ($2000); and 8) ancillary hoses, valves, and fittings ($1000). The daily estimated operating cost of such a system is $750. This operating cost includes; 1) diatomaceous earth and chemicals used for treatment ($550); 2) diesel used for electrical generation ($50); and 3) labor ($150). Daily operating costs would vary by system design and the nature of manure handling previous to treatment by the MAPHEX system, but the results of our pilot-scale testing were roughly $38 kg^{-1} P removed, equivalent to $750 cow^{-1} yr^{-1}. Ongoing work is being performed to further reduce daily operation costs.

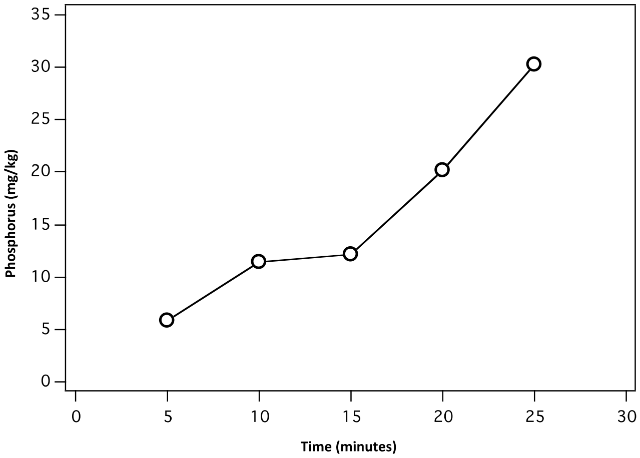

Figure 4. Phosphorus in effluent of AutoVac® when AMDR was incorporated into the filter pack.

Several considerations are noted. Undoubtedly variation in manure handling [particularly with respect to added amendments such as $Ca(OH)_2$] and storage will influence the performance of the MAPHEX System. Furthermore, our objective was to conserve the manure N in the final effluent, which would then have value as a fertigation source or N-rich liquid manure that would be land applied. However, additional steps to remove the N may be preferred, particularly given the potential to volatilize NH_3 from the treated effluent.

Solid rejects from the system (including those mixed with diatomaceous earth) can serve several functions. Bulk solids removed by the auger press comprise about 80% of the total solids, but only contain about 15% of the ARP and are ideal to be left behind on the farm to be composted and serve as bedding material for the cows. Solids removed by the centrifuge comprise about 10% of the total solids and 45% of the ARP, while solids from the AutoVac® comprise 10% of the total solids and 40% of the ARP. These solids can serve as a concentrated source of P and manure solids and can be sold to operations where land application of P is not limited or can be used on the farm, but be economically transported to greater distances away from the milking barn than can liquid manure.

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