Treatment Technologies for Phosphorus Removal from Water Derived from Cattle Feedyards

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Introduction

A major issue facing animal agriculture is phosphorus (P) management. Application of animal wastes often provides P in excess of plant needs; therefore, application of animal wastes can result in an undesirable build up of P levels in soils. Environmental problems may develop as P moves off-site into aquatic systems. Since P is often limiting to plant growth in aquatic systems, the added P can result in increased plant growth that leads to eutrophication as P from agricultural and other sources enters these systems. A potential solution is a reduction in P concentrations in wastewaters prior to field application.

Removal of P from wastewaters has long been a concern of municipalities, and technologies have been developed to lower P concentrations in wastewaters. Traditional secondary biological treatment operations remove P via microbial uptake (ASCE, 1992). As stated by Kirk and Bickert (2002), the wastewater treatment industry has provided the livestock industry with technologies such as aeration and separation of solids/liquids. Additional technologies currently being evaluated for P reduction include anaerobic digestion, P separation, and wetland treatment (Kirk and Bickert, 2002). A promising process that has been used in the swine industry is precipitation of P as a Mg and NH_4^+ containing mineral known as struvite (Burns et al., 2001). Burns et al. (2001) reported reductions of 90% of soluble P concentrations in 140,000 liters (nearly 37,000 gallons) of swine slurry due to forced struvite precipitation.

Phosphorus in Soils and Water

Phosphorus is an essential nutrient and is often second, only to N, as a limiting mineral nutrient to plant production. Due to its tendency to precipitate or undergo sorption reactions, P is often bound in insoluble compounds in the soil, thus making it unavailable for plant uptake or utilization (Southern Cooperative Series, 1998; Ozanne, 1980). Phosphorus is present as either HPO_4^{-2} in alkaline soils or $H_2PO_4^-$ in acidic soils, and apatite (Ca phosphate) is the most common P mineral found in soils (Southern Cooperative Series, 1998). Mallarino et al. (2000) report a pH of 6.0 to 7.0 for maximum P availability in soils. Today, more than 200 forms of naturally occurring P minerals exist (Southern Cooperative Series, 1998).

Phosphorus inputs to the environment can originate both from point and nonpoint sources. Point sources include industrial operations, municipal waste treatment plants, and large, confined livestock operations (Pierzynski et al., 2000). Nonpoint sources of P include soil erosion and water runoff from cropland, lawns and gardens, urban areas, small livestock confinement operations, and livestock grazing operations (Pierzynski et al., 2000). Fertilizer and animal manure also are major nonpoint sources of P (Sharpley, 2000). Even though P is the second most plentiful nutrient in livestock manure, it is relatively immobile in the soil, has limited solubility in wastewater, and lacks toxicity to humans compared to nitrogen (Liu et al., 1997; Miner et al., 2000).

Sharpley (2000) reports that soil P can be categorized into the following four pools: 1) soil-solution P; 2) labile soil organic P; 3) stable organic P; and 4) inorganic solid-phase P. Soil-solution P is the portion of P in the soil water and is dominated by the primary and secondary orthophosphate ions along with several organic and inorganic P compounds (Sharpley, 2000). The Southern Cooperative Series (1998) reports that P enters the soil solution by the following means: 1) dissolution of primary minerals; 2) dissolution of secondary minerals; 3) desorption of P from clays, oxides, and minerals; and 4) biological conversion of P by mineralization. Labile soil organic P includes soil organic material and microbial biomass (Sharpley, 2000). Stable organic P represents a sink for reactive P, and inorganic solid-phase P includes crystalline and amorphous P minerals and physically occluded or entrapped P (Sharpley, 2000).

An over of the P cycle is shown in Figure 1. Phosphorus reacts with iron (Fe) and aluminum (Al) to form insoluble Fe and Al phosphates in acidic soils and with calcium (Ca) to form insoluble Ca phosphates in alkaline soils (Bohn et al., 1979). Phosphorus is released to the soil solution as P-bearing minerals dissolve, as P bound to the surface of soil minerals is released, and as soil organic matter decomposes (Mullins, 2001). These are relatively slow processes, thus, soil solution P concentrations are typically very low (Mullins, 2001).

Three pathways by which P may be transported from a field include surface runoff, subsurface lateral flow, and leaching to groundwater; surface runoff is the main mechanism for P loss from most soils (Sharpley, 2000). If P-enriched runoff enters aquatic systems, eutrophication may occur.

Eutrophication is a major concern when excessive levels of P reach aquatic systems, and has been identified as a major cause of water quality impairment (Sharpley et al., 2000). Sharpley (2000) defines eutrophication as “an increase in the rate of organic matter production due to nutrient additions.” Pierzynski et al. (2000) defines eutrophication as “an increase in the fertility status of natural waters that causes accelerated growth of algae or water plants.” Biological productivity in surface waters is normally limited by the availability of P; therefore, eutrophication is not accelerated under natural conditions (Wendt and Corey, 1980).

Causes of eutrophication include interaction between N and P, temperature, salinity, light, and surface water characteristics (Pierzynski et al., 2000). Freshwater eutrophication can be reduced by controlling P inputs and subsequent runoff from fields (Sharpley et al., 2000). The threat of eutrophication could be reduced by a reduction in the manure nutrient load (Greaves et al., 1999).

Phosphorus in Animal Agriculture

An animal feeding operation is defined as "a lot or facility where animals have or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period," and cattle feedlots hold steers while they increase in weight for approximately six months (Miner et al., 2000). Components of a cattle feedlot include space per animal, feedbunk length per animal, watering facility, slope, pen size, dust control facilities, frequency of cleaning, and fly control (Miner et al., 2000). A schematic plan of a cattle feedlot is shown in Figure 2.

Cattle feedlots have waste handling and collection systems different from municipal systems (Miner et al., 2000); therefore, liquid manure systems require special handling and storage challenges due to the intensive manure production and excessive volume of diluted wastes in concentrated and confined animal feeding operations (Dao and Daniel, 2002). Safley et al. (2003) report a number of features for properly designed lagoons: 1) reduction and stability of organic matter; 2) nutrient concentration reduction; 3) adaptability to area climate and topography; 4) liquid manure handling compatibility; 5) reasonable operating costs; 6) reasonable management requirements; 7) shock loading tolerance; and 8) sludge removal techniques.

Livestock waste management lagoons release ions of ammonium (NH_4^+), P, and magnesium (Mg) during the digestion process (Buchanan, et al. 1994), and generally contain an excess of NH_4^+ over P (Schuiling and Andrade, 1999). Compared to anaerobic lagoons, aerobic lagoons over time develop excess sludge accumulations (Safley et al., 2003). Liquid manure systems involve collection of manure when the manure is flushed from the barns and thoroughly agitated to remix settled solids, accumulation of manure in the form of storage/treatment until the manure is utilized, and utilization of the manure by applying the manure to land as fertilizer; however, recycled flush water has the potential for salt build up (VanDevender et al., 1997).

Ration, animal age, feedlot type, and other factors are functions of the initial chemical and biological composition of manure (Eghball et al., 1997). Cattle manure is composed of approximately 2% N, 0.2% P, and 1.5% K (Ward et al., 1978), and excreted livestock manure is 80-90% water (Miner et al., 2000). Although excess P is predominantly excreted in the feces of animals, P is essential and also one of the most important minerals to all mammals (Klopfenstein and Erickson, 2000). VanDevender et al. (1997) report a maximum of 80 to 85% of manure solids are digestible, and agitation, mixing the settled solids with the liquids, prior to pumping being the most economical way to remove solids. Dao and Cavigelli (2003) suggest the addition of manure additives to reduce the excessive nutrient levels in manure or reducing the N and P excretion by livestock.

Phosphorus Removal Technologies

Phosphorus removal/recovery technology dates back to the 1900s (Table 1). In animal wastewater, P is found as both inorganic and organic compounds (Liu et al., 1997). Wastewater P removal can be achieved by chemical means, advanced biological treatment, a combination of chemical and biological treatment, crystallization, and chemical precipitation (Morse et al., 1998 and Yeoman et al., 1988). Klopfenstein and Erickson (2000) suggest removal of P from supplements and utilizing P from the ingredients of corn, corn byproducts, and roughages.

A summary of the P removal technologies is shown in Table 2, and a summary of the P recovery technologies is shown in Table 3. Chemical precipitation, biological P removal, crystallization, advanced chemical precipitation, and ion exchange technologies are the most common for P removal and recovery from waste water. Chemical precipitation produces P bound as a metal salt within waste sludge, and due to its flexibility, can be applied at any stage during wastewater treatment (Morse et al., 1998). Biological P removal occurs when activated sludge takes up P in considerable excess while avoiding chemical use and excess sludge production (Morse et al., 1998). Crystallization for P removal produces a more marketable end-product in the form of calcium phosphate, and the crystallization occurs by adding either caustic soda or milk of lime (Morse et al., 1998). Advanced chemical precipitation is referred to as HYPRO and occurs by the crystallization of P, organic matter and hydrolysis providing carbon and energy in an available form (Morse et al., 1998). Morse et al. (1998) report the ion exchange technology produces struvite. During the ion-exchange precipitation process, P and NH_3 ions produce struvite when removed from the wastewater (Morse et al., 1998).

Magnetic technology, adsorbents, and tertiary filtration technologies are also utilized for P removal and recovery, but minimal research has made these technologies somewhat secondary. For magnetic technology, calcium phosphate is precipitated in the form of magnetite by the use of lime and separated using a magnetic field (Morse et al., 1998). Adsorbents also have the ability to remove P from wastewater without additional sludge being produced (Morse et al., 1998). Tertiary filtration for P removal is incidental leaving the recovered sludge unsuitable for recycling (Morse et al., 1998).

Alum [$Al_2(SO_4)_3 \cdot 18\ H_2O$], ferric chloride ($FeCl_3$), ferric sulfate [$Fe_2(SO_4)_3$], and hydrated lime [$Ca(OH)_2$] are common chemicals facilitating P removal with optimum pH range being 6.0

- 8.5, except for lime which has a pH optima of 10 or greater (Westerman and Bicudo, 2000); wastewater alkalinity is the main variable that affects P removal by lime (ASCE, 1992). Although a disadvantage by making P unavailable as a nutrient, P removal can also be achieved by precipitation with aluminum, iron, and calcium, with aluminum sulphate being buffered in order to facilitate effective P removal (Booker et al., 1999; Yeoman et al., 1988).

Recovery of P is referred to as any technique allowing P to precipitate or crystallize from wastewater into a pure product for recycling purposes (Jeanmaire, 2001). Crystallization is the site of net P removal with most of the crystals forming in the sludge (Benisch et al., 2002). The pure product produced in this recovery technique of P is calcium phosphate and struvite in most processes (Jeanmaire, 2001). Phosphorus has the ability of being recycled into the plant growth cycle when required with the use of struvite as a slow release fertilizer (Duley, 2004). With the controlled formation of struvite, its commercial value as a fertilizer might prove beneficial (Jaffer et al., 2002; Cranfield University).

In addition to being an effective technique for P removal from municipal wastewaters, a cost effective alternative for recovering P from animal wastes may involve crystallization of struvite from treated calf manure using simple stirred tanks without the complexities (Gaterell et al., 2000) and costs associated with P removal techniques used in municipal systems. Struvite is composed of magnesium (Mg^{2+}), ammonium (NH_4^+), and phosphate ions (PO_4^{-3}) ions (Adnan et al., 2003). Struvite crystals are white or light gray in color. The mineral is also known as magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4 \cdot 6H_2O$, which is the same compound that forms kidney stones (Mancl and Veenhuizen, 1992).

Analysis of animal wastes suggest that Mg is the limiting ion for struvite formation; therefore, Mg is applied to manure slurries to force the precipitation of struvite (Burns and

Moody, 2002). Sources of Mg include MgO, MgOH, and $MgCl_2$ (Burns and Moody, 2002). Magnesium oxide (MgO) can increase both Mg and pH, but has relatively low solubility; therefore, $MgCl_2$ is the preferred reagent for the formation of struvite crystals (Jeanmaire, 2001; Burns and Moody, 2002).

Struvite is soluble in water when the pH is less than 5.0, and in solutions with a pH greater than 5.5, struvite formation will occur (Booker et al., 1999). The dominant P species is HPO_4^{2-} at a pH of 7.5, and as the pH rises, more HPO_4^{2-} becomes available forming excess struvite (Buchanan, et al. 1994). The solubility product constant for struvite is 7.08 x 10^{-14} with concentrations of $[Mg^{2+}]$, $[NH_4^+]$, and $[PO_4^{-3}]$ of importance (Buchanan et al., 1994). Phosphate ions should be in the form of PO_4^{-3}, and pH should be increased for the solubility product of struvite to exceed, which can be accomplished by the addition of MgO (Schuiling and Andrade, 1999). However, Burns and Moody (2002) achieved a 76% reduction in soluble P levels in swine manure holding pond effluent without any pH adjustment. If pH adjustment is not needed, chemical costs are reduced. Burns et al. (2001) report struvite precipitation is optimal at pH 9.0, but that struvite precipitation can occur in animal waste treatment systems at a pH from 7.0 to 11.0. Struvite precipitation can be inhibited when concentrations of total suspended solids (TSS) exceed 1000 ppm (Gaterell et al., 2000).

Potential for struvite formation can be calculated by comparing the solubility product of struvite to the ionic product of struvite, with the ionic product being ($[Mg^{2+}][PO_4^{3-}][NH^{4+}]$) (Jaffer et al., 2002). Jaffer et al. (2002) report precipitation of struvite occurs when the ionic product is greater than the solubility product. Dissolution occurs when the ionic product is less than the solubility product (Jaffer et al., 2002).

In addition to reducing P levels in animal wastes, the production of struvite may yield a marketable product. Schuiling and Andrade (1999) propose three potential outlets for struvite: 1) secondary phosphate ore; 2) phosphate source in industrial processes; and 3) slow-release fertilizer. Guano deposits and cow manure are natural sources of struvite and are available for plant and soil applications as an effective source of N, Mg, and P (Cranfield University).

Struvite can be utilized as a slow release fertilizer when harvested properly (Adnan et al., 2003). As a fertilizer, struvite can be utilized either as a specialty fertilizer in plant nurseries or blended into main agricultural fertilizers (Duley, 2004). Even when applied at relatively high application rates, struvite can act as a slow release fertilizer without damaging plant roots; additionally, since nutrients are released over a prolonged period of time leaching potential is low (Gaterell et al., 2000).

An Example of Reduction in P Concentrations in Swine Wastes via Struvite Precipitation

Reduction of soluble P levels in swine manure slurries through forced precipitation of struvite has been proven successful (Burns et al., 2001, Burns and Moody, 2002). Under laboratory conditions, Burns et al. (2001) reported that soluble P concentrations were reduced from 572 to 135 ppm when $MgCl_2$ was added at a rate of 1.6:1 (Mg to total P molar ratio) to liquid obtained from a swine waste storage pond. This reduction of 76% was achieved without the addition of a base to raise the pH. When NaOH was added to increase the pH to 9.0, a 90% reduction was achieved. Under field conditions, Burns et al. (2001) reported that soluble P concentrations were reduced by 90% (150 to 14.8 ppm) through the addition of $MgCl_2$ (64% solution) at a rate of 80 L/min. For experiments in the field, 2000 L of $MgCl_2$ were added per 140,000 L of liquid manure (Burns et al., 2001). No attempt was made to increase the pH (6.5) under field conditions. The pond was agitated with a 93 kW Houle agitator. Based on these experiments, Burns et al. (2003) state that, "The next step in the development of this technology for farm-scale recovery of P is the optimization of the recovery process and an economic assessment of the cost effectiveness of the method as a manure management option. In Europe and Japan, large municipal sewage-handling facilities have already embraced P recovery technology. Livestock producers have yet to benefit from these practices because farm-scale applications have not been developed."

Economic Evaluation

Eghball et al. (1997) state that feedlots in the United States collect 26.4 million Mg of manure annually, and the total N, P, and potassium (K) in the feedlot manure would value $461 million if collected and utilized properly. There were approximately 5.5 million head of fed cattle marketed in the Texas High Plains region in 2002 (TASS, 2003). Each animal produces about 0.9 Mg of collectable manure solids (Sweeten, 1991); therefore approximately 5 million Mg of dry manure solids were produced in 2002 in feedlots located in the Texas High Plains. The nutrient value of manure was estimated by Eghball et al. (1997) at \$17.46 Mg^{-1}; therefore the estimated nutrient value of the manure produced in Texas High Plains' feedlots in 2002 was $87 million.

Many feedlots have relied on land application of manure as the sole component of their manure management program and have tended to view manure as a waste rather than a resource (Ribaudo et al., 2003). Manure management programs typically consist of stockpiling manure until the appropriate application season for the crop on which the manure is being applied and to allow for adequate drying (Glover et al., 1994). A common practice is for manure contractors to transport and spread the manure on crop land in the vicinity of the feedlot with the cost of the manure to the farmer being the cost of transportation and spreading. Since the manure management program is considered a waste management program, feedlots are not capturing the added value of the individual nutrient components contained in the manure.

An issue of increasing importance to the region's feedlots is the EPA's promulgation of rules under the Clean Water Act. New regulations would require concentrated animal feeding operations (CAFOs) to meet nutrient application standards as defined in a nutrient management plan (Ribaudo et al., 2003). Under a nutrient management plan, land application standards for manure would be either N-based or P-based depending on the most limiting nutrient for the crop on which the manure is being applied. Nutrient management plans would be N-based in areas where soil P is generally low and P-based where soil P is generally high (Ribaudo et al., 2003). In the Texas High Plains region, manure application rates have been typically N-based which has led to excess P application for most crops grown in the region. A nutrient management plan that mandates P-based manure application standards would lower the quantity of manure that may be applied to an acre of land and therefore necessitate an increase in the amount of land necessary to dispose of manure from CAFOs (Ribaudo et al., 2003; Burns et al., 2003).

The ability of a CAFO to dispose of manure under a nutrient management plan using land application as the primary method will depend upon the nutrient standard required, the availability of suitable land within a distance from the feedlot that makes manure application economically feasible, and the willingness of farmers to use manure at a lower application rate. From a waste management standpoint, the land application of manure when possible is the most cost effective method of nutrient recycling (Driver, 1998). However, a regulatory requirement to reduce P loading on crop lands under a nutrient management plan may necessitate the consideration of alternative waste management practices.

In evaluating waste management alternatives, several factors should be considered. What regulatory requirements with regard to waste management must be met to comply with environmental permitting? What value added products may be produced with a given waste treatment technology and does a market for these products exist? What will be the composition and market for the waste product following processing? What is the required investment cost of a given waste treatment technology? What is the benefit/cost relationship of the alternative waste treatment technologies?

Of the treatment technologies for P removal discussed in this paper, the process of P recovery as struvite may be a cost effective method (Gaterell et al., 2000). The recovery of P as struvite may allow CAFOs to successfully implement P-based nutrient management plans on the current land application base (Burns et al., 2003). In addition, this technology has the potential to reduce transportation costs of the remaining waste by isolating the excess P and converting the P into a form that may be cost-effectively transported to cropping systems that require P input (Burns et al., 2003).

To complete a detailed economic evaluation of the recovery of P in the form of struvite from feedlot waste would require specific information on the layout/design of the feedlot. The necessary information to complete an analysis would include the volume of waste produced, the cost to construct or modify the waste treatment facility, the concentration of P in the waste effluent, the expected yield of struvite, the amount and cost of required chemicals within the process, the expected value of the struvite harvested from the facility, and the value/cost of the manure after the treatment to remove the P. Therefore, a specific economic evaluation of this process is not possible due to a lack of published data.

The published literature regarding the removal of struvite from waste water deals mostly with the chemistry and engineering aspects of the treatment process and less with an economic evaluation. The literature mostly deals with the treatment of municipal waste water, with some literature on the treatment of waste water from swine production facilities. Much of the literature is from studies conducted in Europe on municipal waste treatment facilities. The economic evaluations found in the literature typically evaluate the cost of the chemicals used in the struvite production process and do not take into account other production costs such as labor, energy, and the investment cost in the treatment technology.

Woods and Daigger (1999) assessed the viability of implementing P recovery technologies at municipal wastewater treatment facilities in North America. They identified several drivers for P recovery which included potential cost savings of sludge handling costs, potential cost recovery from the sale of recovered products, potential enhanced P removal to achieve lower P concentrations in effluent, and a demand for sustainable P resources. However, they concluded that the value of the recovered P product was insignificant relative to the cost of chemicals required for recovery and the capital costs of the facilities. The recovery of P becomes economically viable only at high influent concentrations of P and/or where sludge handling costs are high.

Gaterell et al. (2000) performed an economic and environmental evaluation of the use of P recovered from wastewater treatment plants in the UK. Struvite can be used as a slow release fertilizer and has been used in Japan to compound commercially available fertilizers. Their analysis indicated that the cost of struvite production was highly influenced by the recovery rate. The cost of recovered struvite at 49% and 80% recovery rates was estimated to be \$363 ton^{-1} and \$232 ton^{-1}, respectively, which compared favorably to the price of diammonium phosphate at

\$372 ton^{-1}. The authors suggest that an assessment of the economic viability of using struvite for fertilizer applications would depend on the substitutability of struvite for existing products and the possibility of substituting struvite for P rock in the manufacture of existing products.

Jaffer et al. (2002) looked at the potential recovery of struvite at the Slough Sewage Treatment Works at Slough, UK. Their analysis was in response to problems with struvite buildup in pipelines within the plant with a possible solution being the participation and recovery of struvite. It was estimated that the annual chemical costs to remove 90% of the P as struvite would be \$960 ton^{-1}. They estimated the struvite could be sold for approximately \$310 ton^{-1}. The estimated revenue from the sale of the struvite only covered one-third of the additional cost of the chemicals used in the process. Doyle et al. (2002) reported that the estimated costs for producing struvite varied from \$140 ton^{-1} in Australia to \$460 ton^{-1} in Japan.

Jeanmaire (2001) presented a review of the literature on P recovery and concluded that the value of the recovered P product is unlikely to be the main driver for P recovery. Factors such as reducing sludge production and nutrient management of land application would be more significant drivers for P recovery.

The economics of P recovery are not well established at this time due to the limited number of processing plants involved in P recovery and their location primarily in Europe and Japan. The recovery P from swine manure in the US is being investigated; however, no economic evaluations are available at this time. Therefore, the review of the literature with regard to an economic evaluation of the production of struvite as a product of waste water treatment was limited and general.

However, a few points can be gleaned from this review. The primary driver for P recovery at this time seems to be the management of manure and solid waste under a nutrient management plan rather than as a value added revenue source. The market for products from P recovery such as struvite are not well developed at this time; therefore, it is difficult to assess the potential for a particular technology as a revenue source. However, the regulatory issues of manure management may necessitate the processing of manure to meet regulatory standards. If this should be the case, a P recovery process that has the potential to at least recover some of the process costs would be attractive.

Based on the data from Burns et al. (2001) suggesting that $MgCl_2$ be used as an Mg source applied at a rate of 1.6:1 (Mg:total P), a preliminary calculation of the costs of chemicals for forced struvite precipitation can be made. Assuming a total P concentration of 100 ppm for a typical cattle feedlot lagoon and assuming a cost of \$0.40/pound of $MgCl_2 \cdot 6H_2O$ (Univar Chemical, Borger, TX), the cost of Mg necessary to treat one acre-foot of waste would be \$1,140. However, this calculation is based solely on literature data for swine effluent and may not accurately reflect the cost to force struvite precipitation of struvite in feedyard wastes.

The ratio of 1.6:1 reported by Burns et al. (2001) resulted in a reduction in soluble P concentration of up to 90% in swine lagoon effluent. However, it may not be necessary to reduce P concentrations to such low levels in the feedyard lagoons. To accurately assess the costs for the feedyard system, it is necessary to conduct research designed to provide data on optimization of P reduction via forced struvite precipitation in the feedyard waste. It may be possible to design a system that results in an acceptable reduction in P and thereby requires less Mg than used in the swine example. The target level for final P concentration could be calculated by conducting a P balance in which the concentration of P in the water, the amounts of irrigation needed to produce a crop, crop P uptake data, and target soil P levels are used to predict application rates and uptake data for applied P. These calculations, in conjunction with actual experimental data from feedlot lagoons, can be used to more accurately define the amount of Mg required to reach acceptable P concentrations in feedyard waste.

Furthermore, it may be possible to negotiate a better price for $MgCl_2 \cdot 6H_2O$ than the full-retail price ($0.40/pound) used in these calculations. Finally, the necessity and cost of mechanical agitation of the lagoons as well as frequency of struvite removal from the lagoon will need to be assessed. To accurately make these assessments for a feedyard system, it is necessary to obtain specific data.

A potential offsetting cost factor is the sale of struvite as a fertilizer. Data on the purity of the struvite produced from feedyard waste and the agronomic characteristics of this mineral are not available.

Summary

The wastewater treatment industry has numerous technologies available to reduce P concentrations in municipal wastewaters. These technologies can be complex and often require large initial outlays of financial capital, which is not very practical for animal systems.

A technology used in the swine industry utilizes the forced precipitation of struvite, a mineral containing Mg, NH_4^+ and P. The advantage of this technology is that it is relatively simple and can be carried out in existing animal waste water lagoons. Addition of $MgCl_2$ to force struvite precipitation has been shown to reduce soluble P concentrations by up to 90% in a swine waste lagoon.

Based on data from the swine system, the chemical cost for a typical feedyard lagoon at 100 ppm of total P would be about $1140/acre- foot. There exists the possibility to lower this cost by optimizing the inputs for feedyard waste and to determine the level of P reduction needed to reduce environmental concerns associated with P application through feedyard waste water. A more detailed economic evaluation is not presently possible due to lack of published data on the economic aspects of the process developed by the swine industry, as well as due to a lack of data specifically related to feedyard systems. Additional research is needed to determine the true potential of this technology in the feedyard industry. The potential benefit of this technology includes the ability to reduce P in existing lagoons without development of a complex treatment process common to municipalities. Additionally the struvite produced may have value as a slow release fertilizer.

References

Adnan, A., D.S. Mavinic, and F.A. Koch. 2003. Pilot-scale study of phosphorus recovery through struvite crystallization – examining the process feasibility. Journal of Environmental Engineering Science 2:315-324.

ASCE. 1992. Design of Municipal Wastewater Treatment Plants. Vol. 2

Benisch, M., C. Clark, R. G. Sprick, and R. Baur. 2002. Struvite deposits – a common and costly nuisance. Water Environment Technology 14(8):51-54.

Bohn, H. L., B. L. McNeal, and G. A. O'Connor. 1979. Soil chemistry. John Wiley and Sons, New York, NY.

Booker, N. A., A. J. Priestley, and I. H. Fraser. 1999. Struvite formation in wastewater treatment plants: opportunities for nutrient recovery. Environmental Technology 20:777-782.

Buchanan, J. R., C. R. Mote, and R. B. Robinson. 1994. Thermodynamics of struvite formation. Transactions of the American Society of Agricultural Engineers 37(2):617-621.

Burns, R. T., L. B. Moody, F. R. Walker, and D. R. Raman. 2001. Laboratory and *in-situ* reductions of soluble phosphorus in swine waste slurries. Environmental Technology 22:1273-1278.

Burns, R. T. and L. B. Moody. 2002. Phosphorus recovery from animal manures using optimized struvite precipitation. Proceedings of Coagulants and Flocculants: Global Market and Technical Opportunities for Water Treatment Chemicals, May.

Burns, R. T., L. B. Moody, I. Celen, and J. R. Buchanan. 2003. Optimization of phosphorus precipitation from swine manure slurries to enhance recovery. Water Science and Technology 48(1):139-146.

Cranfield University. Struvite formation and control. Available online at: http://www.cranfield.ac.uk/sims/water/scale/struvite.htm. (accessed 23 Sep. 2004; verified 30 Sep. 2004)

Dao, T. H. and T. C. Daniel. 2002. Particulate and dissolved phosphorus chemical separation and phosphorus release from treated dairy manure. Journal of Environmental Quality 31:1388-1398.

Dao, T. H. and M. A. Cavigelli. 2003. Mineralizable carbon, nitrogen, and water-extractable phosphorus release from stockpiled and composted manure and manure-amended soils. Agronomy Journal 95:405-413.

Doyle, J. D., and S. A. Parsons. 2002. Struvite formation, control and recovery. Water Research. 36:3925-3940.

Driver, J. 1998. Phosphates recovery for recycling from sewage and animal wastes. Phosphorus and Potassium 216:17.

Duley, B. 2004. Recycling phosphorus by recovery from sewage. The Natural History Museum – Phosphate Recovery. Available online at: http://www.nhm.ac.uk/mineralogy/phos/Duley.doc. (accessed 23 Sep. 2004; verified 30 Sep. 2004)

Eghball, B., J. F. Power, J. E. Gilley, and J. W. Doran. 1997. Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. Journal of Environmental Quality 26:189-193.

Gaterell, M. R., R. Gay, R. Wilson, R. J. Gochin, and J. N. Lester. 2000. An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertilizer markets. Environmental Technology 21:1067-1084.

Glover, T., E. Segarra, and P. Johnson. 1994. An economic analysis of waste management for Texas cattle feedlots. Proceedings of the Great Plains Animal Waste Conference on Confined Animal Production and Water Quality, October 1994, Denver CO. p. 54-58.

Greaves, J., P. Hobbs, D. Chadwick, and P. Haygarth. 1999. Prospects for the recovery of phosphorus from animal manures: A review. Environmental Technology 20:697-708.

Jaffer, Y., T. A. Clark, P. Pearce, and S. A. Parsons. 2002. Potential phosphorus recovery by struvite formation. Water Research. 36:1834-1842.

Jeanmaire, N. 2001. Recycling of Removed Phosphorus: Analysis of the potential interest in wastewater treatment plants. Centre Europeen d'Etudes des Polyphosphates. Available online at: http://www.nhm.ac.uk/mineralogy/phos/Jeanmaire_report.doc (accessed 15 Jun. 2004; verified 30 Sep. 2004)

Kirk, D. M. and W. G. Bickert. 2002. Adapting municipal wastewater treatment methods to animal manure. Available online at: http://www.egr.msu.edu/age/aenewsletter/1_nov_dec_02/kirk_02.htm. Nov/Dec. (accessed 15 Aug. 2003; verified 30 Sep. 2004)

Klopfenstein, T. and G. Erickson. 2000. Feed program options for addressing phosphorus issues facing beef feedlots. Manure Matters 6(9).

Liu, C. C., D. T. Mitchell, J. W. Odom, and E. W. Rochester. 1997. Phosphorus recovery in surface runoff from swine lagoon effluent by overland flow. Journal of Environmental Quality 26:995-1001.

Mallarino, A., J. E. Sawyer, J. Creswell, and M. Tidman. 2000. Soil testing and available phosphorus. Available online at: http://www.ipm.iastate.edu/ipm/icm/2000/9-18-2000/availablep.html. 18 Sep. 2002. (accessed 8 May 2004; verified 30 Sep. 2004)

Mancl, K. and M. A. Veenhuizen. 1992. Managing livestock waste facilities – controlling crystal formation in recycle flush systems. Ohio State University Extension. Available online at: http://ohioline.osu.edu/aex-fact/0709.html (accessed 21 Dec. 2003; verified 30 Sep. 2004)

Miner, J. R., F. J. Humenik, and M. R. Overcash. 2000. Managing livestock wastes to preserve environmental quality. Iowa State University Press, Ames, IA.

Morse, G.K., S.W. Brett, J.A. Guy, and J.N. Lester. 1998. Review: phosphorus removal and recovery technologies. The Science of Total Environment 212:69-81.

Mullins, G. 2001. Phosphorus, agriculture, and the environment. Publication 424-029. Virginia Cooperative Extension, Virginia Tech, Blacksburg, VA.

Ozanne, P.G. 1980. Phosphate nutrition of plants – a general treatise. *In* F. E. Khasawneh et al. (ed.) The role of phosphorus in agriculture. ASA, Madison, WI.

Pierzynski, G. M., J. T. Sims, and G. F. Vance. 2000. Soils and environmental quality. 2nd ed. CRC Press, Boca Raton, FL.

Potash and Phosphate Institute. 2004. Available online at: http://www.ppi-ppic.org/ppiweb/ppibase.nsf/$webindex/article=678CA758852569B5005C148685E4A99F (accessed 08 May 2004; verified 30 Sep. 2004).

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, R. Johansson, J. Agapoff, L. Christensen, V. Breneman, and M. Peters. 2003. Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land. USDA-ERS. Agricultural Economic Report 824.

Safley, L. M., C. D. Fulhage, R. L. Huhnke, and D. D. Jones. 2003. Lagoon management. Available online at: http://www.theticker.org/vnews/display.v/ART/2003/11/03/3fa697ce3445e (accessed 15 Dec. 2003; verified 30 Sep. 2004)

Schuiling, R. D. and A. Andrade. 1999. Recovery of struvite from calf manure. Environmental Technology 20:765-768.

Sharpley, A.N. (ed.) 2000. Agriculture and phosphorus management, the Chesapeake Bay. Lewis Publishers, Washington, DC.

Sharpley, A., B. Foy, and P. Withers. 2000. Practical and innovative measure for the control of agricultural phosphorus losses to water: an overview. Journal of Environmental Quality 29:1-9.

Southern Cooperative Series. 1998. Soil testing for P – environmental uses and implications. S. Coop. Ser. Bull. 389. USDA-CSREE, U.S. Gov. Print. Office, Washington, DC.

Sweeten, J.M. 1991. Odor and Dust From Livestock Feedlots. Texas A&M Experiment Station, Texas A&M University, College Station, TX.

Texas Agricultural Statistics Service (TASS). 2003. Texas Agricultural Statistics 2002. Texas Agricultural Statistics Service, Austin, TX.

VanDevender, K., J. Langston, and J. Boles. 1997. Liquid animal manure management systems. Cooperative Extension Service, University of Arkansas, USDA, and County Governments Cooperating.

Ward, G. M., T. V. Muscato, D. A. Hill, and R. W. Hansen. 1978. Chemical composition of feedlot manure. Journal of Environmental Quality 7:159-164.

Wendt, R. C. and R. B. Corey. 1980. Phosphorus variations in surface runoff from agricultural lands as a function of land use. Journal of Environmental Quality 9(1):130-136.

Westerman, P. W. and J. R. Bicudo. 2000. Tangential flow separation and chemical enhancement to recover swine manure solids, nutrients, and metals. Bioresource Technology 73:1-11.

Woods NC., and Daigger G.T. 1999. Phosphate recovery an economic assessment. http://www.nhm.ac.uk/mineralogy/phos/daiggr/daiggr.htm (accessed 15 Jun. 2004; verified 30 Sep. 2004)

Yeoman, S., T. Stephenson, J. N. Lester, and R. Parry. 1988. The removal of phosphorus during wastewater treatment: A review. Environmental Pollution 49:183-233.

Table 1. History of phosphorus removal and recovery technologies - development and status (Morse et al., 1998).

Phosphorus Removal/Recovery Technology	Development Status	Development Timescale	Originators/ Reference	Country of Origin
Chemical precipitation	Commercial	~1950 to date	Many	Global
Biological P (and N) removal	Commercial	~1960 to date	Many	Global
Phostrip	Commercial	~1965	Levin & Shapiro, 965	USA
Modified Bardenpho	Commercial	~1974 to date	Barnard, 1990	S. Africa
Phoredox	Commercial	~1976 to date	Barnard, 1990	S. Africa
A/O	Commercial	~1980 to date	Randall et al., 1990	USA
University of Cape Town (UCT)	Commercial	~1983 to date	Siebritz et al., 1983	S. Africa
Modified UCT	Commercial	~1990	Farnell et al., 1990	S. Africa
Rotanox	Commercial	~1982	Rachwell et al., 1984	UK
Biodenipho	Commercial	~1980	Bundgaard & Pedersen, 1991	USA
Crystallization				
DHV Crystalactor ®	Full-scale	~1979 to date	DHV Consulting Engineers, 1991	Netherlands
CSIR	Laboratory	~1992 to date	Momberg & Oellermann, 1992	S. Africa
Kurita	Laboratory	~1984 to date	Joko, 1984	Japan
Phosnix	Laboratory	~1994 to date	Unitika Ltd., 1994	Japan
Sydney Water Board	Laboratory	~1993 to date	Angel et al., 1989	Australia
OFMSW	Laboratory	~1994 to date	Cecchi et al., 1994	Italy, Spain
Novel Nutrient Removal				
HYPRO Concept	Full-scale	~1991 to date	Henze & Harremoes, 1992	Scandinavia
AFBP	Pilot	~1994 to date	Shimizu et al., 1994	Japan
Maezawa FBPS	Pilot	~1993 to date	Suzuki et al., 1993	Japan
Other Wastewater				
RIM-NUT (ion exchange)	Demonstration	~1986 to date	Liberti et al, 1986	Italy
Smith-Nymegen (magnetic	Pilot/FS	~1991 to date	Van Velsen et al., 1991	Netherlands
Sirofloc (magnetic)	Demonstration	~1979 to date	Dixon, 1991	Australia
Phosphorus Adsorbents	Laboratory	~1970 to date	Many	Global
Tertiary Filtration	Commercial	~1900 to date	Many	Global
Slow Sand Filters	Commercial	~1900 to date	Many	Global
Shallow Bed Filters	Commercial	~1900 to date	Many	Global
Rapid Gravity Filters	Commercial	~1900 to date	Many	Global
Rapid Deep-bed Filters	Commercial	~1900 to date	Many	Global
Moving Bed Filters	Commercial	~1900 to date	Many	Global
Pressure Filters	Commercial	~1900 to date	Many	Global
Sludge Treatment				
Simon-N-Viro	Full-scale	~1990 to date	Lloyd, 1990	USA
Swiss Combi	Full-scale	~1980 to date	Kunz, 1991	Switzerland
Recovery from Sludge	Laboratory	~1995 to date	Matsuo, 1995	Japan

Table 2. Process summary of phosphorus removal technologies (Morse et al., 1998).

Technology	**Objective**	**Process Summary**	**Main Input**	**Auxiliary Inputs**	**Main Output**	**P Form/Content**
Chemical Precipitation	Phosphorus Removal	Addition of metal salt to precipitate metal phosphate removed in sludge.	Wastewater (primary, secondary, tertiary, or sidestream)	Fe, Al, Ca May require anionic polymer	Chemical Sludge	Mainly chemically bound as metal phosphate.
Biological Phosphorous Removal	Phosphorus Removal (may also include nitrogen removal)	Luxury uptake of P by bacteria in aerobic stage following anaerobic stage.	Wastewater (primary effluent)	May require external carbon source (e.g. methanol)	Biological Sludge	Phosphorus biologically bound.
Crystallization (DHV Crystalactor^{TM})	Phosphorus Removal Recovery	Crystallization of calcium phosphate using sand as a seed material.	Wastewater (secondary effluent or sidestream)	Caustic soda/milk of lime, sand; may need sulfuric acid.	Calcium phosphate, sand	Calcium phosphate (40%-50%)
Advanced Chemical Precipitation (HYPRO)	Phosphorous and Nitrogen Removal	Crystallization of phosphorous/organic matter and hydrolysis to give carbon source for N removal.	Wastewater (primary influent)	Polyaluminium chloride (PAC)	Chemical sludge	Chemical sludge
Ion Exchange (RIM-NUT)	Fertilizer (struvite) Production	Ion exchange removes ammonium and phosphate which are precipitated.	Wastewater (secondary effluent)	H_3PO_4, MgCl, NaCl, $NaCO_3$, NaOH	Struvite ($MgNH_4PO_4$)	Phosphate slurry
Magnetic (Smit-Nymegen)	Phosphorus Removal	Precipitation, magnetite attachment, separation and recovery	Wastewater (secondary effluent)	Lime, magnetite	Primarily calcium phosphate	Calcium phosphate
Phosphorus Adsorbents	Phosphorous Removal	Adsorption and Separation	Wastewater	NA	No Information	Calcium Phosphate
Tertiary Filtration	Effluent polishing	Filtration	Secondary effluent	Media	Tertiary Sludge	Insoluble Phosphate
Sludge Treatment	Sludge Disposal	e.g. Sludge drying, reaction with cement dust	Sludge	Depends on process	Soil Conditioner	Dry granule, low in P
Recovery from sludge ash	Phosphorus Recovery	Extraction from sludge ash	Sludge ash from biological removal	NA	NA	NA

Table 3. Process summary of phosphorus recovery technologies (Morse et al., 1998).

Technology	**Industrial Recovery Value**	**Agriculture Recovery Value**	**Technology Advantages**	**Technology Disadvantages**
Chemical Precipitation	Low – P binding to metals prohibits recycling.	Moderate – P availability variable.	Low technology, easy to install, & high P removal.	Chemicals required, variable P recycle ability, & increase in sludge production.
Biological Phosphorous Removal	Moderate – Biologically bound P is recyclable.	Moderate – Biologically bound P is more available.	Chemicals not necessary, removal possible of N & P, recyclable P, & established technology.	Requires more complex technology & difficulty in handling sludge.
Crystallization (DHV Crystalactor^{TM})	Very High – Easily recycled.	Moderate – P availability variable.	Recyclable product and demonstrated technology.	Operation skills and chemicals required.
Advanced Chemical Precipitation (HYPRO)	Low – P binding to metals prohibits recycling.	Moderate – P availability variable.	P & N removal enhanced with part of a complete recycling concept.	Chemicals required & P may be inconvenient for recyling.
Ion Exchange (RIM-NUT)	Moderate – Requires modifications.	High – Struvite is a good slow-release fertilizer.	Removal of P high & struvite produced can be recycled for agricultural use.	Chemicals required and technology is complex.
Magnetic (Smit-Nymegen)	Moderate – Requires modifications.	Low – Unknown agricultural stability.	Removal of P high.	Chemicals required and technology is complex.
Phosphorus Adsorbents	Low	Low	Few chemicals involved & potential for P recovery.	Technology is unproven.
Tertiary Filtration	No potential.	No potential.	Technology is established and easy to use.	No useful product from recovery.
Sludge Treatment	Low – Recycling is difficult.	High – P reusable.	Sludge value is increased.	Chemicals required and technology is complex.
Recovery from sludge ash	High – P leached readily.	Moderate – Possible P reuse.	High concentrations result in potential for P recovery.	Technology is underdeveloped.

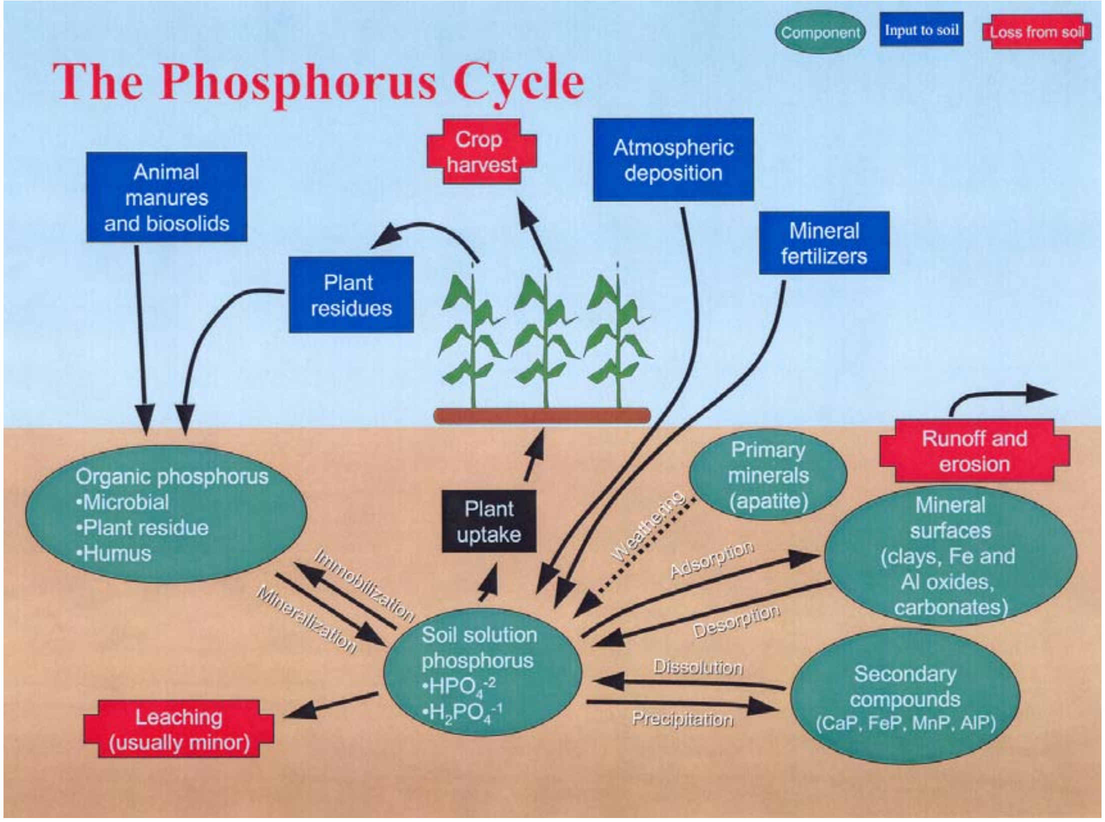

Figure 1. The soil P cycle (Potash and Phosphate Institute, 2004).

Figure 2. Schematic plan of cattle feedlot (Miner et al., 2000).