COMPARISON OF THE EFFECTIVENESS AND ECONOMIC COSTS OF TWO PRODUCTION SCALE POLYACRYLAMIDE ASSISTED SOLID/LIQUID SEPARATION SYSTEMS FOR THE TREATMENT OF LIQUID SWINE MANURE

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ABSTRACT: This study evaluated and compared the effectiveness and economic costs of a polyacrylamide (PAM) assisted continuous gravity belt thickener and a PAM assisted inclined stationary gravity screen separator equipped with a backwash spraybar, each in tandem with an inclined stationary gravity screen-roll press separator to separate the solid and liquid components of liquid swine manure (raw slurry) under production scale operating conditions. The separation systems were operated from June through December processing 7,222,725 L (1,908,048 gal) of raw untreated slurry (RS1). Both treatments, gravity belt thickener and gravity screen, showed significant reductions of 84.9% and 97.8% for Settleable Solids, 93.2% and 93.7% for Total Suspended Solids, 63.7% and 69.5% for Chemical Oxygen Demand, 23.3% and 31.8% for total Nitrogen, and 52.3% and 60.5% for total Phosphorus, respectively, in the treated effluent. The cost for separation with the gravity belt thickener system was 0.474¢ per L (1.791¢ per gal) of raw slurry. The separation cost for the gravity screen system was 0.402¢ per L (1.518¢ per gal) of raw slurry. Application costs for irrigating the separated effluent generated from either system added another 0.061¢ per L (0.234 ¢ per gal) of raw slurry. Either of these solid liquid separation systems would be an effective and economically viable alternative to current disposal methods while providing additional operational and environmental benefits.

Keywords: Swine manure, Solids separation, Polyacrylamide, Gravity screen, Gravity belt thickener, Economics.

Current methods for managing swine manure consist of holding tanks, treatment lagoons, and direct injection application on crop producing fields (Barker, 1996), but these methods create problems for the environment, the public, and the pork producer (Cates et al., 2006). Failure of storage systems to adequately store or treat waste and mishaps during application can result in discharges leading to environmental degradation in both local waterways and those farther downstream (Burkholder et al., 1997). When managed properly, manure from livestock can be used as a valuable resource for fertilizing crops and for effectively recycling important nutrients back into the soil. The nutrient characteristics of untreated swine slurry, with a N:P (nitrogen to phosphorous) ratio of approximately 3.1:1, results in an over application of phosphorous when land applying based on N application rates (USDA, 2005). There are several separation technologies that can be borrowed from municipal wastewater treatment operations to improve the quality of the effluent while extracting solids that can be used for composting (Melse and Verdoes, 2005; Burton, 2007), but there is a need to understand the practicalities and efficiency expectations of the various applications of these technologies to swine manure management (Lorimor et al., 2006). Small-scale treatment using minimal technology has been investigated but efficiency results were low and actual producer costs could not be calculated (Westerman and Argo, 2005). Full-scale, multi-step processes that combine solids separation, denitrification, and phosphorus removal to produce discharge-quality effluent have been proposed for treating swine waste slurry (Martinez-Almela and Barrera, 2005; Vannotti et al., 2007), but surveys have shown that pork producers need a simple, low-tech, low cost, easy-to-operate system that creates more beneficial and easily utilized products from the waste if they are to invest in a treatment system (Cates et al., 2006; Walker, 2008).

This study evaluated the separation effects, efficiency, and economic inputs of an inclined gravity screen-roll press combination separator operated in conjunction (tandem) with either a polyacrylamide (PAM) assisted continuous gravity belt thickener, System 1, or a PAM assisted inclined stationary gravity screen separator equipped with a backwash spraybar, System 2, under production scale conditions. The reductions in the concentrations of solids and other commonly used aquatic pollution indicators in the treated effluent relative to the raw, untreated swine manure (RS1) were measured. Costs for initial setup and ongoing separation operations using each system were compared. An analysis of the resulting data was then used to examine the feasibility of utilizing each of these treatment systems to reduce swine waste pollution indicators and to compare the two systems in terms of efficiency and cost during production scale operations.
MATERIAL AND METHODS
SLURRY SEPARATION

Co-mingled raw slurry generated from gestation, farrowing, nursery, and grow-finish swine buildings located on the Illinois State University (ISU) Farm at Lexington, Illinois, was utilized for this study. Untreated slurry was drained by an underground sewer line from building pits to an in-ground 53,371-L (14,100-gal) concrete holding tank 1.83 m deep located in the slurry processing building. A schematic of the farm buildings and manure handling system is shown in figure 1. All slurry pits in all the swine buildings at the ISU Farm 220 sow farrow-to-finish swine operation were drained once or twice each week and recharged with 5-8 cm (2-3 in.) of separated effluent (SE). While in the holding tank, RS1 was continuously stirred as it was pumped from the bottom of the pit and passed across an inclined gravity screen-roll press combination separator (GSR) to remove separable solids (SS) producing separated slurry (RS2). The RS2 was mixed with polymer using an in-line variable orifice adjustable by means of a weighted external lever arm and a four port polymer injection ring feed manifold. Subsequent to mixing with polyacrylamide (PAM), RS2 was passed across a continuous gravity belt thickener (System 1, fig. 2) or an inclined stationary gravity screen separator with a backwash spraybar (System 2, fig. 3) to remove total suspended solids (TSS). The resulting biosolids (BS) were held in a decanting basin until they were transported to a compost site, mixed with landscape waste, and composted. The resulting separated effluent from System 1 (SE-S1) and System 2 (SE-S2), along with the decanted liquid from the biosolids, was stored in a 3,785,300-L (1-million gal) capacity Slurry Store® until land applied during the corn/soybean growing season via a 16.2-ha (40-acre) center pivot irrigator.

The GSR separator used during this study was a Model 250, manufactured by Key Dollar Cab, Inc. (Milton-Freewater, Oreg.). The screen pore size was 1.59 mm, and the maximum capacity of the separator was 757.1 L/min (200 gal/min). For this study, the separator was operated at a rate of 378.5 L/min (100 gal/min). The continuous gravity belt thickener used in System 1 was a Model GSC-1, Series III manufactured by Komline Sanderson (Peapack, N.J.). The belt fabric permeability (maximum volume of water capable of passing through the belt) was 390 L/min (103 gal/min), and the maximum capacity of this system was 567.8 L/min (150 gal/min). For this study, the belt separator was operated at a rate of 378.5 L/min (100 gal/min). The inclined stationary gravity screen separator used in System 2 was a Model 200, manufactured by Key Dollar Cab, Inc. (Milton-Freewater, Oreg.). The screen size was 50 mesh, 0.009 gauge woven wire containing 19.7 wires/cm (50 wires/in.), and the maximum capacity of the separator was 757.1 L/min (200 gal/min). For this study, the separator was operated at a rate of 378.5 L/min (100 gal/min). The PAM polymer used was Zetag 8160® (Ciba Specialty Chemical Water Treatments, Inc.; Suffolk, Va.) that had a charge density of 60%, an intrinsic viscosity of six to eight units, and percentage active solids of greater than 99.9%. Raw slurry was amended

Figure 1. Building and manure handling diagram.
with an average Zetag 8160® concentration of 66.0 mg/L. The polymer and polymer concentrations chosen were based on previously-determined optimal concentrations for swine slurry (Walker and Kelley, 2003, 2005) and as determined by “in-field” operation observations. Between June and December, separation occurred once or twice a week during the 170 day time span. Slurry was separated on-site under typical production scale conditions at the ISU Farm.

LABORATORY ANALYSIS

One-liter samples of RS1, RS2, SE-S1, and SE-S2 were collected for analysis and stored at 4°C. Prior to sampling, slurry was agitated to re-suspend settled solids. Initial RS1 samples were collected from the bottom of the holding pit during agitation using a 2.40-m probe. The RS2 samples were collected as the liquid was discharged from the GSR separator. Final SE-S1 samples were randomly collected as the SE-S1 was discharged from System 1 and final SE-S2 samples were randomly collected as the SE-S2 was discharged from System 2. Sub-samples were analyzed for pH, dissolved oxygen (DO), chemical oxygen demand (COD), solids dry weight (SDW), settleable solids (SS), total suspended solids (TSS), total nitrogen (N), total phosphorus (P), and ammonia (NH₃). A Hach pH probe, model 51910, and sensen2 ISE meter, model 5172518 (Hach corporation, Loveland, Colo.), was used to measure pH in standard 0- to 12-pH scale units and DO was measured using a Hanna® (Hanna Instruments, Woonsocket, R.I.) DO meter. Chemical Oxygen Demand was determined by Hach method 8000 micro digestion procedure and read using a Hach® DR 2000 Colorimeter (Hach Corporation, Loveland, Colo.). Solids Dry Weight was determined by drying samples at 103°C to 105°C according to Method 2540 B in Standard Methods for the Examination of Water and Wastewater (Eaton, 2005). Settuble Solids were determined by transferring samples to 1.0-L Imhoff cones according to method 2540F in Standard Methods for the Examination of Water and Wastewater (Eaton, 2005). Total Suspended Solids were determined by Hach method 8006 using a Hach® DR700 Colorimeter (Hach Corporation, Loveland, Colo.). Total nitrogen was analyzed by a LECO® nitrogen determinator (model FP528, LECO Corporation, St. Joseph, Mich.). Phosphorus was determined by the nitric acid/ hydrogen peroxide digestion method described by the Association of Analytical Chemists (1975) and subsequent analysis using an IRIS Plasma Spectrometer (ICP) (model number 13283200, Thermo Jarrell Ash, Franklin, Mass.). Ammonia was determined by Hach method 10001 using a Hach® ammonia probe, model 51927-00, and a Hach® sensen2 ISE meter, model 5172518 (Hach Corporation, Loveland, Colo.).

COST CALCULATIONS

The components of both separation systems were powered by electricity and costs in kwh/L (kwh/g) were calculated based on the rate quote from Ameren IP, Decatur, Illinois, for the Bloomington-Normal, Illinois service area of 7.95¢/kwh for the period of time during which operations occurred. Total costs of all component parts specific to the operation of each of the separation systems, including the building, were grouped together and are shown as equipment with a 10 year straight line depreciation schedule. Polymer cost was calculated based on actual rate of polymer used, 66 mg/L (0.55 lb/1000 g) of raw slurry for both systems, and market price ($2.45/lb) as quoted by Ciba Inc. (Suffolk, Va.). Labor cost per hour reflects an estimated value ($15.00/h) but actual hours of labor required were used. The cost of land application of SE via center pivot irrigating was calculated using quoted costs for irrigator equipment, diesel fuel and electricity during the time period of the study. Total separation and application costs were compared to current market costs to pump, transport and inject raw slurry as indicated by surveyed producer responses (Walker, 2008).
RESULTS AND DISCUSSION

During the 7-month time period of this study, 7,222,725 L (1,908,048 gal) of RS were separated producing 6,789,361 L (1,793,565 gal) of SE and 433,364 L (114,483 gal) of BS. This represents a collection rate for SE of 94%. Separation occurred once or twice weekly for 40 separation periods during the 170 day time span (26 weeks). An average of 181,699 L (48,000 gal) of RS was separated at each time producing an average of 170,797 L (45,120 gal) of SE over an 8-h period of time. Separation occurred more frequently during hotter summer weeks when the hogs wasted more water resulting in increased RS1 volume.

Random 1-L grab samples of RS1, RS2, SE‐S1, SE‐S2, BS‐S1, and BS‐S2 were taken during 30 of the 40 separation periods. Results of RS1, RS2, SE‐S1, SE‐S2, BS‐S1, BS‐S2, and decanted BS analysis for SDW, SS, TSS, pH, COD, N, P, and NH3 are presented along with the N:P ratios in table 1. Based on table 1 data it is apparent that concentrations recovered in the SE‐S1 and SE‐S2 were significantly reduced relative to RS1 by 46.3% and 52.8% for SDW, 84.9% and 97.8% for SS, 93.2% and 93.7% for TSS, 63.7% and 69.5% for COD, 23.3% and 31.8% for N, and 52.3% and 60.5% for P, respectively. Mean pH values were similar for RS1, RS2, SE‐S1, and SE‐S2 samples collected. The N:P ratio increased significantly after treatment, from an average of 6.9:1 in RS1 to 11.1:1 in SE‐S1 and 11.9:1 in SE‐S2. Reductions of 4.4% for SDW, 16.2% for SS, 8.4% for TSS, 11.4% for COD, 1.2% for N, and 8.8% for P were found in RS2 relative to RS1, although these reductions were not statistically different (P >0.05). Significant concentration reductions were consistently generated for COD, SDW, SS, TSS, N, and P in SE‐S1 and SE‐S2 relative to RS1, using the GSR separator in tandem with either System 1 or System 2. System 2 showed significantly higher reductions in SDW (52.8% vs. 46.3%) and SS (97.8% vs. 84.9%) when compared to System 1, although practically speaking, these differences are only important if the goal is to meet water quality discharge limits. Significant reductions were found in SDW and SS in SE‐S1 and SE‐S2 relative to RS2, but no significant differences were found between the reductions in SE‐S1 and SE‐S2 relative to each other. No significant reductions were generated for any parameters using only the GSR separator to produce RS2 from RS1. Reductions were calculated using the average concentrations of each sample type:

$$\left(\frac{\text{avg of sample} 1 - \text{avg of sample} 2}{\text{avg of sample} 1}\right) \times 100$$ (1)

Biosolids produced by both System 1 and System 2 were significantly higher than RS1, RS2, and SE in percent SDW, and N and P concentration. Biosolids were left for one week to further decant by simple gravity and showed significantly higher SDW, N, P, and a significantly lower N:P ratio than the fresh biosolids. While this is not necessary, it is encouraged because the weight and volume of the material hauled to the composting site is decreased. The high N and moisture content of the BS suggest they are suitable for use as a raw material providing a source of N for aerobic composting when mixed with a high carbon, low N, and low moisture material such as woodchips, tree leaves, or corn stalks (Walker et al., 2008).

Results generated by this study indicate that both of the combination systems were effective in achieving solids separation from raw slurry, in reducing water quality pollutant indicators in the SE, and in improving the N:P ratio in the SE. The N:P ratio of SE more closely approximates the sufficiency range of these two nutrients in the whole corn plant (Voss, 1993). This suggests that either SE‐S1 or SE‐S2 is more suitable for land application as a soil amendment for corn production than RS1 and should minimize the potential for nutrient overload.

For all classes of swine listed in the Livestock Waste Facilities Handbook (USDA, 1985), the N:P ratio of manure

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>% Solids Dry Weight[^b]</th>
<th>Settleable Solids (mg/L)</th>
<th>Total Suspended Solids (mg/L)</th>
<th>pH</th>
<th>COD (mg/L)</th>
<th>Total Nitrogen (ppm)</th>
<th>Total Phosphorus (ppm)</th>
<th>Ammonia (mg/L)</th>
<th>N:P ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1[^c]</td>
<td>0.82 (0.20)</td>
<td>112.3 (56.4)</td>
<td>5621 (2600)</td>
<td>7.28 (0.26)</td>
<td>7710 (8053)</td>
<td>1152 (310)</td>
<td>166.9 (54.8)</td>
<td>712 (176)</td>
<td>6.9:1</td>
</tr>
<tr>
<td>RS2[^d]</td>
<td>0.79 (0.23)</td>
<td>94.1 (59.7)</td>
<td>5148 (2363)</td>
<td>7.35 (0.26)</td>
<td>6829 (5346)</td>
<td>1139 (330)</td>
<td>152.2 (52.6)</td>
<td>730 (147)</td>
<td>7.5:1</td>
</tr>
<tr>
<td>SE‐S1[^e]</td>
<td>0.44 (0.09)[^a]</td>
<td>16.9 (14.5)[^a]</td>
<td>380 (226)</td>
<td>7.62 (0.32)</td>
<td>2799 (1231)</td>
<td>885 (240)</td>
<td>79.7 (27.5)</td>
<td>806 (192)</td>
<td>11.1:1</td>
</tr>
<tr>
<td>SE‐S2[^f]</td>
<td>0.39 (0.08)[^a]</td>
<td>2.5 (3.0)[^a]</td>
<td>353 (189)</td>
<td>7.66 (0.29)</td>
<td>2555 (988)</td>
<td>786 (210)</td>
<td>66.0 (25.9)</td>
<td>746 (183)</td>
<td>11.9:1</td>
</tr>
<tr>
<td>BS‐S[^g]</td>
<td>0.73 (1.58) c</td>
<td>3512 (1430) b</td>
<td>1673 (666) b</td>
<td>7.68 (0.27)</td>
<td>5312 (1430)</td>
<td>1673 (666) b</td>
<td>7.68 (0.27)</td>
<td>2.5:1</td>
<td></td>
</tr>
<tr>
<td>BS‐S2[^h]</td>
<td>0.76 (1.69) c</td>
<td>4863 (1770) b</td>
<td>1766 (694) b</td>
<td>7.68 (0.27)</td>
<td>5312 (1430)</td>
<td>1673 (666) b</td>
<td>7.68 (0.27)</td>
<td>2.5:1</td>
<td></td>
</tr>
</tbody>
</table>

[^b] a,b,c,d Means within a column with different superscripts differ (p < 0.05).
[^c] Unprocessed raw slurry.
[^e] Biosolids from System 1, continuous gravity belt thickener.
[^f] Separated effluent after System 2, inclined stationary gravity screen separator equipped with backwash spraybar.
[^g] Biosolids 1 week old subsequent to spontaneous decanting in decanting basin.
[^h] Biosolids from System 2, inclined stationary gravity screen separator equipped with backwash spraybar.
produced per day can be calculated from the listed N and P₂O₅ equivalents. The calculated mean N:P ratio is 3.1:1 and ranges from 2.9:1 for growing pigs to 3.4:1 for finishing pigs. The Soil Fertility Manual (Potash & Phosphate Institute, 1999) reports the N and P requirements per bushel of shelled corn produced as 603.82 and 99.88 g (1.33 and 0.22 lb), respectively. These requirements equate to a N:P ratio of 11.6:1. Removing more P relative to N from liquid swine manure plant compositions correspond to a N:P ratio of 11.6:1.

N and P are 2.9% and 0.25%, respectively. These percent requirements for corn growth without concomitant increases in N:P. The Illinois Agronomy Handbook (Hoeft and Peck, 2002) suggests that the critical corn plant nutrient levels for N and P are 2.9% and 96.1% for P in this study, respectively. These requirements equate to a 6.04:1 ratio of N:P. The calculated mean N:P ratio is 3.1:1 and ranges from 2.9:1 for growing pigs to 3.4:1 for finishing pigs. The separation efficiencies of this study are comparable to those found in previous studies (Sievers, et al, 1994; Zhang and Westerman, 1997; Zhang and Lei, 1998; Vanotti and Hunt, 1999; Vanotti et al., 2002; Walker and Kelley, 2003 and 2005; Szogi and Vanotti, 2007). It is important to note that pollutant concentrations in the RS1 generated in this study are lower than raw slurry analyses in similar studies due to the recharging of swine building pits with SE subsequent to each separation and to maintaining relatively fresh RS1. Recharging pits with SE reduces solid build up in the pits over time and generates a more diluted, cleaner raw slurry stream. While treatment by the GSR separator alone did not produce statistically significant reductions in solids and pollutant indicators, this step was critical to the process because the solids composition of the raw slurry (RS1) became more uniform as RS2 and, therefore, the amount of polymer required was more easily regulated, resulting in more effective and efficient separation.

The itemized costs of separation (including equipment and building depreciation, labor, polymer, and fuel) are shown in table 2. For System 1 the cost was 0.474¢/L (1.79¢/gal) of raw slurry. The cost of separation for System 2 was 0.402¢/L (1.518¢/gal) of raw slurry. Application costs for irrigating the separated effluent generated from either system via center pivot irrigation are shown in table 3 and added another 0.061¢/L (0.234¢/gal) of raw slurry. Costs are approximately 6.0% higher for SE than RS because the collection rate for SE was 94% the amount of RS processed. Table 4 shows the total cost for separation of RS and land application via center pivot irrigation of SE based on (liters) gallons of RS processed for each system and is compared to the actual cost for land applying raw slurry via direct injection with either a drag line system or a portable slurry tank system. The cost for separating RS and land applying the resulting SE via center pivot irrigation is within the reported cost range of land applying RS via direct injection for the volume of RS separated in this study (Walker, 2008). Based on the survey of Illinois Commercial Manure Haulers and Applicators (Walker, 2008), the average price to land apply swine slurry was 0.53e/L (2.01e/gal) for up to 3,785,300 L (1 million gal) and 0.44e/L (1.67e/gal) when applying between 3,785,300 and 15,141,200 L (1 and 4 million gal). If land applying more than 15,141,200 L (4 million gal), the cost was 0.235¢/L (0.89¢/gal). The time required to separate the 7,222,725 L (1,908,048 gal) in this study was one to two days per week utilizing 8-h days. Neither of the two separation systems evaluated in this study required continuous monitoring by a monitor; therefore, under normal production scale operating conditions, an operator could separate slurry and conduct other duties simultaneously, such as feeding, proving pig care, etc. A decision for several producers, since separation and land application of SE is cost neutral to traditional land application then, is whether the environmental advantages and reduced acreage required for land application recognized for separation justifies separation as a weekly operational strategy compared to traditional land application of RS once or twice per year. Future EPA regulations regarding P application rates and odor assessments along with producing desire to adopt environmentally beneficial technologies will impact producer decisions.

**CONCLUSION**

The adaptation of waste treatment technology consisting of an inclined stationary gravity screen rollpress combination separator in tandem with a polyacrylamide assisted continuous gravity belt thickener or with a polyacrylamide assisted inclined stationary gravity screen separator with backwash spraybar was used to effectively separate liquid swine manure into its biosolid and liquid fractions while improving N:P ratios and reducing water quality pollutant indicators in the separated effluent. This systems approach results in economically beneficial product development by allowing

<table>
<thead>
<tr>
<th>Item</th>
<th>Separated Effluent System 1</th>
<th>Separated Effluent System 2</th>
<th>Raw Slurry System 1</th>
<th>Raw Slurry System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor[b]</td>
<td>0.088 (0.333)</td>
<td>0.088 (0.333)</td>
<td>0.083 (0.313)</td>
<td>0.083 (0.313)</td>
</tr>
<tr>
<td>Polymer[c]</td>
<td>0.038 (0.144)</td>
<td>0.038 (0.144)</td>
<td>0.036 (0.135)</td>
<td>0.036 (0.135)</td>
</tr>
<tr>
<td>Electricity[d]</td>
<td>0.133 (0.503)</td>
<td>0.104 (0.394)</td>
<td>0.125 (0.473)</td>
<td>0.098 (0.370)</td>
</tr>
<tr>
<td>Depreciation[e]</td>
<td>0.244 (0.926)</td>
<td>0.197 (0.745)</td>
<td>0.230 (0.870)</td>
<td>0.185 (0.700)</td>
</tr>
<tr>
<td>Total</td>
<td>0.503 (1.906)</td>
<td>0.427 (1.616)</td>
<td>0.474 (1.791)</td>
<td>0.402 (1.518)</td>
</tr>
</tbody>
</table>

[a] Costs reflect 2008 prices.
[b] $15/h.
[c] $2.45/lb.
[d] 7.95¢/kwh.
[e] Based on initial equipment and building cost of $173,000 for the continuous gravity belt thickener and $140,000 for the inclined stationary gravity screen and using a straight-line10-year depreciation schedule.
the biosolids fraction to be composted for ultimate use as either an on-farm or off-farm soil amendment while also producing a liquid fraction with low solids and low phosphorus concentrations that can be irrigated as a nitrogen fertilizer for row crops. The use of these post treatment end products instead of raw slurry for field application reduces the potential for nutrient overload and potential surface and groundwater pollution; and reduces the amount of land required for disposal. Additionally, either of these systems is an economically viable process for producers with total separation costs, including equipment, labor, polymer and fuel, of 0.474e/L (1.791¢/gal) or of 0.402e/L (1.518¢/gal) of raw slurry, for the gravity belt thickener and gravity screen separator, respectively. Considering the lower cost, the slightly higher pollutant reductions, and the ease of operation, the gravity screen system was shown to be a marginally more desirable option for solid liquid separation.

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