SOLID-LIQUID SEPARATION OF SWINE MANURE WITH POLYMER TREATMENT AND SAND FILTRATION

M. B. Vanotti, J. M. Rice, A. Q. Ellison, P. G. Hunt, F. J. Humenik, C. L. Baird

ABSTRACT. *Small particles typical of liquid swine manure often clog sand filter beds and fine filters. We evaluated the effectiveness of polymer flocculants to improve drainage and filtration performance of sand filter beds by increasing the particle size of manure. A pilot separation unit was evaluated at the Swine Unit of the NCSU Lake Wheeler Road Laboratory in Raleigh, North Carolina, in 40 consecutive cycles during a 20-month period. The unit consisted of a homogenization tank that mixed the flushed swine manure, an in-line polymer mixer, and two sand filter beds (29.7 m^2) designed to receive 30.5 cm (1 ft) depth of the polymer-treated effluent. Flocculation treatment using polyacrylamide (PAM) polymer improved drainage characteristics of the sand filter by preventing clogging and surface sealing. The combination of flocculation and filtration treatment removed 97% of total suspended solids (TSS) and volatile suspended solids (VSS), 85% of biochemical oxygen demand (BOD_5), and 83% of chemical oxygen demand (COD) from the flushed manure. Along with the solids, treatment resulted in capture of 61% total Kjeldahl nitrogen (TKN) and 72% total phosphorus (TP). Most of the nutrients removed in the solids were organic forms. Drying time to produce removable cakes varied significantly with the loading rate of solids applied to the sand filter bed. A load of <2 kg TSS m^{-2} per drying cycle allowed completion of the drying cycle in about 8 days, which is desirable to reduce potential fly problems. Our results indicate that PAM flocculation enhances performance of dewatering sand filter beds for swine manure applications.*

Keywords. *Animal waste, Flocculation, Liquid-solids separation, Manure treatment, Nutrient removal, Phosphorus, Polyacrylamide, Swine wastewater.*

Organic polymers such as polyacrylamide (PAM) are useful to increase separation of suspended solids and carbon compounds from liquid swine manure (Vanotti and Hunt, 1999; Zhang and Lei, 1998). Along with the solids, there is a significant separation of organic nutrient elements contained in small suspended particles typical of these wastes. Vanotti et al. (2002) showed that 80.4% of the total suspended solids (TSS), 78% of the nitrogen (N), and 93% of the phosphorus (P) fractions in flushed swine manure that are potentially removable by phase separation were contained in particles less than 0.3 mm in size.

Polyacrylamides are moderate to high molecular weight, long-chained, water-soluble organic polymers. The long polymer molecules destabilize suspended, charged particles by adsorbing onto them and building bridges between several suspended particles. With flocculation, the effective particle size is increased by agglomeration of small particles into a larger particle, or floc, that separates from the liquid and dewaters more readily. This larger size can significantly enhance manure solids retention by screens and separation of colloidal particles by settling (Vanotti and Hunt, 1999; Vanotti et al., 2002). Polyacrylamides have varied characteristics, such as molecular weight and charge type (+, 0, −), density distribution of charge (0% to 100%), chain structure, and comonomer, that provide them with a variety of chemical performance characteristics and uses. For example, PAM is extensively used as a settling agent for food processing and packing, paper production, and mine and municipal wastewater treatment, as a clarifier for sugar extraction and potable water treatment, and as a soil conditioner to reduce irrigation water erosion (Barvenik, 1994). Thus, PAM is widely available and relatively economical for several applications.

Sand drying beds are the most widely used method for solid-liquid separation of municipal digested sludge in the U.S., especially in small- and medium-sized communities (Tchobanoglous and Burton, 1991). Their advantages include lower cost, infrequent operator attention, and high solids content of the dried product. Thus, this technology could be attractive to livestock producers looking for effective, passive separation treatment systems for liquid manure. However, the use of filtering media having a small pore opening for dewatering of swine manure has been a problem in the past due to rapid clogging and sealing with the fine particles typical of these wastes. We thought that these problems could be solved if flocculation technology were

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combined with dewatering sand filter beds for enhanced solid-liquid separation treatment of animal wastewater.

In this study, we evaluated whether the use of PAM flocculants could improve the drainage characteristics of dewatering sand filter beds by increasing the effective particle size and preventing clogging with repeated applications. In addition, we established optimum polymer addition rates, determined solids and nutrient removal efficiencies, and determined the drying time of solid cakes as affected by manure loading rates. The study was done at pilot scale.

MATERIALS AND METHODS

PILOT TREATMENT UNIT

Enhanced polymer separation of solids and nutrients from flushed swine manure was evaluated in a field prototype constructed at the Swine Unit of North Carolina State University's Lake Wheeler Road Field Laboratory in Raleigh, North Carolina. This farm is designed and operated as a research and teaching facility. The Swine Unit contains several swine houses that use under-slat flushing and an anaerobic lagoon for treatment and storage of the flushed manure. The houses were flushed with lagoon supernatant. The lagoon liquid characteristics were, on average (20-month data, $n = 40$), pH = 7.62 ±0.49, total solids (TS) = 1411 ±491 mg L^{-1}, total suspended solids (TSS) = 376 ±155 mg L^{-1}, chemical oxygen demand (COD) = 771 ±354 mg L^{-1}, 5-day biochemical oxygen demand (BOD_5) = 115 ±84 mg L^{-1}, total Kjeldahl N (TKN) = 176 ±86 mg L^{-1}, ammonia-N (NH_3-N) = 114 ±45 mg L^{-1}, nitrate-N (NO_3-N) = 3 ±14 mg L^{-1}, total phosphorus (TP) = 64 ±32 mg L^{-1}, and orthophosphate-P (o-PO_4) = 22 ±12 mg L^{-1}.

The prototype unit consisted of: (1) a homogenization tank that received and mixed the flushed manure, (2) an in-line polyacrylamide (PAM) injector and mixer to flocculate the manure solids in the flush, and (3) two identical 4.88 × 6.10 m (16 × 20 ft) sand filter beds for dewatering (29.7 m^2 bed^{-1}). Both the in-line PAM injector and filter beds were components of the Deskins process (F.D. Deskins Company, Inc., Alexandria, Ind.) used for municipal and industrial sludge dewatering (fig. 1).

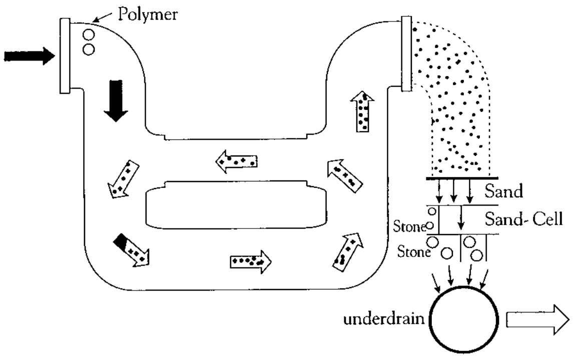

Figure 1. Diagram showing solids separation process using PAM and sand filtration as used in the pilot study (not to scale). Polymer was injected and mixed with liquid swine manure using an in-line static flocculator that used internal baffles to create turbulence and mixing. The flocculated liquid was then poured into a sand filter bed with gravel substratum and an underdrain system.

The filter beds were completely sealed with plastic liners and constructed with several layers of media starting with a 45 cm layer of washed stone (1.9 cm size), then a 15 cm middle layer of PVC media cells filled with pea gravel (0.95 cm size), and finished with 15 cm of coarse sand (0.5 mm size) on top. The PVC media provides surface and subsurface bed stabilization by eliminating compaction of the sand by the machinery used to retrieve the solids in commercial units. However, this feature was not fully tested in the pilot unit because the dry solids were harvested manually using shovels and rakes.

An underdrain system consisting of a sloping bottom and PVC drains directed the filtrate to a sump in the corner of each bed. A submersible pump (1.1 kW, 5.08 cm discharge size) emptied the liquid at the conclusion of each pour. The filtrate was collected in a 15 m^3 storage tank and further used to evaluate a nitrification-denitrification process unit (Vanotti et al., 2001). A total of 40 cycles (runs) was conducted during a 20-month evaluation period. Precipitation, atmospheric temperature, and relative humidity conditions are listed in table 1.

POLYMER SELECTION

The polymer used was a commercially available emulsion formulation of PAM with 34% active ingredient (Magnifloc c-1596, Cytec Industries, Inc., West Paterson, N.J.). This polymer is a moderately charged (40 mole % charge density), high-molecular weight (5×10^6 g $mole^{-1}$), cationic PAM. This polymer was selected after preliminary laboratory tests of six commercially available cationic PAMs with varying charge density (4, 7, 13, 20, 40, and 70 mole %) using flushed manure from the same farm and laboratory filtration columns filled with 15 cm of coarse sand (0.5 mm size). Results of these bench tests indicated that both 20% and 40% charge type polymers were better than the others for removing TSS, but we selected the 40% charge polymer because it produced larger flocs and the liquid drained faster through the sand columns.

Table 1. Precipitation, atmospheric temperature, and relative humidity conditions during the study.[a]

	Total Precipitation (mm)		Average Temperature (°C)		Average Relative Humidity (%)	
Month	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
April	86	69	15.4	16.3	79	74
May	19	65	21.6	20.0	76	81
June	174	265	24.9	24.0	--	87
July	121	257	24.5	24.4	92	--
Aug.	140	107	24.5	25.3	90	--
Sept.	257	40	21.2	20.6	93	75
Oct.	0	56	16.5	15.5	73	68
Nov.	67	25	9.3	14.1	78	69
Dec.	34	54	2.6	9.6	69	68
Jan.	36	156	5.4	7.3	66	71
Feb.	60	37	9.3	8.3	76	56
March	167	78	9.7	12.3	69	70
Yearly sum or average	1162	1208	15.4	16.5	78.4	68.1

[a] Lake Wheeler Road Field Laboratory Weather Station, Raleigh, N.C. Data compiled by State Climate Office of North Carolina, CRONOS Database. Annual normals (30 year) for Raleigh are: precipitation = 1181 mm, temperature = 16.0°C, and relative humidity = 70%.

SETUP AND OPERATION

Flushed manure from finishing and gestation houses in the facility was diverted into a 15 m^3 (4,000 gal) glass-lined influent mixing tank. Concentration of TSS in the flushes at the beginning of the study (cycles 1 to 6) was very low (<1 g L^{-1}) due to the frequent flushing schedule used at the university farm. After cycle 6, the flushes were held for 24 to 48 h before each cycle. This change in flushing management increased the accumulation of manure in the houses and provided wastewater for testing with characteristic concentrations that were more representative of manure flushes encountered in commercial swine operations. This protocol was later adopted by the USEPA Environmental Technology Verification Program (ETV) for evaluation of swine waste solids separators at the same site (ETV, 2002).

The liquid manure was thoroughly mixed in the homogenization tank at 84 rpm, using a 3.7 kW mixer (Lightnin Series 10, model 1401, Lightnin Co., Rochester, N.Y.) fitted with three impeller blades (61 cm size). The mixer was designed to keep solids suspended with minimum turbulence, so aeration and physical changes to the manure were minimized. Homogenized manure was transferred into the separation unit using a trash pump (5.2 kW, 7.62 cm size). Rubber hoses of 10.2 cm size (4 in.) were used to move the wastewater from the homogenization tank to the injection unit (80 m) and then from the injection unit to the sand beds (20 m). A manifold near each bed divided the flow in two 10.2 cm (4 in.) polyvinyl hoses that were placed on the sand along the bed. A doppler flowmeter and manual valve were used to monitor and adjust wastewater flow to the desired level.

The polymer feed system (PolyBlend M series, USFilter Stranco Products, Bradley, Ill.) consisted of a chemical feed pump (0 to 0.6 L min^{-1}) that pulled the emulsion polymer up and pumped it into a mixing chamber, where it was mixed with dilution water and further injected in the in-line static flocculator (fig. 2). Fresh water, at a rate of 30 to 42 L min^{-1} (8 to 11 gpm), was used to dilute and activate the polymer before injection. Immediately after the injection of polymer into the flocculation unit started, the mixed raw waste was pumped into the flocculation unit using a flow rate of 490 L min^{-1} (130 gpm). The flocculated manure was discharged onto the bed through 16 holes cut 30.5 cm apart on the upper side of the polyvinyl hoses. The last eight holes had a larger size (3.2 cm diameter) than those closer to the manifold (2.5 cm diameter) to provide an even distribution of liquid throughout the sand bed. The wastewater flow rate and the number of manifolds used were selected after initial tests conducted during runs 1 to 4 using one, two, or four manifolds per filter bed and wastewater flow rates that varied from 380 to 760 L min^{-1} (100 to 200 gpm), which is the flow range recommended by the manufacturer. Results of these initial tests showed that 490 L min^{-1} flow and two polyvinyl hoses per bed provided satisfactory flow and minimized liquid disturbance of the sand surface in this pilot experiment.

The pilot experiment was conducted so as to obtain optimum flocculation of the liquid swine manure before pouring it onto the sand filter bed. To achieve this goal, jar tests were conducted *in situ* before starting each run to determine the initial polymer dosage used to setup the polymer injection pump. The jar tests consisted of adding and mixing 1 mL increments of 1% polymer stock into two clear 1 L Imhoff vessels containing samples collected from the homogenization tank until additional application in one of the vessels did not increase flocculation or reduce transparency of the background liquid by visual observation. Mixing in these 1 L vessels was done manually by stirring added polymer and manure for 30 s using a metal rod. Final polymer dosage settings of the injection pump were established when the flocculated liquid started pouring on the bed. At that moment, flocculated liquid samples were collected through a diversion valve located near the distribution manifold, and the polymer application rate was further adjusted so that the liquid clarity and floc appearance in these samples was similar to results obtained in the jar tests.

The beds received approximately 34.5 cm depth of flocculated liquid during each pour (average 10,300 L volume). Once the pour was finished, the submersible pump

Figure 2. The in-line PAM injector and mixer used in the pilot study to flocculate the solids in the flushed manure. A polymer feed system (foreground) was used to dilute and prepare the polymer before injection into the in-line static mixer (background), where diluted polymer was mixed with the flushed manure.

in the sump was activated to empty the liquid from the filter bed. The filter bed was usually drained at the same rate as the submersible pump (760 L min^{-1} or 200 gpm). The solids were left to dry on the bed until they were sufficiently dry to be removed using shovels. Solids samples were taken frequently during this drying period to measure moisture content and drying characteristics at various manure loading rates applied during the evaluation period. Total volume applied in each pour was calculated from the depth of the liquid in the homogenization tank at the beginning and end of a run. The polymer container was weighed before and after each run to measure the actual amount of polymer used for separation.

Analytical Methods

Liquid grab samples were taken at the beginning, middle, and end of each run from both the homogenization tank and the sand filter effluent. Each sample was analyzed separately.

Solids analyses of the treated and untreated liquid samples included total solids (TS), total suspended solids (TSS), and volatile suspended solids (VSS). Total solids are the solids remaining after evaporation of a sample to constant weight at 105°C and include TSS and dissolved solids (DS). Total suspended solids (TSS) are the solids portion retained on a glass microfiber filter (Whatman grade 934-AH, Whatman Inc., Clifton, N.J.) after filtration and drying to constant weight at 105°C, while volatile suspended solids (VSS) are the fraction of the TSS that is lost on ignition in a muffle furnace at 500°C for 15 min. Therefore, the TSS and VSS are measurements of the insoluble total and volatile solids that are removable by separation. The soluble fraction or dissolved solids can be determined by subtracting the TSS from the TS.

Chemical analyses consisted of pH, chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), ammonia-N (NH_3-N), nitrate-N (NO_3-N), total Kjeldahl N (TKN), orthophosphate-P (*o*-PO_4), and total P (TP). All the analyses were done according to Standard Methods (APHA, 1998). For COD, we used the closed reflux, colorimetric method (Standard Method 5220 D). The inorganic *o*-PO_4 fraction, also termed reactive P, was determined by the automated ascorbic acid method (Standard Method 4500-P F) after filtration through a 0.45 micron membrane filter (Gelman type Supor-450, Pall Corp., Ann Arbor, Mich.). The same filtrate was used to measure NH_3-N by the automated phenate method (Standard Method 4500-NH_3 G) and NO_3-N by the automated cadmium reduction method (Standard Method 4500-NO_3^- F). Total P and TKN were determined using the ascorbic acid method and the phenate method, respectively, adapted to digested extracts (Technicon, 1977). Organic P fraction is the difference between total P and *o*-PO_4 analyses and includes condensed and organically bound phosphates. Organic N fraction is the difference between Kjeldahl N and ammonia-N determinations.

Solids samples were collected periodically during each drying cycle to assess cake moisture content. Solid samples were comprised of five subsamples (1.9 L volume) collected throughout the bed over the entire thickness of the cake. Composite samples were analyzed for moisture content using a microwave moisture analyzer. The last sample collected in a drying cycle was dried at 45°C in a forced-air chamber and analyzed for TKN and TP using the acid block digestion procedure of Gallaher et al. (1976) and the automated methods described before. Carbon content was also determined using dry combustion analysis.

Treatment performance was determined by the difference between the solids, nutrient, and BOD concentrations in the filtrate and those in the initial sample before PAM application and sand filtration. Loading rates were calculated from suspended solids retained and volume of wastewater applied.

Results and Discussion

Separation of Solids and BOD

Total solids strength of the flushes varied greatly during the evaluation period, from 2.6 to 18.9 g L^{-1}. Solids strength was very low (<2.6 g L^{-1}) during the first six cycles due to the frequent flushing schedule used in the Swine Unit facilities. Starting with cycle 7, the flushes were held for 1 to 2 days before a run. This change effectively increased the solids strength of the liquid manure to a range of values consistent with values of 5 to 20 g L^{-1} (0.5% to 2.0%) described for commercial flushing systems in the U.S. (Chastain et al., 1999). The suspended solids concentration before treatment also varied greatly, from 1 to 17.5 g L^{-1} (0.1% to 1.75%) for TSS, and from 0.9 to 14.0 g L^{-1} (0.09% to 1.4%) for VSS. On the average, 84% of the TS were suspended and removable by liquid-solids separation, and 16% were dissolved solids (DS) and not amenable to separation. Most (81%) of the TSS were volatile solids (VSS). High separation efficiencies (97%) were consistently obtained for both TSS and VSS (table 2). Separation efficiency of TSS in individual runs ranged from 93.3% to 99.2%, with a standard deviation of 1.5%. Similarly, separation efficiency of VSS ranged from 94.8% to 99.1%, with a standard deviation of 1.3%. The TSS concentration in the effluent was uniformly low in spite of the large variation in solids strength among cycles (fig. 3a). Separation efficiencies obtained using flocculation and sand filtration in this pilot-scale experiment were higher than efficiencies of 92% to 96% previously reported using flocculation and screening (1 mm opening size) in bench studies (Vanotti and Hunt, 1999; Vanotti et al., 2002).

Flocculation improved drainage characteristics of the sand filter and prevented clogging and surface sealing. This was demonstrated with repeated applications in the study; the filter bed was usually drained at the same rate as the pump used to drain the bed (760 L min^{-1} or 200 gpm), and this performance was maintained during the 20-month evaluation

Table 2. Enhanced separation of solids and oxygen-demanding substances from flushed swine manure using polymer flocculation and separation with sand filter bed.[a]

Wastewater Parameter	Flushed Manure[b] (mg L^{-1})	Treated Effluent (mg L^{-1})	Separation Efficiency[c] (%)
TS	8340 ±4170	1690 ±440	76.3 ±8.6
TSS	6990 ±4120	160 ±80	97.3 ±1.5
VSS	5660 ±3330	130 ±60	97.3 ±1.3
BOD_5	2880 ±1930	390 ±270	84.5 ±8.0
COD	8130 ±4130	1230 ±470	83.0 ±5.9

[a] Means ±SD of 34 trials (cycle 7 - 40): TS = total solids, TSS = total suspended solids, VSS = volatile suspended solids, BOD_5 = 5-day biochemical oxygen demand, COD = chemical oxygen demand.

[b] Range of flushed manure concentrations in the study: TS = 2603 to 18,857 mg L^{-1}, TSS = 1045 to 17,477 mg L^{-1}, VSS = 912 to 13,983 mg L^{-1}, BOD = 595 to 8,591 mg L^{-1}, COD = 2347 to 16,590 mg L^{-1}.

[c] Means ±SD efficiencies of individual trials.

period. The following experience illustrates the potential problem of using sand filter beds with untreated liquid swine manure: The polymer injection was not activated when raw manure was pumped into the flocculation unit during the first 5 min of the pour in run 5. This resulted in application of about 2500 L of untreated waste to the sand filter. Even though polymer injection was subsequently activated and treated liquid manure was applied during the remainder of the pour (about 7700 L), the untreated manure that was initially applied rapidly sealed and clogged the sand filter. Clogging was evident by very slow drainage and standing water on the beds 24 h after the pour was completed. This compares to the quick drainage (<2 h) obtained when polymer was used to treat the raw manure in all other runs. Thus, using sand filter beds as a method for manure dewatering requires coalescence of the fine solids to prevent system failure. Our results indicate that PAM polymers are useful additives to improve drainage function of sand filter beds for swine manure applications.

Two indicators of oxygen-demanding substances present in wastewater were evaluated: BOD_5 and COD. The BOD_5 test measures the oxygen utilized during a 5-day incubation period for biochemical degradation of organic material and oxidation of inorganic materials (APHA, 1998), while COD is used as a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. Averaged across cycles, the polymer treatment and sand filtration reduced 85% of the BOD_5 concentration (fig. 3b) and 83% of the COD concentration (table 2). Large reduction of COD from the swine effluent prior to it entering anaerobic lagoons is an important factor in reducing odor (Humenik and Overcash, 1976). These results are significant to producers who wish to incorporate biological N oxidation processes for the purpose of ammonia control. By capturing the suspended particles, most of the volatile and oxygen-demanding compounds are removed from the liquid stream. Instead of the oxygen being used to break down organic compounds, it is used in the aeration treatment to more efficiently convert ammonia to nitrite or nitrate (Vanotti et al., 2001).

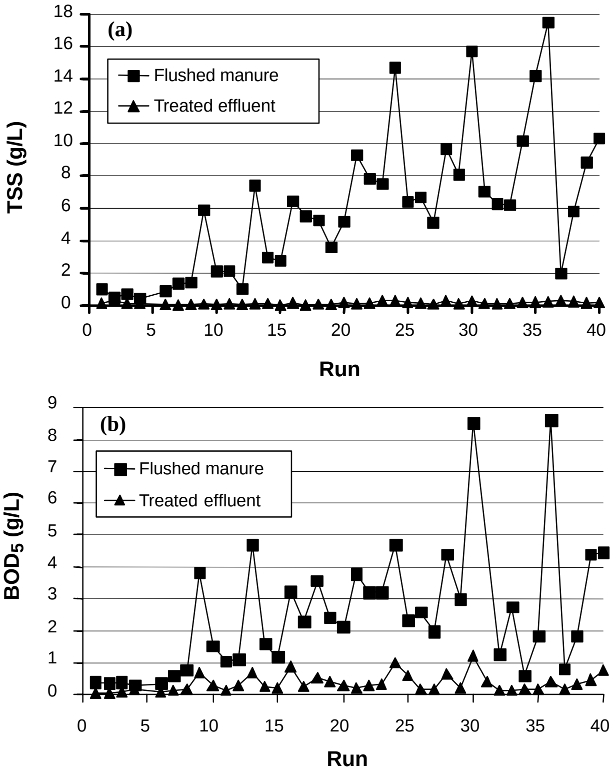

Figure 3. Solid-liquid separation with PAM and sand filtration: (a) total suspended solids, (b) 5-day biochemical oxygen demand.

POLYMER USE EFFICIENCY

Polymer dosage requirement varied with the strength of the wastewater. There was a significant positive correlation (r = 0.77) between polymer need and TSS concentration. A power function [polymer rate (mg PAM L^{-1}) = 67.524 $TSS^{0.3401}$ (g L^{-1}), $R^2 = 0.66$] best described this relationship. The average polymer application in the study was 348 mg L^{-1} of polymer formulation (118 mg PAM a.i. L^{-1}). This amount was 36.9% higher than the optimum rate determined with the jar tests conducted before each run. This higher requirement was not affected by changes in wastewater flow rates in the range tested (380 to 760 L min^{-1} or 100 to 200 gpm), suggesting that changes in polymer mixing equipment or piping could improve performance and reduce chemical needs for separation.

Polymer use efficiency based on solids removal (g TSS removed per g PAM) also increased with wastewater strength (fig. 4). It varied greatly from 6 to 100 with increased TSS concentration in the range of 0.5 to 17.5 g L^{-1} found in the study. These results, obtained at pilot scale, confirm previous conclusions (Vanotti et al., 2002) that polymer-enhanced solid-liquid separation of flushed swine manure is more efficient with higher solids content wastewater.

SEPARATION OF NUTRIENTS

The combination of polymer treatment and sand filtration removed 61% of the TKN and 72% of the total phosphorus (TP) from the liquid manure (table 3 and fig. 5). The organic N fraction comprised 65% of the TKN contained in the flushes, while ammoniacal nitrogen (NH_3) comprised 35% of the TKN. The organic P fraction made up a large proportion (88%) of the TP in the flushes, with the remaining (12%) as soluble phosphate ($o\text{-}PO_4$). Polymer treatment had no significant ($P < 0.05$) effect on reduction of NH_3 and $o\text{-}PO_4$, reflecting the fact that solid-liquid separation *per se* has little effect on the dissolved fraction (Burton, 1997). Nitrate ($NO_3\text{-}N$) was the exception; although the influent manure

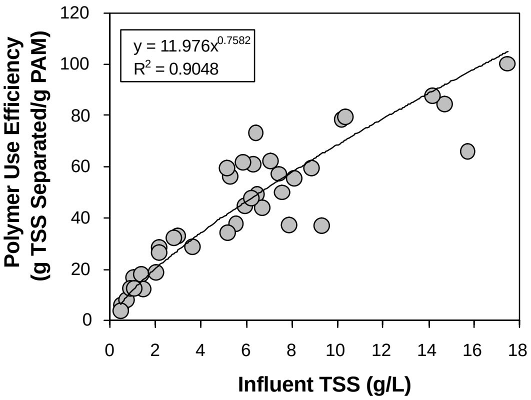

Figure 4. Effect of wastewater strength on polymer use efficiency. Data shown are individual runs shown in figure 3a.

Table 3. Enhanced nutrient separation from flushed swine manure using polymer flocculation and separation with sand filter bed.[a]

Wastewater Parameter	Flushed Manure[b] (mg L^{-1})	Treated Effluent (mg L^{-1})	Separation Efficiency[c] (%)
TKN	592 ±217	217 ±63	61.3 ±8.6
Organic N	386 ±173	41 ±19	88.3 ±4.6
NH$_3$-N	206 ±63	176 ±52	13.8 ±12.3
TP	296 ±183	69 ±33	71.5 ±13.5
Organic P	260 ±184	23 ±34	91.6 ±5.6
o-PO$_4$	35 ±19	46 ±14	−50.3 ±58.7

[a] Means ±SD of 34 trials (cycle 7 - 40): TKN = total Kjeldahl nitrogen, NH$_3$-N = ammonia-N, organic N = TKN − NH$_3$; TP = total phosphorus, *o*-PO$_4$ = orthophosphate-P, organic P = TP − *o*-PO$_4$.

[b] Range of flushed manure concentrations in the study: TKN = 303 to 1143 mg L^{-1}, organic N = 149 to 772 mg L^{-1}, NH$_3$ = 132 to 423 mg L^{-1}, TP = 87 to 1008 mg L^{-1}, organic P = 52 to 969 mg L^{-1}, *o*-PO$_4$ = 17 to 88 mg L^{-1}.

[c] Means ±SD efficiencies of individual trials.

liquid contained only <0.5 mg L^{-1}, its concentration measured in the sand filter effluent increased (9.4 ±13.0 mg L^{-1}). Averaged across runs, NO$_3$-N concentration was highest (19.0 ±24.0 mg L^{-1}) in effluent samples collected at the beginning of the draining operation, and lowest (2.7 ±7.7 mg L^{-1}) in the effluent sampled at the end of the run. This indicates that a nitrification biofilm developed in the sand filter media, and that NO$_3$-N found in the effluent was a residual N that was nitrified during the previous drying cycle and rinsed with the new pour. Alkalinity concentration was 1930 ±480 mg CaCO$_3$ L^{-1} in the untreated wastewater and 1250 ± 290 CaCO$_3$ L^{-1} in the treated effluent. Corresponding pH values were 7.1 ±0.3 and 7.3 ±0.2, respectively.

The separation treatment was very effective in the capture of the organic nutrients in liquid swine manure. Separation efficiencies of 88% and 92% were obtained on the average for organic N and P, respectively (table 3). Removals of organic N and P from the liquid were both highly correlated (r = 0.96) with removal of TSS. This indicates that organic nutrients in the flushed effluent were mostly contained in suspended manure particles, which in turn were efficiently separated from the liquid by flocculation treatment and sand filtration. Averaged across runs, the separated solids contained 5.10% (± 1.10) TKN, 2.57% (± 1.29) TP, 0.17% (±0.08) NH$_3$-N, 0.25% (±0.06) *o*-PO$_4$ (soluble-P), and 37.81% (± 5.28) carbon. Thus, 97% of the nitrogen and 90% of the phosphorus recovered in the separated solids were organic compounds.

DRYING OF THE MANURE SOLIDS

Drainage of the standing liquid was usually completed within 1 to 2 h after pouring. However, the moisture content of the solids at this point was relatively high (70% to 90%), and a drying period was necessary to reduce moisture content to levels where the solids could be harvested. This drying period varied with the loading rate of solids applied to the bed. During the first few cycles when TSS concentration was low (<2 g L^{-1}, fig. 3a), the manure cake was thin and solids dried very quickly, usually in about one day. The drying time was much longer with higher solids strength and thicker cakes, even when the same amount of water was applied. The effect of loading rate on drying time was characterized based on data in figure 6 showing the decrease in solids moisture after initial drainage. Individual cycles were grouped based on loading rates of 0-1, 1-2, 2-3, and >3 kg TSS m^{-2} calculated from TSS retained by the sand bed. An exponentially decaying model fitted to each loading rate category was used to calculate the drying time needed for harvesting the solids (table 4). For the lowest load category (<1 kg TSS m^{-2}), the solids reached 50% and 40% moisture content in 0.8 and 1.0 days, respectively. The same moisture levels were reached in the second load rate (1 to 2 kg TSS m^{-2}) after 4.4 and 7.9 days, respectively. Drying time was extended to about 10 and 17 days for the 2 to 3 kg TSS m^{-2} load rate and to 18 to 33 days for the > 3 kg TSS m^{-2} loads. Loading rates of the sand filter were also calculated yearly to compare with other uses. Using drying cycles of 7.9 days and 4.4 days as the

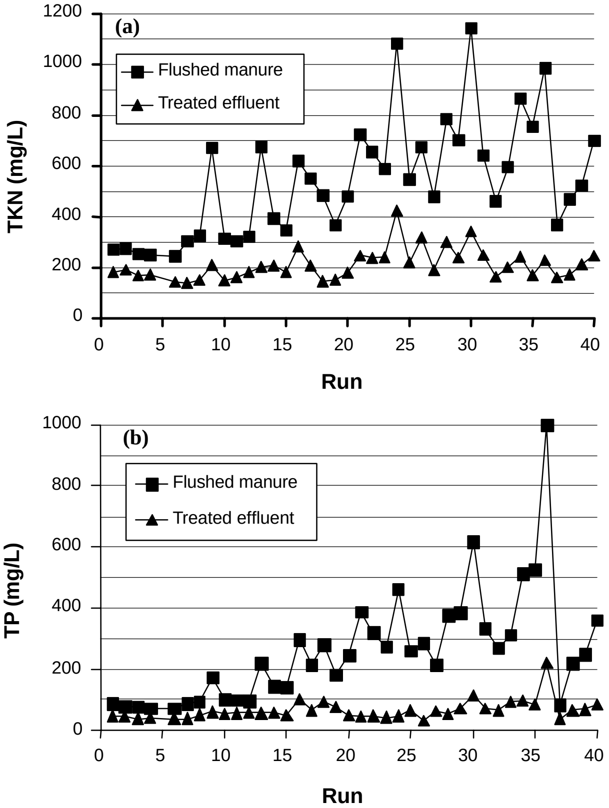

Figure 5. Nutrients removal with PAM and sand filtration: (a) total Kjeldahl nitrogen, and (b) total phosphorus.

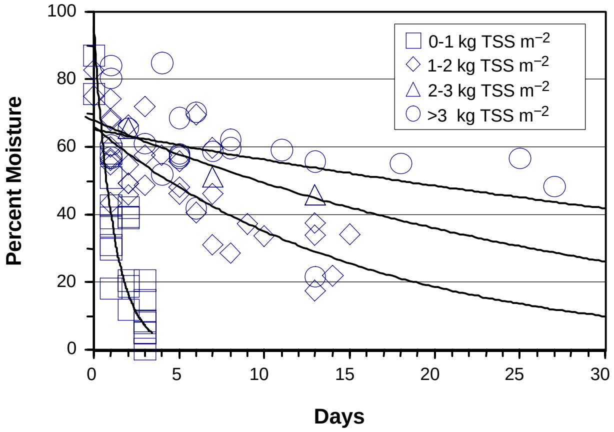

Figure 6. Decrease in moisture content of separated solids as affected by manure loading rates. Regression equations shown in table 4.

Table 4. Effect of loading rate on manure drying time.

Loading Rate (Range)[a] (kg TSS m^{-2})	Average TSS Concentration in Flush[b] (g L^{-1})	Average Liquid Applied (cm)	Loading Rate Average (kg TSS m^{-2})	Drying Time[c] (days)	
				50% MC	40% MC
0-1	1.14 ±0.63	36.6 ±8.6	0.4 ±0.2	0.8	1.0
1-2	4.97 ±1.23	35.0 ±3.8	1.6 ±0.3	4.4	7.9
2-3	7.19 ±1.28	33.6 ±2.3	2.4 ±0.3	9.6	16.6
>3	12.10 ±4.23	34.5 ±2.8	4.3 ±1.3	17.9	33.1

[a] Individual cycles were grouped based on loading rates calculated from TSS retained by the sand filter.

[b] Mean ±SD.

[c] Drying time to reach 50% and 40% moisture content (MC) calculated from data shown in figure 6 and the following regression equations:

Loading rate	Moisture	R^2
0-1 kg TSS m^{-2}	95.51 exp($-$0.8658 days)	0.55
1-2 kg TSS m^{-2}	65.98 exp($-$0.0634 days)	0.63
2-3 kg TSS m^{-2}	67.75 exp($-$0.0318 days)	0.92
>3 kg TSS m^{-2}	65.08 exp($-$0.0147 days)	0.15

basis for comparison, manure loading rates were 92 and 166 kg dry solids m^{-2} year^{-1}, respectively. These values are within the range of municipal uses of 59 to 98 kg dry solids m^{-2} year^{-1} for dewatering waste-activated digested sludge, and 122 to 146 kg dry solids m^{-2} year^{-1} for primary digested sludge (Tchobanoglous and Burton, 1991).

The manure cake usually dried from top to bottom and along cracks formed on the surface. With the higher loads, the area in the cake in contact with the sand remained wet for long periods, making manual harvesting difficult. The longer the manure remains wet on the bed, the higher the potential for odor and fly problems. For example, immature flies live and thrive on moist (moisture content 50% to 85%) manure (Smith and Langman, 2001). During warm weather, house flies can complete their life cycle in as few as 10 to 14 days. To reduce the risk of nuisance and disease transmission caused by flies, a loading rate should be selected to allow the completion of the drying cycle within about 10 days. Therefore, a loading rate <2 kg TSS m^{-2} is suggested based on conditions in this study (tables 1 and 4). For a TSS production rate of 5.05 kg per 1000 kg live pig mass per day (NRCS, 1992), a removal efficiency of 98%, and a drying cycle of 7.9 days (final moisture = 40%), the total surface of sand filter bed needed to treat the waste from a 1000-head finishing operation (22.7 to 100 kg) is 1195 m^2, or 1.20 m^2 pig^{-1}. The corresponding surface area for a drying cycle of 4.4 days (final moisture = 50%) is reduced to 662 m^2, or 0.66 m^2 pig^{-1}. Other considerations beyond the scope of this study, such as a drier climate than North Carolina, the end use of the solids, transport cost, and capacity of machinery to harvest the solids at the higher moisture level, should be considered for selecting target solids moisture for drying bed design purposes. But this study indicates that sand bed size and construction could be an important component of the overall cost of the technology.

CONCLUSIONS

A pilot treatment unit for solid-liquid separation using polymer treatment with an in-line flocculator and sand-bed filtration was evaluated for 20 months at the NCSU Lake Wheeler Road Field Laboratory to determine separation efficiency and function of the bed with repeated applications. With the polymer, the small particles in swine wastewater are agglomerated into larger particles, or flocs. Collectively, our findings indicate:

- Flocculation improved drainage characteristics of the sand filter and prevented clogging and surface sealing with repeated applications.
- Polymer flocculation and sand filtration removed 97% of TSS and VSS, 85% of BOD, and 83% of COD from the flushed swine manure.
- Along with the solids, there was a capture of 61% TKN and 72% TP; most of the nutrients removed in the solids were organic forms.
- Polymer treatment of liquid swine manure is more efficient with higher solids content wastewater.
- The sand filter beds drained quickly, usually within 1 to 2 h after pouring.
- Drying time to produce removable cakes was significantly affected by solids loading rate; a load of 2 kg TSS m^{-2} allowed the completion of the drying cycle in <10 days, reducing potential for fly problems.

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REFERENCES

APHA. 1998. *Standard Methods for the Examination of Water and Wastewater.* 20th ed. Washington, D.C.: American Public Health Association, American Water Works Association, and Water Environment Federation.

Barvenik, F. W. 1994. Polyacrylamide characteristics related to soil applications. *Soil Science* 158(4): 235-243.

Burton, C. H. 1997. *Manure Management: Treatment Strategies for Sustainable Agriculture*. Silsoe, Bedford, U.K.: Silsoe Research Institute.

Chastain, J. P., J. J. Camberato, J. E. Albrecht, and J. Adams. 1999. Swine manure production and nutrient content. In *South Carolina Confined Animal Manure Managers Certification Program*, Chapter 3: 1-17. Clemson, S.C.: Clemson University.

ETV. 2002. Test plan for the verification of technologies for separation of manure solids from flushed swine waste. Environmental Technology Verification Water Quality Protection Center. Ann Arbor, Mich.: U.S. EPA and NSF International.

Gallaher, R. N., C. O. Weldon, and F. C. Boswell. 1976. A semiautomated procedure for total nitrogen in plant and soil samples. *SSSA J.* 40(6): 887-889.

Humenik, F. J., and M. R. Overcash. 1976. Design criteria for swine waste treatment systems. EPA Project No. 600/2-76-233. Washington, D.C.: U.S. EPA.

NRCS. 1992. Table 4-11: Swine waste characterization - As excreted. In *Agricultural Waste Management Field Handbook*, Part 651. Washington, D.C.: USDA Natural Resource Conservation Service (previously SCS).

Smith, G. C., and M. Langman. 2001. Manure management to minimize fly populations on layer farms. Poultry fact sheet. Truro, Nova Scotia, Canada: Nova Scotia Department of Agriculture and Fisheries.

Tchobanoglous, G., and F. L. Burton. 1991. *Wastewater Engineering: Treatment, Disposal, and Reuse.* Boston, Mass.: Irwin/McGraw-Hill.

Technicon. 1977. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests (dializer). Industrial method 337-74W/B. Tarrytown, N.Y.: Technicon Instruments Corp.

Vanotti, M. B., and P. G. Hunt. 1999. Solids and nutrient removal from flushed swine manure using polyacrylamides. *Trans. ASAE* 42(6): 1833-1840.

Vanotti, M. B., J. M. Rice, P. G. Hunt, F. J. Humenik, A. Q. Ellison, C. A. Baird, P. Millner, and A. A. Szogi. 2001. Evaluation of polymer solids separation, nitrification-denitrification, and soluble phosphorus removal system for treating swine manure. In *Proc. Intl. Symposium Addressing Animal Production and Environment*, CD-ROM. Research Triangle Park, N.C.: North Carolina State University.

Vanotti, M. B., D. M. C. Rashash, and P. G. Hunt. 2002. Solid-liquid separation of flushed swine manure with PAM: Effect of wastewater strength. *Trans. ASAE* 45(6): 1959-1969.

Zhang, R. H., and F. Lei. 1998. Chemical treatment of animal manure for solid-liquid separation. *Trans. ASAE* 41(4): 1103-1108.