Solid–Liquid Separation of Flushed Swine Manure with PAM: Effect of Wastewater Strength

M. B. Vanotti, D. M. C. Rashash, P. G. Hunt

Abstract. *Organic polymers are useful to increase separation of suspended solids and reduced carbon compounds from liquid swine manure. Along with the solids, there is a capture of the nutrients associated with small particles typical of these wastes. The combined effect increases the amount of materials available for value–added products, reduces the size of process units necessary to treat the liquid, and provides needed alternatives to land application. In this work, we evaluated the effect of solids strength typical of flushing systems on optimum polymer dose requirement and chemical use efficiency. Seven flush samples of varied strength were obtained two weeks apart during a three–month period in a feeder–to–finish operation (22.7 to 100 kg weight) in Bladen County, North Carolina. Treatments consisted of eight rates (0 to 140 mg L^{-1}) of polyacrylamide (PAM) followed by screening. Manure samples were characterized for solids, nutrients, and oxygen–demanding compounds amenable for separation. Their concentration varied greatly: 0.4% to 2.5% total solids (TS), 0.1% to 1.6% total suspended solids (TSS), 5.9 to 31.3 g L^{-1} chemical oxygen demand (COD), 0.7 to 10.6 g L^{-1} biochemical oxygen demand (BOD_5), 749 to 2442 mg total Kjeldahl (TKN) L^{-1}, and 96 to 585 mg total phosphorus (TP) L^{-1}. About 87% of P and 45% of N were organic forms, and 80% of TSS were volatile (VSS).*

Separation by screening alone was not effective; efficiencies were <20% TSS and VSS, <10% COD and BOD_5, and <15% N and P. Mixing with PAM before screening substantially increased separation; efficiencies using 140 mg L^{-1} rate were 95% TSS and VSS, 69% COD, 59% BOD_5, and 67% carbonaceous BOD_5. Inorganic P and N were not reduced by treatment. However, PAM significantly enhanced removal of both organic P and N (92% and 85%, respectively). For every 100 g of TSS removed, there was a 1.32–g reduction of COD, 3.32–g reduction of organic P, and 7.26–g reduction of organic N. The N:P nutrient ratio was improved from 4.79 to 12.11, resulting in a more balanced effluent for crops. It was more economical to treat flushed manure with the higher strength. Changes in optimum PAM rate were small (70 to 110 mg L^{-1}) and, consequently, polymer usage rate based on solids produced decreased significantly (from 5.34 to 0.75 g PAM/100 g dry solids separated) with increased wastewater strength. Therefore, reduction of total water volume to clean the houses can result in significant savings (about 700%) in total polymer cost. Chemical cost to capture 95% of the suspended solids was estimated to be $1.37 to $1.27 per finished pig for liquid waste containing 2% to 2.5% TS, respectively. Our results indicate that PAM technology can be enhanced for better liquid manure handling systems and associated management of nutrients.

Keywords. *Animal waste, Polymers, Swine wastewater, Solid–liquid separation, Liquid–solids separation, Phosphorus, Manure treatment.*

When properly managed, manure can be used to provide nutrients for crops and to build up soil organic matter. On the other hand, improperly managed manure and byproducts can pose a threat to soil, water, and air quality, and human and animal health. Manure nutrients in excess of the assimilative capacity of land available on farms are an environmental concern often associated with confined livestock production. Although the majority of the manure produced in confined operations is considered collectable, transport of this manure for long distances in a liquid form is not economically feasible. Thus, for farms producing excessive nutrients in liquid form, solid–liquid separation and distribution of solids to nutrient–deficient areas could be a viable alternative. For the U.S. as a whole, in 1997 about 8% of the 1500 million pounds of farm–level excess nitrogen exceeded the assimilative capacity with existing crop acreage at the county level (Kellog et al., 2000). This means that most counties can handle the manure nitrogen generated if the manure is moved within a county. For phosphorus, about 20% of the 929 million pounds of farm–level excess phosphorus exceeded the land assimilative capacity with the 1997 crop acreage at the county level (Kellog et al., 2000), indicating that some of the P needs to be transported longer distances to solve distribution problems of this nutrient.

The basic problem with solid–liquid separation of swine manure is that most of the organic nutrient elements (nitrogen and phosphorus) are contained in fine particles. Zhang and

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The authors are **Matias B. Vanotti,** Soil Scientist, and **Patrick G. Hunt, ASAE Member,** Soil Scientist, USDA–ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, South Carolina; and **Diana M. C. Rashash,** Area Specialized Agent–Environmental Education, North Carolina Cooperative Extension Service, Jacksonville, North Carolina. **Corresponding author:** Matias B. Vanotti, USDA–ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 West Lucas Street, Florence, SC 29501; phone: 843–669–5203, ext. 108; fax: 843–669–6970; e–mail: vanotti@florence.ars.usda.gov.

Westerman (1997) indicated that it is necessary to remove particles smaller than 0.25 mm in order to effectively reduce nutrient and odor–generating compounds contained in liquid manure. Thus, separation of suspended solids from animal wastewater requires chemical treatment to bind together the small particles of solids into larger clumps (Sievers et al., 1994). Organic polymers and inorganic coagulants are both effective (Loehr, 1973; Vanotti and Hunt, 1999). The main advantage of organic polymers is that the amounts needed are about 10 times lower than those of inorganic substances, which minimizes generation of additional solids. Flocs obtained using organic polymers have a higher shear strength, i.e., more inter–particle bridging resulting from stronger elastic bonding. In addition, flocs obtained using inorganic coagulants are not very compressible; therefore, they take up more space on a filter medium and rapidly increase head loss (SNF Floerger, 2000).

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. This action results in newer, larger particles (flocs) that separate from the liquid and dewater more readily (fig. 1). Polymer flocculants have varied characteristics such as molecular weight and charge type (+, O, –), 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, 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.

Vanotti and Hunt (1999) found that cationic PAMs with moderate charge density (20 to 35 mole %) were more effective than polymers with higher charge density for solid–liquid separation of swine manure and that neutral or anionic types were not useful for this application. Total suspended solids (TSS) removal efficiencies obtained were 90% to 94% when polymers were used in combination with a 1–mm screen but only 5% to 14% with the screen alone

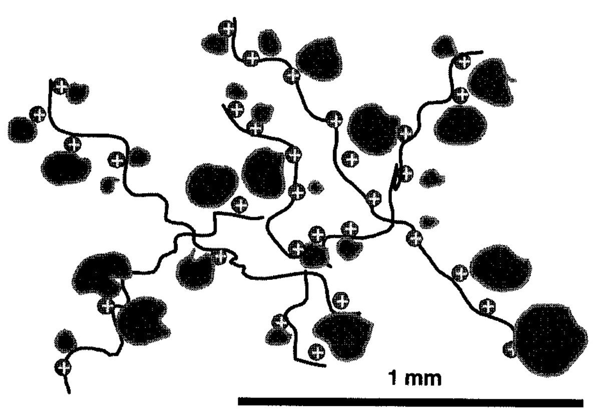

Figure 1. Polyacrylamides are long–chain, water–soluble, polymer molecules that destabilize suspended charged particles by adsorbing them and building bridges among them, resulting in newer, much larger particles (or flocs) that can be readily removed by screens and filters. The diagram illustrates floc formation in swine manure by action of cationic PAM.

(control). Zhang and Lei (1998) also used cationic polymer and screening to flocculate and separate swine manure with 71% to 76% total solids (TS) removal and 77% to 84% volatile solids (VS) removal compared to only 15% and 17% without polymers, respectively. Both studies used fresh water to obtain diluted manure used in the evaluations. However, manure handling systems in confined swine operations generally recycle treated wastewater to clean the houses. Lagoon liquid and treated effluents contain high dissolved solid concentration, high ionic strength, and elevated electrical conductivity, which are parameters known to affect flocculation. Since the proportion of recycle liquid to fresh manure in flushing systems is high, polymer efficiency may be affected. Solids concentration of flushed manure also varies greatly among production facilities that use flushing systems and within growing stages in the same unit.

Our objective was to evaluate the effect of wastewater strength on separation of solids and nutrients from flushed swine manure in a situation where lagoon liquid recycle is used to clean the houses. In this work, we determined polymer use efficiencies in flushed manure of varied strength and established optimum polymer addition rates. Further, we evaluated relationships between solids separation and removable nutrients and oxygen–demanding compounds, and we determined changes in nitrogen to phosphorus ratio of treated wastewater that can result in improved land application strategies.

Materials and Methods

Swine Wastewater Samples

Enhanced polymer separation of solids and nutrients from liquid swine manure was evaluated in laboratory experiments using flushed effluent that was collected during a three–month period from a commercial swine operation located in Bladen County, North Carolina. The operation was a feeder–to–finish operation [growing pigs from 22.7 to 100 kg (50 to 220 lb)] and consisted of four swine houses with concrete slatted floors containing 1200 pigs in each house. An under–slat flushing system typical of many livestock farms in the region was used to remove the manure from the buildings. The flushes were discharged into a single–stage anaerobic lagoon for treatment and storage of the wastewater. The treated liquid was subsequently land applied to nearby grass pastures. The water used for flushing the houses was a 100% recycle of the lagoon liquid supernatant. Each flush cycle was repeated five times per day and utilized 3.0 m^3 (800 gal) of lagoon liquid recycle to remove the waste from one side of each house. The flush was operated in an alternating mode, which provided a total of ten flushes per house each day for a total water usage of 30.3 m^3 (8,000 gal) per day for each 1200–pig building. This flushing schedule provided a fixed rate of 25 L wash water per pig per day, which was maintained throughout the production cycle of the pigs. Thus, the resulting total flush volume to animal weight ratio varied greatly with the size of the pigs from about 1110 L per 1000 kg live mass per day (17.8 ft^3/1,000 lb/day) at the start of the growing cycle when pigs weighed 22.7 kg (50 lb) each to about 250 L per 1000 kg live mass per day (4.1 ft^3/1,000 lb/day) at the end of the cycle when the pigs weighed 100 kg (220 lb) each. Since the amount of manure produced varies with the size of the pigs, the constant flushing schedule

Table 1. Characteristics of flushed swine manure in a North Carolina finishing operation.[a]

Wastewater Parameter	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	P>F	CV (%)
Total solids (g/L)	4.30	5.7	7.65	9.73	11.40	12.57	24.8	0.0001	1.9
Total suspended solids (g/L)	1.47	2.19	4.39	5.33	7.21	7.63	15.84	0.0001	3.8
Volatile suspended solids (g/L)	1.13	1.72	3.84	4.17	5.65	6.35	12.59	0.0001	4.5
Chemical oxygen demand (g/L)	5.88	6.03	5.36	11.01	13.45	14.90	31.31	0.0001	8.1
Biological oxygen demand (g/L)	0.70	1.18	1.80	4.80	3.75	4.53	10.58	0.0001	11.7
Total phosphorus (mg/L)	96	111	144	235	350	367	585	0.0001	7.9
Inorganic phosphorus (mg/L)	25	49	27	21	47	89	72	0.0001	5.7
Organic phosphorus (mg/L)	72	63	117	214	304	278	513	0.0001	9.2
Total Kjeldahl nitrogen (mg/L)	903	855	749	1490	1302	1314	2442	0.0001	6.7
Ammonia–N (mg/L)	552	646	351	903	754	701	1164	0.0001	4.2
Organic–N (mg/L)	350	209	398	587	548	613	1278	0.0001	16.2
pH	7.8	8.1	7.0	8.5	7.9	7.9	8.0	0.0001	2.0
Electrical conductivity (mS/cm)	7.4	8.4	5.1	11.3	9.1	7.8	16.0	0.0001	0.3

[a] Flushes were obtained during a three–month sampling period. Individual pig weight increased from 22.7 kg (50 lb) in run 1 to 100 kg (220 lb) in run 7. Data are average of three replicates.

greatly affected the solids strength of the effluent wastewater during the growing cycle of the pigs (table 1).

A total of eight liquid manure samples was collected approximately two weeks apart during a three–month period to encompass the range of manure solids strength generated during a typical growing cycle; only seven were used. When the experiment started, the pigs weighed approximately 50 kg (110 lb) each. The waste obtained during a 55–day period was used for the first five polymer trials, with the last of these trials corresponding to animals of market size (100 kg or 220 lb). Another sample was obtained in the transition period when houses were about empty, but it was not used for polymer evaluation because strength was very low and similar to the lagoon liquid used to clean the houses. Two more samples were obtained 21 days apart with the new batch of pigs and used for two more polymer trials, representing the initial growth period between 23 kg (50 lb) and 39 kg (85 lb). The sample runs were labeled 1 to 7 following the approximate size of the pigs when samples were taken in the study (50, 85, 110, 140, 165, 190, and 220 lb/pig for runs 1 to 7, respectively).

The liquid manure samples were obtained from a mixing pit that collected the flush from the four houses before it was pumped to a screen solid–liquid separator. Samples were taken at the beginning, middle, and end of a flushing cycle from the second or third flush in the day using a bucket that held 7 L. The samples were combined to create composite samples that were collected in 18.9–L containers. The composite samples were transported on ice to the ARS Florence laboratory and were kept at 4° C to prevent digestion and dissolution of solids and organic nutrients. Polymer treatment experiments were performed the following day, and water quality determinations of treated and untreated liquid manure were initiated within 48 h of sample arrival. Samples of lagoon supernatant liquid used to flush the buildings were taken from the flush tanks prior to starting each of the flushes in the experiment and also analyzed for water quality characteristics.

Polyacrylamide

The polymer used was a commercially available dry formulation of PAM (Magnifloc 234GD, Cytec Industries Inc., West Paterson, N.J.). This polymer is a moderately charged (35 mole % charge density), high–molecular weight (5×10^6 g/mole), cationic powder and is a copolymer of acrylamide and methyl chloride quaternary ammonium salt of dimethylaminoethyl acrylate. The comonomer provides the positive charge, and it is quaternized using methyl chloride to provide a permanent charge independent of pH. The Magnifloc G series products contain low amounts of residual acrylamide monomer and are marketed as flocculants and dewatering aids for food processing waste destined for recycling as animal feed, such as poultry wastes and corn processing wastes. Typical uses are to improve solid–liquid separation and reduce sludge volumes to rendering plants and for replacement of inorganic coagulants in dissolved air flotation processes. When used for these purposes and applied up to the indicated maximum dosage levels, they are considered Generally Recognized As Safe (GRAS) products (Cytec Industries, Inc., 1992; Schechter et al., 1995).

Flocculation Treatments

Flocculation and screening separation procedures were used to study the PAM dosage needs of the flushed wastewater with varied strength. The same procedures were applied to each of the seven composite samples using dry formulations of a cationic polymer. They included eight PAM rate treatments that were applied in increments of 20 mg/L, providing a final dosage range of 0 to 140 mg PAM/L. The exception was run 7 where PAM dosage was increased to 180 mg/L to better characterize the response. Composite samples corresponding to each run were transferred into 25–L vessels and stirred at 150 rpm with a high–torque laboratory mixer with a 7.87 cm (3.1 in.) diameter A–100 impeller (LabMaster SI, Lightnin Co., Rochester, N.Y.) to obtain homogeneous liquid manure subsamples. A peristaltic pump was used to transfer subsamples from the mixing vessel into eight 1–L jars used for the various PAM rate treatments.

After the jars were filled to the 500–mL mark with the well–mixed liquid manure sample, the chemical treatments were added to the wastewater with a syringe using 0.5% primary stocks (WERF, 1993). The stocks were prepared in stirred beakers with distilled water by first turning the bench stirrer (6.0 cm diameter impeller) to maximum speed (approximately 300 rpm), then slowly sprinkling the polymer powder into turbulent regions of the dilution water to accomplish good dispersion and avoid clumps (or fish eyes), and continuing mixing for about 1 h until complete dissolution of the polymer. The polymer solution was set on the bench for 1 h before use for aging and activation. After polymer injection, the samples were mixed with a bench stirrer at 100 rpm for 1 min and then at 40 rpm for about 2 min. The treated samples were passed through a perforated screen with openings of 1.0 mm and collected in beakers. Treatment performance was determined by the difference between the solids, nutrient, and COD concentrations in the effluent passing the screen and those in the initial sample before PAM application and screening. The separation experiments were repeated three times for each of the seven runs.

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) is the fraction of the TSS that was 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, electrical conductivity (EC), chemical oxygen demand (COD), 5–d biochemical oxygen demand (BOD_5), 5–d carbonaceous biochemical oxygen demand ($CBOD_5$), ammonia–N (NH_3–N), total Kjeldahl N (TKN), orthophosphate–P (o–PO_4), and total P (TP). All the analyses were done according to Standard Methods for the Examination of Water and Wastewater (APHA, 1998). For COD, we used the closed reflux, colorimetric method (Standard Method 5220 D). Carbonaceous BOD_5 was determined using the 5–Day BOD test and nitrification inhibition with 2–chloro–6–(trichloro methyl) pyridine (TCMP) (Standard Method 5210 B). 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–μm 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). Total P and TKN were determined using the ascorbic acid method and the phenate method, respectively, adapted to digested extracts (Technicon Instruments Corp., 1977). The organic P fraction is the difference between total P and o–PO_4 analyses and includes condensed and organically bound phosphates. The organic N fraction is the difference between Kjeldahl N and ammonia–N determinations. Nitrate–N was also measured in lagoon and flush samples but was not detected in any of the samples.

Statistical Analysis

Data were subjected to analysis of variance to evaluate PAM treatment rate effects and changes in wastewater characteristics among runs (SAS, 1988). Significant differences among treatment means were evaluated using a least significant difference (LSD) test at the 5% level. Linear and non–linear regression analyses (Draper and Smith, 1981; Freund and Littell, 1991) were used to describe the relationship among measured variables and to quantify the PAM dosage needs with varied wastewater strength.

Results and Discussion

Removable Solids and Nutrients

The solids and nutrient contents of the flushed manure during the various runs are shown in table 1. Manure samples used for run 1 through 7 correspond to flushes obtained periodically throughout the 50 to 220 lb weight range typical of feeder–to–finish production. Total solids (TS) strength of the flushes increased greatly during the production cycle, from 0.4% at the beginning of the cycle to a maximum of 2.5% at the end of the cycle. The range of TS obtained is consistent with values of 0.5% to 2% described for flush systems in the U.S. (Chastain et al., 1999). The total suspended solids fraction also varied significantly (from 0.15% to 1.6%) during the same period. On the average, 58% of the TS were suspended and removable by solid–liquid separation, and 80% of the suspended solids (TSS) were volatile solids (VSS). The TSS concentration was highly correlated with both COD concentration ($r = 0.98$) and BOD_5 concentration ($r = 0.97$). Therefore, removal of these constituents in significant quantities is linked to the successful separation of suspended particles from the liquid manure.

Nutrient concentration in the liquid manure also varied significantly among runs, with the highest TKN and TP concentration at the end of the production cycle (run 7). The soluble reactive P represented, on average, a small fraction (17%) of the total P in the flushes and was not significantly correlated ($p = 0.14$) with either TSS or TS. On the other hand, the organic P fraction made up a large proportion of the TP (87%), and this fraction was significantly ($p = 0.001$) correlated with TSS ($r = 0.98$) and TS ($r = 0.97$). For N, the ammonia fraction in the flushes comprised 55% of the TKN, while the organic N fraction comprised 45% of the total N. Changes in organic N concentration in the manure samples were closely associated ($r = 0.97$) with the variation in TSS. These results indicate that most of the organic N and P in liquid swine manure are contained in particulate solids and amenable to removal by solid–liquid separation.

The lagoon liquid used for flushing the houses contained a high TKN concentration that showed little variation throughout the three–month study (range 618 to 798 mg/L); about 79% of the total N was in the form of ammonia (table 2). The high ammonia in the cleaning water most likely decreased the proportion of organic N to total N in the flushes compared to a system where cleaner recycled water is used. Other soluble compounds were also present in high amounts in the recycle liquid; the average dissolved solids concentration was 2720 mg/L, and electrical conductivity was 6.8 mS/cm (table 2). Previous work on evaluation of PAM separation of liquid swine manure (Vanotti and Hunt, 1999; Zhang and Lei, 1998) used fresh–water flush or tap–water dilutions. The manure samples used in this work were obtained using cleaning water with high dissolved solids and ionic strength representative of flushing systems that use a recycling loop to clean the houses.

Removal of Solids and Nutrients by Screening

Homogenized waste from each run was passed through a 1–mm opening screen, and effectiveness of the screening treatment was determined by the difference between the solids, nutrient, COD, and BOD_5 concentrations in the effluent passing the screen and in the initial sample before screening. Results shown in table 3 indicate that screening

Table 2. Wastewater strength of lagoon liquid used to flush the houses compared to that of flushed manure.[a]

	Lagoon Liquid (1)	Flushed Manure (2)	Ratio (2)/(1)
Total solids (g/L)	3.32 (0.10)	10.89 (2.58)	3.28
Total suspended solids (g/L)	0.60 (0.03)	6.29 (1.82)	10.48
Volatile suspended solids (g/L)	0.46 (0.02)	5.07 (1.44)	11.02
Chemical oxygen demand (g/L)	2.04 (0.23)	12.56 (3.45)	6.16
Biological oxygen demand (g/L)	0.38 (0.09)	3.91 (1.27)	10.29
Total phosphorus (mg/L)	66 (7)	270 (67)	4.09
Inorganic phosphorus (mg/L)	37 (4)	47 (10)	1.27
Organic phosphorus (mg/L)	29 (7)	223 (61)	7.69
Total Kjeldahl nitrogen (mg/L)	673 (28)	1293 (218)	1.92
Ammonia–N (mg/L)	528 (21)	724 (98)	1.37
Organic–N (mg/L)	144 (37)	569 (130)	3.95
pH	8.2 (0.1)	7.9 (0.2)	0.96
Electrical conductivity (mS/cm)	6.8 (0.2)	9.3 (1.3)	0.73

[a] Means (SE) of seven runs. Individual run data for flushed manure are listed in table 1. Strength of lagoon liquid recycle varied little among runs, as shown by smaller SE.

Table 3. Reduction in concentration of suspended solids, COD, BOD_5, and nutrients in flushed swine manure by a screen separator.[a]

	Flushed Manure	After 1–mm Screen	Reduction in Concentration (%)
Total suspended solids (g/L)	6.29	5.33	15.3
Volatile suspended solids (g/L)	5.07	4.21	16.9
Chemical oxygen demand (g/L)	12.56	11.99	4.8
Biological oxygen demand (g/L)	3.91	3.64	6.8
Total phosphorus (mg/L)	270	243	10.0
Organic phosphorus (mg/L)	223	200	10.3
Total Kjeldahl nitrogen (mg/L)	1293	1200	7.2
Organic–N (mg/L)	569	497	12.7

[a] Means of seven runs and three replicates.

treatment *per se* was not effective in removing substantial amounts of suspended solids, oxygen demanding compounds, or nutrients from the flushed manure. Separation efficiencies were consistently low among the various runs. Furthermore, they did not increase over the range of flushwater solids strengths (0.4% to 2.5% TS) observed during this study (data not shown). On average, screening removed less than 20% of the suspended and volatile solids, less than 15% of the N and P, and less than 10% of the COD and BOD_5 (table 3). Hegg et al. (1981) and Holmberg et al. (1983) also reported low separation efficiencies of swine slurries with screens. Hegg et al. (1981) obtained removal efficiencies of 4% for TS and 9% for COD using a rotating screen of a 0.750–mm opening and slurries containing 2.4% TS. The removal efficiency increased to 8% and 16%, respectively, with slurries of about twice the strength (4.12% TS). For vibrating screens and 1.5% to 2.9% TS slurries, the percent TS removal they obtained ranged from 3% on a 1.574–mm screen to 10% on a 0.840–mm screen. Similarly, Holmberg et al. (1983) concluded that screening is not a useful practice for anaerobic digestion of flushed swine manure since a large portion of the reduced carbon remains in the liquid fraction. On the basis of COD removal, their data showed that only about 21% of the methane producing material is retained by screens having a 0.98–mm opening.

Particle size distribution and nutrient capture by smaller screens were evaluated by passing homogenized waste (run 7) through screens of decreasing mesh sizes in the range of 3.36 to 0.297 mm. Results of this particle size analysis are shown in table 4. The data indicate that most of the suspended solids (80%), N (78%), and P (93%) that are potentially removable by phase separation were contained in very fine particles that passed a 0.297–mm screen. This indicates that screens of 0.5 to 1.6 mm opening size commonly used in mechanical screen–type commercial separators are not adequate with liquid swine manure. On the other hand, using screens or filters with small pore opening size (i.e., <0.2 mm) is difficult due to plugging with small particles and swine hair. These considerations illustrate the need for chemical flocculation treatment to enhance mechanical separation. With flocculation, the effective particle size is increased by agglomeration of small particles into a larger particle or floc (fig. 1). This larger size not only enhances solids retention by screens and separation of colloidal particles by settling (Vanotti and Hunt, 1999; Zhang and Lei, 1998) but also prevents clogging of finer filters such as sand filter beds (Vanotti et al., 2001).

To illustrate problems of poor separation with screens, we describe the following results obtained at the same production unit (4800 pigs) where the samples were obtained. In this unit, the waste liquid was passed through a stationary, inclined separator with a 1/16 in. screen before discharge into a lagoon (the study samples were taken from a homogenization pit before going through this screen). The farm contained two other identical units of 4800 pigs, each discharging into their own lagoon but without a screen solids separator. The TKN, TP, and COD concentrations in the test and control lagoons were monitored during a 10–month period (Rashash et al., 1999). Results showed the lagoon that received screened effluent contained approximately 13% less TKN and 12% less TP than did the control lagoons; for COD, the differences were not significant. This case supports our conclusion that for flushed swine manure, screening alone does not provide substantial reduction of organic and nutrient loads to either existing lagoons or other treatment processes.

Enhanced Solid–Liquid Separation with PAM

Table 5 shows the effect of PAM dosage on average TSS, VSS, COD, and BOD_5 removal from flushed swine manure during a grow–out cycle. Suspended solids (TSS and VSS) concentrations after flocculation with PAM were significantly decreased (>90%) by increased rates of PAM application. The flocs were large enough to be effectively retained by the 1–mm screen. This size was chosen for the evaluation

Table 4. Retention of suspended solids and nutrients in flushed swine manure using screens of various sizes.[a]

	Solids		TKN		TP	
Screen Size[b]	Amount Retained (g/L)	Fraction of TSS (%)	Amount Retained (mg/L)	Fraction of Non–soluble N (%)	Amount Retained (mg/L)	Fraction of Non–soluble P (%)
3.360 mm	0.41	2.6	35	2.7	3.3	0.6
1.588 mm	1.01	6.4	100	7.8	11.1	2.2
1.000 mm	1.66	10.5	152	11.9	17.2	3.4
0.794 mm	2.18	13.8	199	15.6	21.9	4.3
0.590 mm	2.41	15.2	219	17.1	24.7	4.8
0.297 mm	3.10	19.6	278	21.8	38.0	7.4
<0.297 mm[c]						
Suspended	12.75	80.4	1000	78.2	475.4	92.6
Dissolved	9.03		1164		71.7	
Initial sample[d]						
Total suspended	15.84	100.0	1278	100.0	513.4	100.0
Total concentration	24.87		2442		585.1	

[a] Data are average of three replicate tests performed on run 7 effluent.
[b] 3.360, 1.000, 0.590, and 0.297 mm size screens are ASTM standard wire screen sieves with numbers 6, 18, 30, and 50, respectively. 1.588 and 0.794 mm size screens are stainless steel screens with round perforations of 1/16 and 1/32 in., respectively, commonly used in commercial screen separators.
[c] <0.297 mm is the fraction passing through this screen. This fraction was then filtered with a glass microfiber filter to separate between suspended and dissolved (soluble) components.
[d] Initial sample is the homogenized flushed manure before screening (table 1).

Table 5. Removal of solids, COD, and BOD_5 from flushed swine manure by PAM flocculation and screening.[a]

	TSS		VSS		COD		BOD_5	
Polymer Rate (mg/L)	Conc.[b] (g/L)	Removal Efficiency[c] (%)	Conc.[b] (g/L)	Removal Efficiency[c] (%)	Conc.[b] (g/L)	Removal Efficiency[c] (%)	Conc.[b] (g/L)	Removal Efficiency[c] (%)
0	5.33 a	15	4.21 a	17	11.99 a	5	3.64 a	7
20	4.49 b	29	3.52 b	31	10.15 b	19	2.88 b	26
40	3.27 c	48	2.34 c	54	8.97 c	29	2.37 c	39
60	1.99 d	68	1.56 d	69	6.60 d	47	2.02 d	48
80	1.31 de	79	1.08 de	79	5.12 e	59	1.89 de	52
100	0.71 ef	89	0.59 ef	88	4.41 f	65	1.79 ef	54
120	0.43 f	93	0.36 f	93	4.00 f	68	1.73 ef	56
140	0.34 f	95	0.27 f	95	3.87 f	69	1.60 f	59

[a] Average of seven runs and three replicates. Different letters in columns indicate significant differences among means at $P \leq 0.05$. TSS = total suspended solids, VSS = volatile suspended solids, COD = chemical oxygen demand, BOD_5 = 5–day biological oxygen demand.
[b] Concentration in manure liquid passing 1–mm screen after flocculation treatment.
[c] Removal efficiency relative to concentration of flushed manure before chemical treatment and screening (table 2).

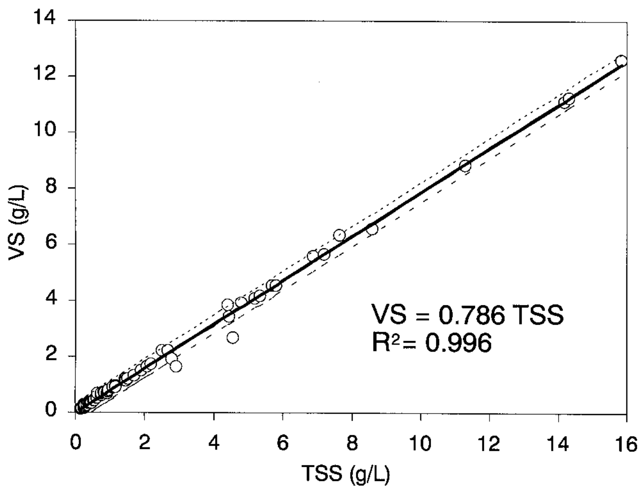

Figure 2. Relationship between volatile and total suspended solids in flushed swine manure. Dashed lines indicate 95% confidence interval (CI) for an individual prediction. Each point is the mean of three replicates.

because preliminary tests (data not shown) indicated that effectiveness of the 1–mm screen to retain flocs was similar to effectiveness of a 0.8–mm size (95% and 96% TSS efficiency, respectively). However, the use of a larger screen (1.6 mm) greatly decreased performance (67% efficiency). Volatile suspended solids (VSS) were highly correlated with TSS (r = 0.996, fig 2) and, therefore, the removal efficiencies of both fractions were almost identical (table 5). Averaged across all runs and treatments (n = 67), VSS comprised 78.6% of TSS (±0.5%).

Flocculation intensity increased linearly with increasing PAM rates up to an optimum level of "total flocculation" (WERF, 1993), where further increases of polymer dosage had little (non–significant) effect on suspended solids concentration in the separated effluent. The response was different for the various wastewater samples, as revealed by a significant waste strength and polymer rate interaction in the combined ANOVA ($p = 0.0001$, not shown). This interaction effect on TSS and VSS is an important finding, because it means that the rates of solids removal vary with the strength of the flushes. It was always more efficient in terms of polymer use to remove suspended solids from the more concentrated wastewater (fig. 3).

A linear–plateau spline function was fitted to these data to determine optimum PAM application rates and maximum TSS separation at various wastewater strengths using non–linear least square iteration and a Gauss–Newton method (Freund and Littell, 1991). These parameters were then used to determine TSS removal efficiency and polymer efficiency based on TSS removal at optimum dosage. Results of these calculations are presented in table 6. Optimum PAM application rates did not change in the same proportion as TSS concentration. For example, TSS concentration varied 10–fold (1.5 to 15.8 g/L), while optimum polymer application rates varied less than 1 fold (from about 70 to 110 mg/L). There was a significant trend of increased polymer need with increased total solids concentration (optimum polymer rate = 57 + 2.17 TS, R^2 = 0.95). However, these changes in dosage requirements were small, in the order of about 11 mg/L PAM increase per 5 g/L TS increase for a range of about 0.5% to 2.5% TS found in the study. At optimum PAM rates, TSS removal efficiencies ranged from 87% to 96% (table 6).

Corresponding PAM use efficiencies (g TSS removed/g PAM) increased greatly from 18.7 to 133.6 with increased TS concentration (fig. 4). Polymer usage was also calculated in terms of lb of polymer per ton of dry solids produced to compare with other uses. At optimum flocculation, the weight of polymer used to produce a ton of dry solids ranged between 107 to 15 lb (5.34% to 0.75% TSS produced, table 6), and it was greatly affected by manure strength. The polymer usage rate obtained when the liquid swine manure had medium to high strength (TS > 0.75%, runs 3 to 7) was less than 40 lb/ton (<2%). This is within the range of typical wastewater and industrial applications (8 to 50 lb/ton). As explained in the following section, usage rates obtained with more dilute manure (TS < 0.60%, runs 1 and 2) were excessively high and costly.

Economic Considerations

Based on the results of polymer use efficiency obtained in this study (fig. 4), it is more economical to use PAM to remove solids and nutrients from swine manure wastewater when strength is higher in the range of normal operations. The chemical cost to flocculate suspended solids from flushed swine manure was calculated on the basis of treating the effluent from a 1000–head finishing operation growing pigs from 22.7 to 100 kg (50 to 220 lb). On average, each pig weighs 61.4 kg (135 lb). The amount of PAM required for 1000 pigs is 2.21 kg/day with the following conditions:

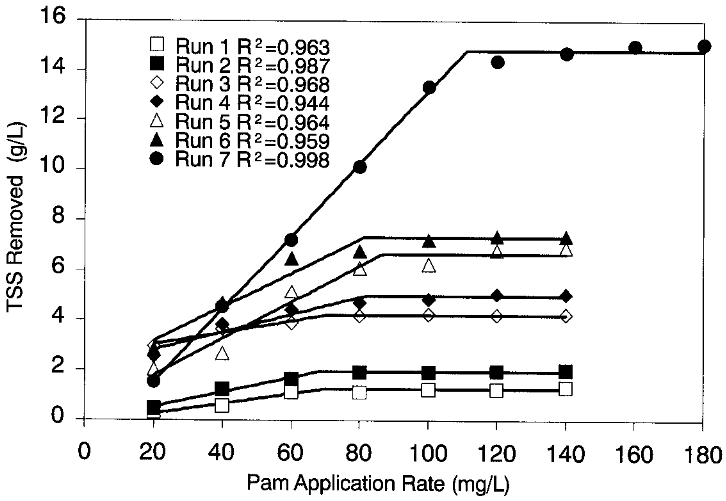

Figure 3. Capture of total suspended solids (TSS) from flushed swine manure using PAM treatment and screening (table 4). Corresponding optimum PAM application rates, maximum TSS removal, and TSS removal efficiencies are listed in table 6. Each point is the mean of three replicates.

Table 6. Changes in polymer use efficiency with wastewater strength.

Run	TSS Conc. (g/L)	Regression Equation[a] Slope (g/mg)	Optimum PAM Rate (mg/L)	Max. TSS Removed (g/L)	TSS Removal Efficiency[b] (%)	Polymer Use Efficiency[c] (g solids/g polymer)	Polymer Usage Rate[d] (%)	Polymer Usage Rate[d] (lb/ton)
1	1.47	0.0201	68	1.28	87	18.7	5.34	107
2	2.19	0.0291	68	1.95	89	28.6	3.50	70
3	4.39	0.0234	71	4.21	96	59.1	1.68	34
4	5.33	0.0355	82	4.99	94	61.0	1.63	32
5	7.21	0.0737	87	6.69	93	77.2	1.30	26
6	7.63	0.0682	81	7.33	96	90.3	1.11	22
7	15.84	0.1464	111	14.81	94	133.6	0.75	15

[a] Linear–plateau functions in figure 3: $Y = a + bX$ for X < knot, and Y = plateau for X > knot, where Y = TSS removed (g/L), X = PAM rate (mg/L), a = intercept, b = slope, knot = optimum PAM rate, and plateau = maximum TSS removed.
[b] TSS removal efficiency = max TSS removed/initial TSS concentration.
[c] Polymer use efficiency calculated from parameters of regression equations (maximum TSS removed/optimum rate).
[d] Polymer usage rate given both in percent (g PAM/100 g dry solids separated) and lb/ton (lb polymer/2000 lb dry solids separated).

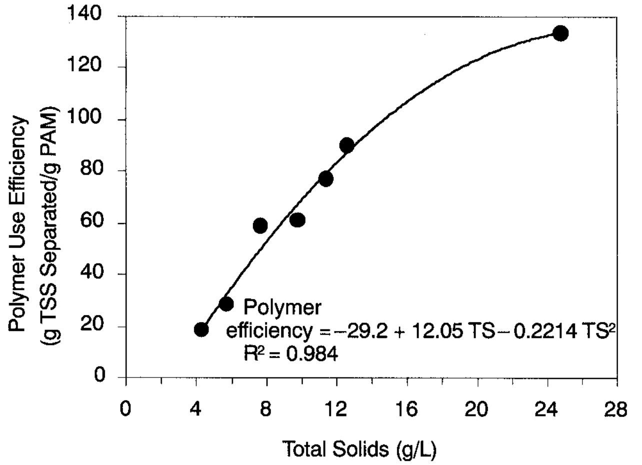

Figure 4. Effect of wastewater strength on polymer efficiency. Efficiency calculations are provided in table 6.

- Polymer usage rate of 0.75% (0.75 g polymer/100 g dry solids produced) associated with high–strength flushes (2.5% TS, run 7).
- TSS removal efficiency of 95%.
- TSS production rate of 5.05 kg/1000 kg live mass/day (NRCS, 1992).

The cost of PAM is approximately $4.41/kg for dry formulations ($2.00/lb). This results in a daily chemical cost of $9.75/1000 pigs. For an operation that grows 2.8 groups of pigs per year, the annual chemical cost for the 1000–head operation is $3,557, and the chemical cost per finished pig is $1.27. This contrasts with the calculated chemical cost associated with a very diluted flush (0.4% TS, run 1). With a polymer usage rate of 5.34% (fig. 4), the chemical cost per finished pig is $9.04, which is about seven times more expensive than treating higher strength waste. The flushing schedule used at the production facility provided a fixed rate of 25 L wash water per pig per day, which was maintained throughout the production cycle of the pigs. Thus, adjustments in management, such as reducing the frequency of flushing in periods when manure production is low so that a high wastewater strength is maintained, can result in significant savings in total polymer cost for separation.

The technology is also attractive for pit–recharge systems that are gaining popularity over flush systems because less water volume is required to clean the building. A pit–recharge system is typically emptied every five to seven days, resulting in a TS concentration that varies from 1.5% to 2.6% (Chastain et al., 1999). The chemical cost for this situation can be calculated based on polymer efficiency predicted by the equation in figure 4. This calculation indicates that treatment of liquid manure with 2% TS would be associated with a polymer efficiency of 123 g dry solids/g polymer (0.81% polymer usage rate) and a corresponding chemical cost of $1.37 per finished pig. An important consideration for pit–recharge systems may be the potential for dissolution of solids in the pit, which can affect separation efficiency. Zhu et al. (2000) studied the problem and concluded that a 5–day storage should be satisfactory to maintain integrity of particles less than 0.5 mm for separation purposes.

Reduction of Oxygen–Demanding Substances with PAM

PAM treatment significantly enhanced the COD and BOD_5 removal efficiency of screens from 5% to 69% and 7% to 59%, respectively (table 5). The 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. The BOD_5 test measures the oxygen utilized during a 5–day incubation period for the biochemical degradation of organic material (carbonaceous demand) plus the oxygen used to oxidize inorganic materials (APHA, 1998). The BOD determination is commonly used to determine the relative oxygen requirements of wastewaters, effluents, and polluted waters, and it is also applied to measure waste loadings to treatment plants and efficiency of these treatments. These two indicators of oxygen–demanding substances present in wastewater are closely associated; the empirical relationship ($R^2 = 0.93$) that we found for the liquid swine manure samples was 1 g COD = 0.341 g BOD (±0.011) (fig. 5). Although overall removal efficiencies were not as high as those obtained with suspended solids, as shown in fig. 6, most of the variation in COD (93%) observed after treatment was explained by the removal of flocculated suspended particles. On average, every 1 g of TSS separated from the liquid by treatment was associated with a 1.32–g reduction of COD (±0.03) and with a 0.394–g reduction of BOD_5 (±0.015). Because of the high concentration of soluble N (ammonia), which is not affected by polymer treatment, a fraction of the COD and BOD_5 measured in the treated effluent was due to ammonia oxidation (nitrification). We determined the effect of soluble N by measuring $CBOD_5$ and comparing with corresponding BOD_5 values so that the difference is the ammonia contribution. Measurements were done in the effluent of all treatments in five of the seven runs. Results showed that most of the variation in BOD_5 in the experiments was due to removal of carbonaceous materials (fig. 7). Overall removal efficiencies were higher for $CBOD_5$ than BOD_5; they increased from 6% in the control treatment (PAM = 0 mg/L) to 67% at the highest PAM rate. The oxygen demand of ammonia during the 5–d incubation test ($NBOD_5$) was consistent among PAM treatments and averaged 520 mg/L (±74).

Large COD reduction in the liquid effluent before discharge into a treatment lagoon is an important consider–ation to reduce odor from existing anaerobic lagoons. For

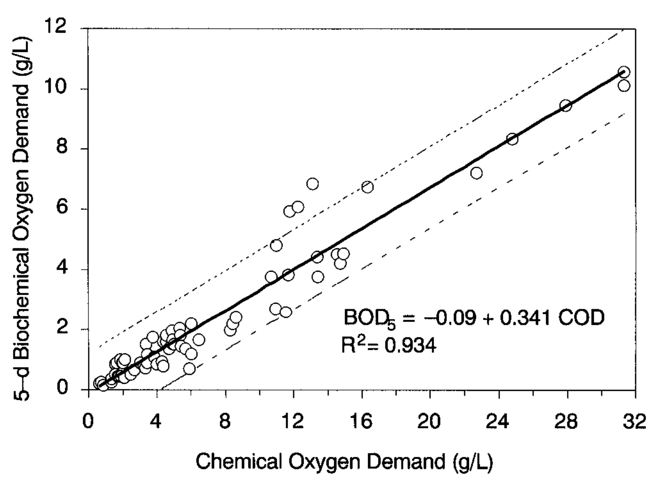

Figure 5. Relationship between effluent biochemical oxygen demand (BOD_5) concentration and chemical oxygen demand concentration. Data include eight PAM rate treatments and seven runs. Dashed lines indicate 95% CI for individual prediction. Each point is the mean of three replicates.

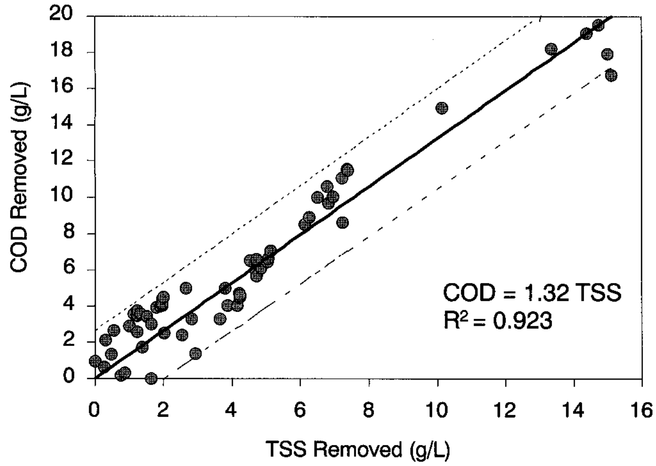

Figure 6. Relationship between the removal of chemical oxygen demand (COD) and removal of total suspended solids (TSS) by PAM treatment and screening. Data include eight PAM rate treatments and seven runs. Dashed lines indicate 95% CI for an individual prediction. Each point is the mean of three replicates.

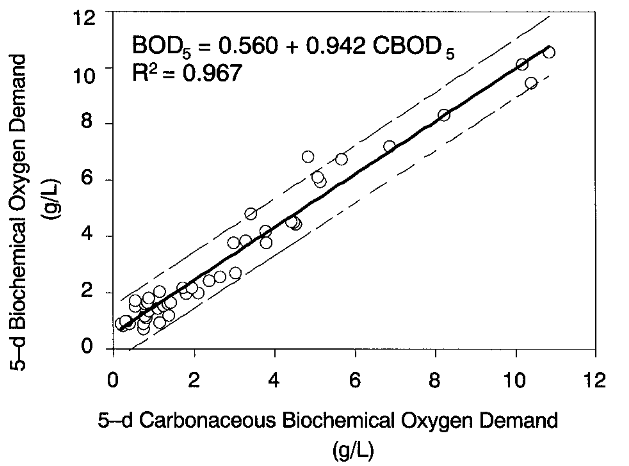

Figure 7. Relationship between BOD_5 and carbonaceous BOD_5 in the treated effluent. Data include eight PAM rate treatments and five flushed manure samples. Dashed lines indicate 95% CI. Each point is the mean of three replicates.

example, Humenik and Overcash (1976) indicate that odor is minimal with loading rates below 60 g of COD per m^3 of lagoon per day. This is approximately 40% to 76% lower than typical organic loads of 150 to 250 g COD/m^3/d used for lagoon design criteria (Burton, 1997). However, the minimal odor value is comparable to COD reduction levels obtained with PAM treatment. Our results indicate that PAM flocculation can substantially increase capture of energy–yielding feedstock for anaerobic digestion reactors, methane production, or burning in gasification processes, and that these materials can be effectively retained even with a relatively large screen (1–mm opening). These results are also significant to the swine producer who wishes to incorporate biological N removal processes for the purpose of ammonia control. By capturing the suspended particles, most of the volatile and oxygen–demanding organic compounds are removed from the liquid stream. Instead of oxygen being used to break down organic compounds, it is used in the aeration treatment to more efficiently convert ammonia to nitrite or nitrate (Becker, 2001; Vanotti et al., 2001).

Enhanced Nutrient Separation with PAM

Polymer treatment followed by screening significantly enhanced the removal efficiency of total phosphorus (TP) and total nitrogen (TKN) from 10% to 74% and from 7% to 35%, respectively, and significantly decreased nutrient concentration in the liquid phase (table 7). The effect of enhanced solids separation on nutrient removal was totally different for organic and inorganic compounds. The inorganic N and P fractions were not affected by PAM treatment; o–PO_4–P treatment means varied from 43 to 51 mg/L, and NH_3–N varied from 703 to 755 mg/L. This was also true for electrical conductivity (means ranged from 8.80 to 8.97 mS/cm) and pH (means varied from 7.82 to 7.97). On the other hand, PAM was very effective in the capture of organic nutrients contained in the small particles. PAM treatment increased removal efficiency of organic P and N from 10% to 92% and from 13% to 85%, respectively (table 7). Comparison of these values with suspended solids performance (table 5) indicates that for about 1% of TSS or VSS captured by PAM flocculation, a similar percentage of organic N or P is removed from the effluent. This indicates that organic nutrients in flushed effluent were mostly contained in suspended manure particles, which in turn were efficiently separated from the liquid by flocculation treatment.

The relationship for all treatments and runs between organic N and P separation and suspended solids separation as affected by PAM is shown in fig. 8. On average, 7.26 g of organic N (SE = 0.16) and 3.32 g of organic P (SE = 0.07) were removed from the liquid phase for every 100 g of TSS separated by PAM flocculation and screening. This enhanced removal of organic nutrients significantly improved the overall N:P ratio of the effluent. This is because, compared to N, a much larger fraction of total P in manure is made of organic compounds (for example, 87% vs. 45%, table 1). Since only the nutrients contained in the organic pool are affected by flocculation/separation treatment, separation of this N and P into the solid fraction effectively changes the N:P ratio of the liquid phase. As shown in table 7, effluent N:P ratios increased more than 100% with polymer treatment, from <5:1 to >11:1.

A higher N:P ratio results in a more balanced effluent from the point of view of crop nutrient needs. The implications are large; one of the main problems in sustainability of animal production is the imbalance between N and P in the waste. For example, the mean N:P ratio (4:1) in manure is generally lower than the mean N:P ratio (8:1) taken up by major grain and hay crops (USDA, 2001). Therefore, when manure is applied based on N, there is a P buildup in soil and increased potential for P losses through runoff and eutrophication of surface waters (Heathwaite et al., 2000; USEPA, 2001). Our results indicate that with a polymer–enhanced separation process, the treated wastewater is land applied with reduced total P loads.

Conclusions

Organic nutrients and volatile solids in liquid swine manure are important to both agricultural crop production and environmental quality. The continued trend toward fewer but larger operations means that more manure nutrients are being generated and concentrated within relatively small

Table 7. Removal of phosphorus and nitrogen from flushed swine manure by PAM flocculation and screening.[a]

Polymer Rate (mg/L)	TP Conc.[b] (g/L)	TP Removal Efficiency[c] (%)	Organic P Conc.[b] (g/L)	Organic P Removal Efficiency[c] (%)	TKN Conc.[b] (g/L)	TKN Removal Efficiency[c] (%)	Organic N Conc.[b] (g/L)	Organic N Removal Efficiency[c] (%)	N/P Ratio[d]
0	243 a	10	200 a	10	1200 a	7	497 a	13	4.94
20	214 b	21	177 a	21	1129 b	13	437 b	23	5.28
40	167 c	38	124 b	44	1061 c	18	337 c	41	6.35
60	128 d	53	87 c	61	999 d	23	291 d	49	7.80
80	99 e	63	52 d	77	960 e	26	221 e	61	9.70
100	77 f	71	28 e	87	880 f	32	120 f	79	11.43
120	71 f	74	20 e	91	860 fg	33	95 f	83	12.11
140	71 f	74	18 e	92	841 g	35	85 f	85	11.85

[a] Average of seven runs and three replicates. Different letters in columns indicate significant differences among means at $P \leq 0.05$.
[b] Nutrient concentration in liquid manure passing 1–mm screen after flocculation treatment.
[c] Removal efficiency relative to concentration before chemical treatment and screening (table 2).
[d] N/P ratio = TKN concentration/TP concentration. Average N/P ratio for initial sample was 4.79.

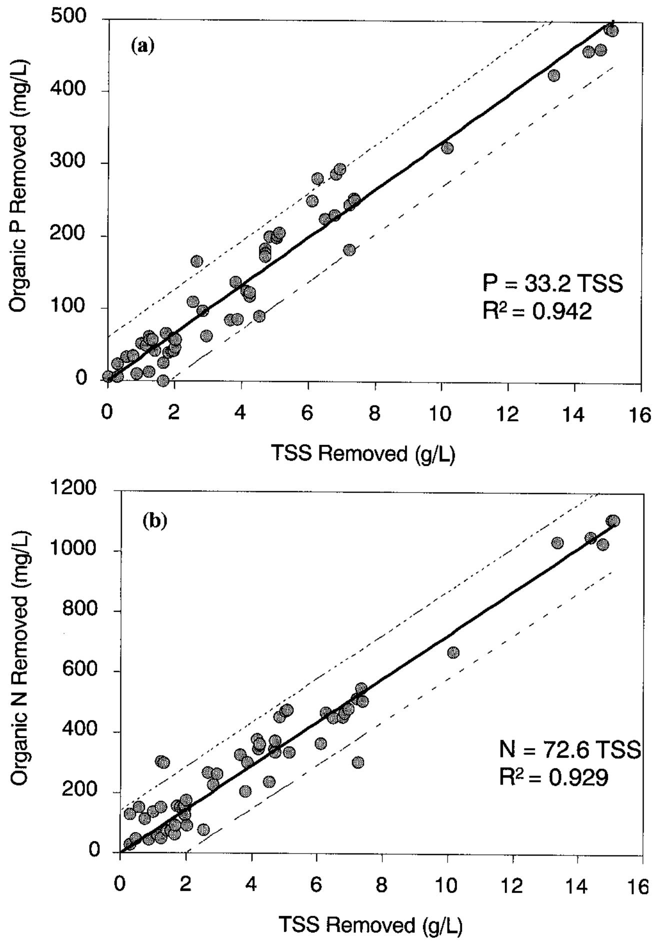

Figure 8. Relationship between the removal of (a) organic phosphorus or (b) organic nitrogen and the removal of total suspended solids (TSS) by PAM treatment and screening. Data include eight PAM rate treatments and seven swine waste effluent samples from a finishing operation. Dashed lines indicate 95% CI for an individual prediction. Each point is the mean of three replicates.

geographic areas. These spatial distribution problems could be solved if the nutrients were separated from the liquid phase and moved short distances, mostly within a county. Nutrients in swine manure are mostly contained in very fine suspended particles that are not separated by mechanical separators. We showed in this study that 78% of the N and 93% of the P fractions that are potentially removable by phase separation were contained in particles less than 0.3 mm in size. Organic polymers offer a solution to this problem because they flocculate suspended and colloidal solids and, therefore, screening or filters after flocculation can capture the nutrients associated with small particles typical of these wastes.

Manure handling systems in confined operations often use large volumes of water to clean the houses. We evaluated the effect of typical flush–system solids strengths on both optimum polymer dose requirement and chemical use efficiency. We found that it was more efficient and economical to treat the higher strength flushed manure, over the range of 0.4% to 2.5% TS concentration that was evaluated. This study also showed that reduction of water volume to clean the houses can result in significant savings (about 700%) in total polymer cost by providing a higher strength waste for flocculation. Chemical cost was estimated to be $1.37 to $1.27 per finished pig for liquid waste containing 2% to 2.5% TS.

Flocculation treatment with PAM before screening substantially increased separation efficiency of TSS (95%), VSS (95%), COD (69%), and carbon BOD_5 (67%). For every 100 g of TSS removed, there was a 1.32–g reduction of COD, 3.32–g reduction of organic P, and 7.26–g reduction of organic N. PAM effectively removed organic nutrients (92% P and 85% N) but had no effect on the dissolved ammonia and phosphate fractions. The selective separation of the nutrients (organic vs. dissolved) increased the N:P ratio of the effluent (from 4.8 to 12.1), which resulted in a more balanced effluent for crop nutrient needs. This could help solve current problems of excess phosphorus accumulation in soils of wastewater spray fields.

Collectively, these findings indicate that:

- Polymer–enhanced solid–liquid separation of flushed swine manure is more efficient with higher solids content wastewater.
- When this technology is integrated into a liquid manure handling system, it has the potential to substantially increase capture of materials with potential to generate income, such as energy–yielding feedstock and plant growth media.
- Transport of solids and handling of remaining liquids is made easier, with accompanying implications for

improved management of nutrients in areas where swine production is concentrated. Such secondary benefits need to be duly considered when determining the economic costs of the technology.

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