SOLIDS AND NUTRIENT REMOVAL FROM FLUSHED SWINE MANURE USING POLYACRYLAMIDES

M. B. Vanotti, P. G. Hunt

ABSTRACT. *Most of the organic nutrients and reduced carbon (C) materials in liquid swine manure are contained in fine suspended particles that are not separated by available mechanical separators. Treatment with polyacrylamide (PAM) polymers prior to mechanical removal or gravity settling has the potential for enhancing solids-liquid separation, thus concentrating nitrogen (N), phosphorous (P), and organic C. In this work, we determined PAM charge and density characteristics most desirable for swine wastewater applications and established the optimum chemical requirement. Treatments were applied to flushed manure from two swine operations in North Carolina. Cationic PAMs significantly increased solids separation while performance of neutral and anionic types was not different from a control. Cationic PAMs with moderate-charge density (20%) were more effective than polymers with higher charge density. Flocs were large and effectively retained with a 1-mm screen. Optimum PAM rate varied with the amount of total suspended solids (TSS) in the liquid manure; 26 and 79 mg PAM/L for samples containing 1.5 and 4.1 g TSS/L, respectively. Corresponding TSS removal efficiencies were 90 to 94%. In contrast, screening without PAM treatment captured only 5 to 14% of the suspended solids. Polymer usage rate was consistent and averaged 2.0% based on weight of dry solids produced. Volatile suspended solids (VSS) were highly correlated with TSS and comprised 79.5% of TSS. Chemical oxygen demand (COD) and organic nutrient concentrations in the effluent were also significantly decreased by PAM treatment. The decrease of COD concentration, an important consideration for odor control, was linearly related with removal of suspended solids, at a rate of 2.0 g COD/g TSS and 2.6 g COD/g VSS. Removal efficiency of organic N and P followed approximately a 1:1 relationship with removal efficiency of TSS. Chemical cost to capture 90% of the suspended solids was estimated to be $0.026 per hog per day ($2.79 per finished hog). Results obtained indicate that PAM treatment is very effective for removal of manure solids, COD, and organic nutrients from flushed swine effluents. The technology provides an attractive alternative to existing liquid manure handling methods for conserving nutrients and avoiding excessive nutrient application in areas where swine production is concentrated.*

Keywords. *Animal waste treatment, Polymers, Swine wastewater, Solid-liquid separation, Nutrient removal, Odor control.*

Sustainable swine production systems should conserve the maximum amount of nutrients that land can assimilate without causing overapplication or pollution. Animal feeding operations in the United States are being developed with a larger number of animals concentrated on fewer farms. Large, concentrated herds generate vast amounts of waste in a relatively small area. Many areas in the southeastern U.S. are producing more manure nutrients than available cropland can absorb. At the same time, other areas with lower animal concentration have to purchase fertilizers to meet their crop nutrient demands. In North Carolina, the swine industry generates each year approximately 13 million tons of fresh manure containing 81,000 tons of nitrogen and 27,000 tons of phosphorus, and about 90% of the total manure produced is considered collectable (Barker and Zublena, 1995). This amount of untreated manure could annually provide all the fertilizer needs for North Carolina's six largest agricultural counties: Johnston, Sampson, Pitt, Wilson, Nash, and Robeson (NCSU, 1995). However, transport of this manure in a liquid form is not feasible. Thus, solids-liquid separation of untreated liquid manure and subsequent transport of solids to nutrient deficient areas are critical for conserving nutrients and lessening the environmental impact of confined animal production systems. When solids-liquid separation is combined with more sophisticated process designs, there is the added benefit of advanced treatment methods that may eventually replace anaerobic lagoons.

Modern swine production typically utilizes some type of water conveyance system to move the waste from the confinement house. Flushing systems are preferred because of their simplicity, economy, and lower ammonia emissions compared to manure scrapping systems (Barker and Driggers, 1981; Sievers, 1989). Flushing is done at rates that vary from 500 to 2000 L/1000 kg live mass per day. This high dilution results in wastewaters that have very low solids concentrations, often in the range of 0.2 to 1.5% total solids content. Although substantial amounts of carbon (C) and nutrients can be removed from industrial

Submitted for publication in January 1999; reviewed and approved for publication by the Structures & Environment Division of ASAE in August 1999. Presented as ASAE Paper No. 96-4052.

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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, S.C. **Corresponding author:** Matias B. Vanotti, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 W. Lucas St., Florence, SC 29501, voice: (843) 669-5203, ext. 108, fax: (843) 669-6970, e-mail: vanotti@florence.ars.usda.gov.

and municipal wastewaters by solids-liquid separation using dewatering presses and screens, most of the organic nutrients in swine wastewater effluents are contained in fine suspended particles that are not separated by available mechanical separators (Hill and Tollner, 1980). Separation of suspended solids from animal wastewater using screens and presses is very inefficient (5 to 15%), and requires chemical coagulation to bind together the small particles of solids into larger clumps (Sievers et al., 1994). Previous work (Loehr, 1973) with inorganic flocculants, such as alum or calcium and iron salts, showed that even though these compounds are very effective, they have limited application for animal wastewater treatment because of the large amounts of material needed and the large quantity of additional solids generated.

Polyacrylamides

Polyacrylamide (PAM) flocculants have the potential for enhancing solids and nutrient separation from diluted wastewaters, but little information is available on their application to animal waste treatment. Polyacrylamides are high molecular weight, long chain, water soluble polymers. The long polymer molecules destabilize suspended charged particles by adsorbing them and building bridges between several suspended particles, resulting in newer, larger particles (or flocs) that settle out of the liquid. Characteristics such as molecular weight (chain length) and type and density distribution of charge provide these polymers 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.

Our objective was to determine if PAM polymers are useful for solids and nutrient removal from flushed swine manure. In this work, we determined charge and density characteristics most desirable for treatment of animal wastewater. Further, we evaluated solids and nutrient removal efficiency using screens with and without PAM treatment and established optimum application rates.

Materials and Methods

Swine Wastewater Samples

Polymer separation of solids and nutrients from liquid swine manure was evaluated in a series of bench experiments using flushed effluent collected from two commercial operations in North Carolina. The first operation was a nursery farm that raises pigs from 4.5 to 22.7 kg (10 to 50 lb), and the second operation was a feeder-to-finish operation that grows pigs from 22.7 to 100 kg (50 to 220 lb). The nursery was located in Duplin County, North Carolina, and consisted of a single house that contained 2,600 pigs (average pig weight at sampling = 13 kg). The system used under-slat flushing and an anaerobic lagoon for treatment and storage of the flushed manure. One-third of the house was flushed every 6 h using 6.06 m^3 (1,600 gal) of lagoon-liquid recycle at a rate of about 2100 L/1000 kg live mass per day (7.3 gal/pig/day). Liquid manure samples were collected directly from the effluent pipe discharging into the lagoon. The feeder-to-finish operation was located in Bladen County, North Carolina, and consisted of four swine houses with slatted floors that discharged into one lagoon. Each house contained 1,200 pigs that weighed approximately 91 kg apiece. This was a new operation, which at the time of sampling was still filling the lagoon; therefore, the material was collected prior to the flush cycle being switched from fresh-water flush to lagoon-liquid recycle. Each flush cycle was repeated five times per day and utilized a total of 12.1 m^3 (3,200 gal) of fresh water to remove the waste from one side of each of the four houses. The resulting total flush volume to animal weight rate was about 300 L/1000 kg live mass per day (6.7 gal/pig/day). Two liquid manure samples were obtained five days apart from a mixing pit that collected the flush from the four houses before it was pumped to a screen solids-liquid separator. One of the samples was obtained from the first flush in the day and the other from the second flush. The first flush was more concentrated because it contained manure accumulated during the previous 8-h period, while the second through fifth flushes removed the manure produced in the previous 4-h period. Liquid manure samples from both farms were taken at the beginning, middle, and end of a flushing cycle and combined to create composite samples (table 1). All samples were kept at 4°C to prevent digestion and dissolution of solids and organic nutrients. The liquid manure sample from the nursery house was used in the initial experiments for polymer type evaluation. Subsequent tests to study polymer rate needs were done using the liquid manure samples obtained from the finishing operation.

Table 1. Characteristics of flushed manure samples from two swine operations*

Effluent Parameter	Nursery	Feeder-to-Finish 1st Flush	Feeder-to-Finish 2nd Flush
Total solids (g/L)	1.83 (0.01)	6.75 (0.14)	3.22 (0.08)
Total suspended solids (g/L)	0.34 (0.01)	4.12 (0.14)	1.49 (0.12)
Volatile suspended solids (g/L)	0.25 (0.01)	3.36 (0.12)	1.10 (0.07)
Chemical oxygen demand (g/L)	1.37 (0.05)	10.95 (0.16)	4.49 (0.10)
pH	8.1 (0.1)	7.6 (0.1)	8.1 (0.1)
Total phosphorus (mg/L)	60 (2)	189 (6)	71 (3)
Organic phosphorus (mg/L)	44 (1)	122 (8)	39 (4)
Total Kjeldahl nitrogen (mg/L)	374 (4)	505 (7)	385 (4)
Organic nitrogen (mg/L)	88 (3)	234 (15)	115 (5)

* Means (SE), n = 4. The nursery house effluent was used in the PAM type evaluation study, and the effluent from the feeder-to-finish operation was used for evaluation of PAM dosage needs.

PAM Type Evaluation

Sedimentation tests following flocculation were used to determine the effect of PAM charge type and density on solids and nutrient removal. In a first flocculation and sedimentation experiment, we compared the performance of cationic, nonionic, and anionic PAMs. The polymers employed are commercially available PAM formulations (Magnifloc 494C, 985N, and 844A, respectively, table 2). Magnifloc 494C is a moderately charged (20 mole %), high-molecular weight (5×10^6 g/mole), cationic PAM. It 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

Table 2. Characteristics of the polyacrylamides tested

Polymer Name*	Charge Type	Charge Density (mole %)	Active Polymer (%)	Physical Form
Magnifloc 494C	Cationic	20	85	Powder
Magnifloc 985N	Neutral	0	85	Powder
Magnifloc 844A	Anionic	33	85	Powder
Excel 5020	Cationic	20	30	Emulsion
Excel 5040	Cationic	40	29	Emulsion
Excel 5055	Cationic	55	28	Emulsion
Excel 5000	Cationic	75	27	Emulsion

* Commercial formulations, Cytec Industries Inc., West Paterson, N.J.

charge independent of pH. Magnifloc 985N flocculant is a nonionic (<1 to 2 mole % charge), very high-molecular weight (18×10^6 g/mole) polymer of acrylamide. Magnifloc 844A is a highly charged (33 mole %), very high-molecular weight (18×10^6 mole), anionic PAM that is made from acrylamide monomer and sodium acrylate which provides the negative charge. The three polymers were applied at a rate of 10 mg active polymer per liter. The test also included an alum treatment to compare performance with PAMs because alum is a material widely used to precipitate P in municipal wastewater. Alum was applied at a rate of 1.43 g $Al_2(SO_4)_3 \cdot 14H_2O$/L of wastewater, equivalent to a 2.5 Al/P molar ratio. This rate was based on a preliminary rate study using lagoon liquid from the same nursery operation indicating that an Al/P molar ratio >2 is needed to precipitate 90% of the P contained in the wastewater.

A second flocculation and sedimentation experiment compared the performance of cationic PAMs having a wide range of charge density characteristics [Excel Ultra 5020 (20 mole %), 5040 (40 mole %), 5055 (55 mole %), and 5000 (75 mole %), table 2]. These polymers are high-molecular weight (5×10^6 g/mole), water-in-oil inverse emulsions and are polyacrylamides which have been aminomethylated by addition of formaldehyde and dimethylamine (the Mannich reaction) and further reacted with a quaternizing agent to be positively charged at all pH values (Barvenik, 1994). Two application rates (3 and 15 mg active polymer per liter) were used with each of the four polymers to evaluate charge density effects.

The sedimentation tests were performed in 1-L Imhoff cones, used for standard settleable solids tests (APHA, 1992). Chemical treatments were added into the wastewater in 10-mL working solutions after the Imhoff cones were filled to the 1-L mark with a well-mixed liquid manure nursery sample. Working solutions for PAM were secondary dilutions after preparation of 0.5% primary stocks (WERF, 1993). The samples were then mixed with a rod for 10 s and allowed to settle for 1 h. Flocculation performance was determined by measuring the solids and nutrient concentration in the supernatant and the volume of solids that accumulated in the bottom of the cone vessel. Solids analyses of the liquid supernatant samples included total solids (TS), total suspended solids (TSS), and volatile suspended solids (VSS). Chemical analyses consisted of pH, chemical oxygen demand (COD), ammonia-N (NH_3-N), total organic N, orthophospate (o-PO_4), and total organic P. All the analyses were done according to Standard Methods (APHA, 1992). The o-PO_4 fraction, also termed *reactive P*, was determined by the ascorbic acid method (Murphy and Riley, 1962). The organic P fraction is the difference between total P and o-PO_4 analyses and includes condensed and organically bound phosphates, while the organic N fraction is the difference between Kjeldhal N and ammonia-N determinations. The experiments were repeated four times and included a control treatment consisting of 10 mL of distilled water.

PAM Rate Evaluation

Flocculation and screening separation procedures were used to study the PAM dosage needs of flushed swine wastewater. The study was done using two cationic polymers (Magnifloc 494C and 234GD). Both polymers have similar molecular weight and charge characteristics. Magnifloc 234GD product is marketed as a flocculant and dewatering aid for food processing waste destined for recycling as animal feed, such as poultry and corn processing wastes, and considered a Generally Recognized As Safe (GRAS) product when used for that purpose (Cytec Industries, Inc., 1992; Schechter et al., 1995). The study included seven PAM rate treatments (0 to 200 mg of active polymer per liter), which were applied to 200-mL duplicate samples contained in 250-mL flasks. After the chemicals were added into the wastewater, the samples were mixed with a bench stirrer at 100 rpm for 2 min and passed through a sieve with a 1.0 mm opening. Removal performance was determined by the difference between the solids and nutrient concentration (APHA, 1992) in the effluent passing the screen and those in the original sample before PAM application and screening.

Statistical Analysis

Performance data were subjected to an analysis of variance performed separately on each wastewater sample (SAS Institute, 1988). Significant differences among treatment means were evaluated using a least significant difference (LSD) test at the 5% level. Data reported in this manuscript for the rate evaluation study are the average of the two PAM products because the product (494C vs 234GD) and product × rate interaction effects on both solids and nutrient in the analysis of variance were not significant. Linear and non-linear regression analysis (Draper and Smith, 1981; Freund and Littell, 1991) was used to describe the relationship among measured variables and to quantify the PAM dosage needs.

Results and Discussion

PAM Type Evaluation

The reaction of cationic PAM and swine wastewater was instantaneous and produced large, dark-brown flocs that rapidly settled out of the matrix wastewater, leaving a remarkably clear supernatant. Effects of PAM charge type on nutrient and solids separation from flushed swine manure (nursery sample) are shown in table 3. Without chemical addition (control), the amount of solids removed after 1-h gravity settling was minimal. Reduction of TSS in the control was <2% compared to initial levels (table 1), and volume of settled solids was just above detectable limit (0.1 mL). This indicates that most of the suspended solids in the nursery effluent were colloidal in nature and needed coagulation treatment. Polymer charge type had a significant influence on solids separation efficiency. The

Table 3. Effect of polymer charge type on separation of solids and nutrients from flushed swine manure (nursery operation) using flocculation and sedimentation*

Chemical Treatment†	Settled Solids Volume (mL)	Water Quality Characteristics of Supernatant						
		TSS	COD	Organic-N	NH_3-N	Organic -P	o-PO_4-P	pH
		-------g/L-------		----------mg/L----------				
Control	0.2 c	0.37 a	1.33 a	67 a	296 a	31 a	15 a	8.3 a
PAM-C	10.2 b	0.23 b	0.85 b	16 b	300 a	10 b	15 a	8.2 a
PAM-N	0.3 c	0.38 a	1.26 a	74 a	302 a	34 a	14 a	8.4 a
PAM-A	0.2 c	0.37 a	1.25 a	60 a	293 a	32 a	14 a	8.3 a
Alum	139.6 a	0.14 c	0.58 b	37 ab	306 a	5 b	1 b	7.1 b

* Sedimentation test was done in 1-L Imhoff sedimentation cone using the nursery sample and a settling time of 1 h after chemical application. Average of four replications; mean separation by LSD at 5% level.

† PAM rate = 10-mg active polymer/L; C = cationic (Magnifloc 494C), N = neutral (Magnifloc 985N), and A = anionic (Magnifloc 844A). Alum rate = 1430 mg/L, equivalent to a 2.5 Al/P molar ratio. Control = no chemical added and 1 h settling. Initial waste characteristics given in table 1.

performance of both neutral and anionic PAMs (PAM-N and PAM-A, table 3) was not different than the control. In contrast, cationic PAM treatment (PAM-C) significantly affected solids and nutrient separation. Relative to initial levels (see table 1), application of 10 mg/L of cationic PAM removed 33% of TSS, 38% of COD, 82% of organic N, and 77% of organic P from the liquid portion of the flushed waste. PAM treatment did not affect inorganic N and P concentration or pH of the effluent. Our results confirm the general premise that cationic polymers would be more useful for animal wastewater because organic particles suspended in neutral and alkaline wastewaters generally have a negative charge. Other results were plausible; adsorption of anionic PAM on negatively charged surfaces is also common (Stumm and O'Melia, 1968; Lentz et al., 1993). However, this test resolved the charge type issue for treatment of animal wastewaters.

Alum was more effective than cationic PAM in reducing suspended solids and phosphorus by sedimentation (table 3). Alum reacted instantly with swine wastewater producing a voluminous, gelatinous floc that provided clarification by enmeshing and adsorbing the colloidal manure particles. The light-grey sludge that was formed did not have any consistency, and further processing showed that it was not retained even with relatively small screens (0.3 mm opening). This treatment removed not only organic P (89%) but also inorganic phosphates (94%). Phosphate removal mechanism is by adsorption on the aluminum hydroxide floc formed in the presence of alkalinity (HCO_3^-) and also by incorporation into a phosphate complex with aluminum. Although the liquid supernatant was clear, the settled sludge volume was very large (14% of the total wastewater volume, table 3). The large sludge production, which foretells subsequent handling and disposal problems, is probably the largest disadvantage of alum relative to PAM when used for livestock wastewater treatment. For example, addition of alum to animal wastewater typically produces a 0.6-1.0 g/L solids increase per gram per liter of chemical used (Loehr, 1973). Our results with alum revealed a significant increase (0.5 g/L) of the dissolve solids fraction in the supernatant (data not shown) and possibly a much larger increase in the precipitated fraction. In contrast, PAM was used at much lower concentrations, minimizing solids generation during treatment. If subsequent biological treatment is considered, such as the use of nitrification-denitrification to remove surplus ammoniacal nitrogen, the treatment with alum produces another potential problem that is the reduction of alkalinity (HCO_3^-), evident in the lower pH of the treated effluent (table 3). Although approaches other than conventional chemical treatment are needed for animal waste soluble phosphate control, PAM will frequently be a better option for solids and organic nutrient removal from both the standpoint of additional solids generation and alkalinity considerations.

Contrary to the general expectation, however, cationic PAMs with lower charge density were more effective for removing suspended solids from swine wastewater than those with higher charge density. This is illustrated in figure 1 which shows that flocculation performance significantly decreased with increased charge density in the range of 20 to 75% and that the moderately charged PAM (20%) destabilized suspended particles and started flocculation at lower polymer concentration. At the 15 mg/L application rate, the PAM with a 20% charge removed 73% of the total suspended solids or about twice as effective as the PAM with a 75% charge. La Mer and Healy (1963) postulated a chemical bridging theory to understand the ability of polymers to destabilize colloidal suspensions. The bridging model proposes that a polymer macromolecule can attach itself to a particle surface at one or more adsorption sites with the remainder of the molecule extending into the solution and free to interact with vacant sites in other particles. Optimum flocculation occurs when only a portion of the available adsorption sites on the surface of the colloidal particles is covered allowing aggregation into a three-dimensional floc network. Saturation of the available surfaces produces a restabilized colloid because no sites are available for the formation of polymer bridges. Our result fits this model and suggests that, with suspended manure particles, highly charged polymers may saturate the available adsorption sites resulting in a poor bridging/flocculation performance. Therefore, moderate-charged cationic polymers were selected for conducting polymer dosage studies.

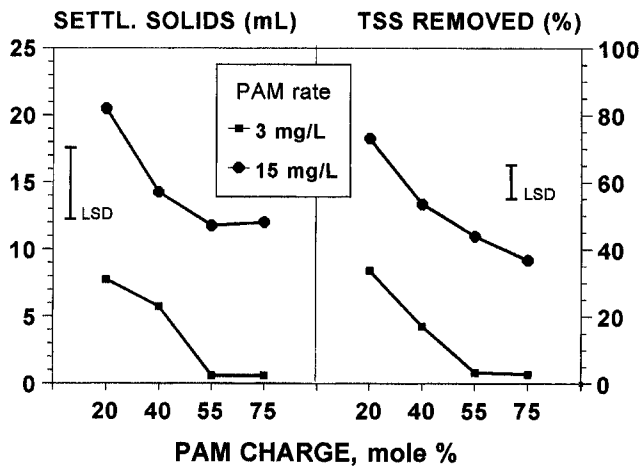

Figure 1–Effect of PAM charge density (+) on solids removal from swine wastewater (nursery operation, table 1). Polymers used were Excel series (table 2). Sedimentation test was done in 1-L Imhoff sedimentation cone with 1-h settling time after application. Total suspended solid concentration (TSS) was measured in the supernatant. Settled solids is the volume of flocculated solids in the bottom of the vessel. Each point is the mean of four replications. $LSD_{0.05}$ applies for comparisons between any two means.

Table 4. Effect of PAM on solids and COD removal from flushed swine manure (feeder/finish operation)*

Polymer Rate (mg/L)	TSS Concentration† (g/L)	TSS Removal Efficiency‡ (%)	VSS Concentration (g/L)	VSS Removal Efficiency (%)	COD Concentration (g/L)	COD Removal Efficiency (%)
1st Flush Sample (TS = 6.75 g/L)						
0	3.57	13	2.91	14	10.18	7
5	3.35	19	2.77	18	10.15	7
10	3.25	21	2.64	21	9.88	10
25	2.67	36	2.08	38	7.77	29
50	1.42	66	1.14	66	5.26	52
100	0.32	92	0.26	92	3.44	69
200	0.17	96	0.13	96	2.84	74
$LSD_{0.05}$	0.58	14	0.49	15	1.31	12
2nd Flush Sample (TS = 3.22 g/L)						
0	1.41	5	1.04	5	4.26	5
2	1.09	26	0.82	25	3.87	14
5	0.78	49	0.57	48	3.52	22
10	0.61	59	0.46	58	2.97	34
25	0.28	81	0.20	82	2.20	51
50	0.17	88	0.10	91	1.88	58
100	0.13	92	0.08	93	1.92	57
$LSD_{0.05}$	0.16	10	0.11	10	0.99	22

* Average of two cationic PAMs (494C and 234GD) and two replications. The 1st flush sample contained manure produced overnight (8 h), and 2nd flush sample contained manure generated during a 4-h period.

† Concentration in manure liquid passing 1-mm screen after flocculation treatment. TSS = Total Suspended Solids, VSS = Volatile Suspended Solids, COD = Chemical Oxygen Demand, TS = Total Solids.

‡ Removal efficiency relative to concentration before chemical treatment and screening (table 1).

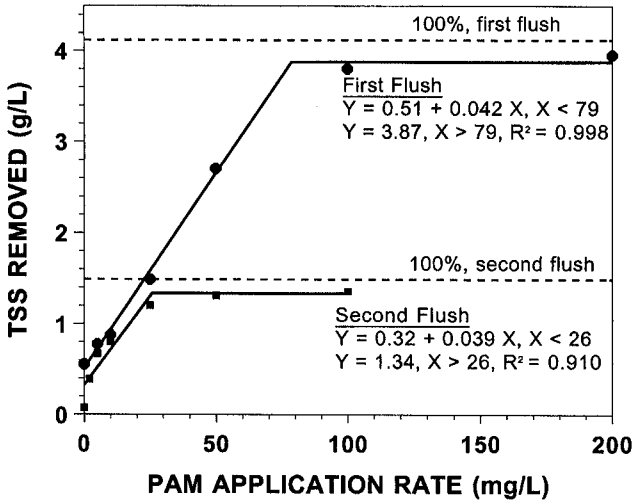

Figure 2–Capture of total suspended solids (TSS) from flushed swine manure (feeder/finish operation) using PAM treatment and screening (table 4). Optimum PAM application rates were 79 mg/L in the first flush sample and 26 mg/L in the second flush sample. At these rates, TSS removal efficiencies were 94% and 90%, respectively. Initial TSS concentration (dashed lines): first flush sample = 4.12 g/L, second flush sample = 1.49 g/L. Each point is the mean of two cationic polymers and two replications.

PAM Rate Evaluation

The effect of polymer dosage on suspended solids and COD removal from flushed swine manure (feeder/finish samples) is shown in table 4. Data for the two polymers were averaged because of similar performance as revealed by statistical analysis. Suspended solids (TSS and VSS) concentrations after screening were significantly decreased (>90%) by increased rates of PAM application. By comparison, screening without polymer application (PAM rate = 0) removed only 5 to 14% of suspended solids. Flocculation intensity increased linearly with increasing PAM rates up to an optimum level of total flocculation (WERF, 1993) where further increase of polymer dosage had little (non-significant) effect on solids concentration in the effluent. The flocs were large and effectively retained by the 1-mm opening screen used. A linear-plateau function was used to determine optimum PAM application rates based on TSS removal (fig. 2). Optimum PAM application rates occurred at 79 mg/L in the first flush sample and 26 mg/L at the second flush sample. At these rates, TSS removal efficiencies were 94% and 90%, respectively. Corresponding PAM use efficiencies (gram TSS removed/gram PAM) were 49.3 and 51.8. Volatile suspended solids (VSS) were highly correlated with TSS (r = 0.998) and, therefore, the removal efficiencies of both fractions were almost identical (table 4). Averaged across all treatments and replicates (n = 64), VSS comprised 79.5% of TSS (±1.1%). Polymer usage was also calculated in terms of lb of polymer per ton of dry solids produced to compare with other uses. At optimum swine manure flocculation, the weight of polymer used ranged between 39 to 41 lb of polymer per ton of dry solids produced (1.95 to 2.05% TSS produced). The polymer usage rate obtained is within the range of typical wastewater/industrial applications (8 to 50 lb/ton) but significantly lower than polymer usage rates of 480 to 580 lb/ton reported for dairy manure (McKenney, 1998). This difference between manure types is consistent with Zhang and Lei (1996) reporting a lower proportion (0.15:1) of polymer dosage requirement for swine manure compared to dairy manure with similar TS content.

Although PAM treatment removed as much as 74% of COD, removal efficiencies were not as high as those associated with suspended solids (table 4). This apparent difference in performance is due to a background COD (2 to 3 g/L; from reduced inorganic compounds such as ammonia) that was not affected by PAM treatment but was

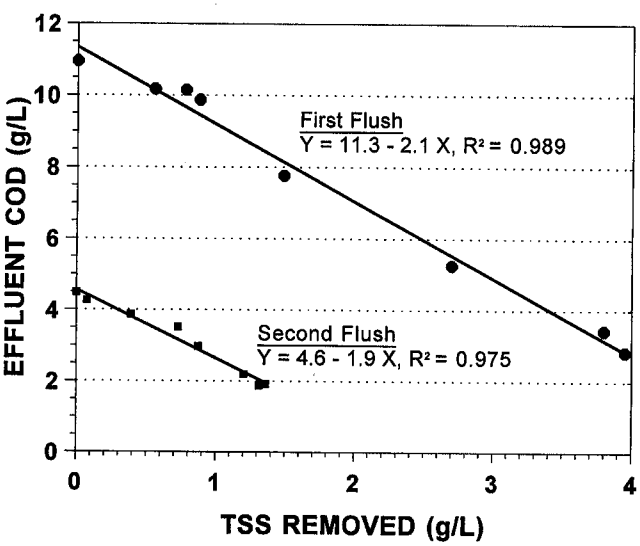

Figure 3–Relationship between effluent chemical oxygen demand (COD) concentration and the total suspended solids (TSS) removed using PAM treatment and screening. Data include seven PAM rate treatments (0 to 200 mg/L, table 4) and the initial sample (TSS removed = 0). Each point is the mean of two cationic polymers and two replications.

included in the COD analyses. In reality, about 98 to 99% of the variation in COD concentration in the treated effluent is explained by the removal of flocculated suspended particles (fig. 3). The corresponding rate of COD reduction obtained in both liquid manure samples was similar. It averaged 2.0 g COD/g TSS removed and 2.6 g COD/g VSS removed. Large COD reductions in the liquid effluent can reduce odor from existing anaerobic lagoons. For example, Humenik and Overcash (1976) indicate that odor is minimal with loading rates below 60 g of COD/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) and comparable to COD reduction levels obtained with PAM treatment. These results are also significant to the swine producer who wishes to incorporate an anaerobic digestor for methane production. Holmberg et al. (1983) indicate that screening *per se* 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 show that only about 21 and 37% of the methane producing material is retained by screens having a 0.98- and 0.23-mm opening, respectively. Our results indicate that PAM flocculation can substantially increase capture of methane-yielding feedstock for anaerobic digestion and that these materials can be effectively retained even with a relatively large screen (1-mm opening).

The effect of PAM dosage on nutrient removal is shown in table 5. Polymer application significantly decreased nutrient concentration in the liquid phase. Similar to results in the gravity settling tests, the NH_3-N and o-PO_4-P fractions remained unchanged by treatment. The organic part of the total N and P accounted for all the nutrients removed as solid by PAM flocculation. The proportion of organic nutrients to total nutrients in the liquid manure samples was 30 to 46% for N and 55 to 65% for P (table 1). Since the samples were collected using fresh-water flush and not a lagoon recycle, these values parallel the composition of swine manure as excreted. The organic nutrients in the flushed effluent were mostly contained in suspended manure particles, which in turn were efficiently separated by flocculation treatment. This relationship is better shown in figure 4, indicating that for each 1% of TSS captured by PAM flocculation, a similar percentage of organic N or P was removed from the effluent. For example, at the 90 to 94% TSS removal efficiencies obtained with optimum PAM rates, the corresponding nutrient removal efficiencies were 86 to 89% for organic N and 91 to 95% for organic P. As a comparison, removal efficiencies using screening without PAM treatment (PAM rate = 0) were only 11 to 21% for organic N and 16 to 17% for organic P. In the average, 7.0 g of organic N (SE = 0.4%) and 3.0 g of organic P (SE = 0.1%) were removed from the liquid phase for every 100 g of TSS separated by PAM flocculation.

Cost of chemical to flocculate suspended solids from flushed swine manure was calculated on the basis of treating the effluent from 1,000-head finishing operation growing pigs from 18.1 to 100 kg (40 to 220 lb). In the average, each pig weighs 59 kg (130 lb). For a polymer usage of 2.0% (2 g polymer/100 g dry solids produced) and a TSS removal efficiency of 90% (values obtained in this study) and for a TSS production rate of 5.05 kg/1000 kg live mass/day (NRCS, 1992), the amount of PAM required for 1,000 pigs is 5.36 kg/day. The cost of cationic PAM is approximately $4.96/kg for dry formulations ($2.25/lb). This results in a daily chemical cost of $26.60/1,000 pigs. For an operation that grows three groups of pigs per year in 105 day/group, the chemical cost

Table 5. Nutrient removal from flushed swine manure (feeder/finish operation) by PAM flocculation and screening*

Polymer Rate (mg/L)	Organic Nitrogen Concentration† (mg/L)	Organic Nitrogen Removal Efficiency‡ (%)	Organic Phosphorus Concentration (mg/L)	Organic Phosphorus Removal Efficiency (%)
First Flush Sample (TS = 6.75 g/L)				
0	209	11	102	17
5	175	25	92	25
10	177	24	93	24
25	143	39	73	40
50	99	58	48	60
100	46	80	20	83
200	40	83	14	89
$LSD_{0.05}$	63	27	25	20
Second Flush Sample (TS = 3.22 g/L)				
0	91	21	33	16
2	83	27	30	24
5	57	51	19	53
10	38	67	13	67
25	23	80	8	81
50	10	92	2	96
100	6	95	0	100
$LSD_{0.05}$	34	30	7	19

* Average of two cationic PAMs (494C and 234GD) and two replications.

† Nutrient concentration in liquid manure passing 1-mm screen after flocculation treatment. Inorganic forms were not affected by PAM application; control NH_4-N concentrations were 265 and 274 mg/L in the first and second flush, respectively; corresponding o-PO_4-P concentration were 65 and 34 mg/L.

‡ Removal efficiency relative to concentration before chemical treatment and screening (table 1).

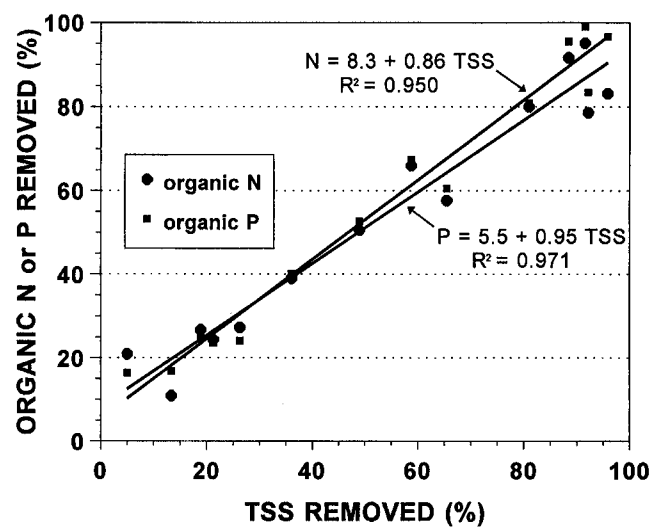

Figure 4–Relationship between the removal of nutrients and removal of total suspended solids by PAM treatment and screening. Data include seven PAM rate treatments (0 to 200 mg/L, table 4) and two swine waste effluent samples from a finishing operation. Each point is the mean of two cationic polymers and two replications.

per finished pig is $2.79 and the annual chemical cost for the 1,000 head operation is $8,379. The feasibility of this technology needs to consider not only the direct impact on air and water quality but also its effect on development of new manure management options for flushing systems. For example: odor can be reduced from reduced organic loads to existing anaerobic lagoons; nutrients can be concentrated in the solid fraction and transported to other regions without a nutrient surplus; methane gas can be produced more efficiently; and since very little volatile solids remain in the liquid effluent, it may be possible to apply aeration treatment at reasonable cost to further lower odor and ammonia emissions along with on-farm nutrient loads.

CONCLUSIONS

Most of the organic nutrients in liquid swine manure are contained in fine suspended particles that are not separated by available mechanical separators. In this study, for example, only 5 to 13% of TSS, 5 to 7% of COD, and about 10 to 20% of organic N and P were removed with a 1-mm opening screen. Separation of solids and nutrients from untreated liquid manure and redistribution of solids to nutrient-deficient areas are critical for conserving nutrients and avoiding nutrient pollution in areas where animal production is concentrated. Our proposal of using PAM flocculants (Vanotti and Hunt, 1996) fits this solids separation strategy because PAM can substantially increase capture and removal of fine suspended solids and associated organic nutrients. Our evaluation of cationic, anionic, and neutral PAMs showed that the cationic type is very effective and probably a better option than alum for separating solids and nutrients from flushed swine wastewater. Within the cationic PAM type, materials that had moderate-charge density (20%) were more effective than polymers with higher charge density. The reaction of PAM with the wastewater was fast and produced large, dark-brown flocs that rapidly settled out of the matrix wastewater, leaving a remarkably clear supernatant. The flocs were large enough to be effectively retained by a 1-mm opening screen. High TSS removal efficiencies (>90%) were obtained with PAM rates of 26 and 79 mg/L applied to samples containing 1.5 and 4.1 g TSS/L, respectively. At these optimum rates, the polymer usage rate was about 2.0% of the TSS produced. For a typical feeder-to-finish operation, the calculated chemical cost per finished pig is $2.79. Flocculation and separation of suspended solids in turn significantly decreased COD and organic nutrient concentration in the treated effluent. Removal efficiency of organic N and P followed approximately a 1:1 relationship with removal efficiency of TSS. Our results indicate that PAM polymers have a potential for efficient separation of manure solids, COD, and nutrients from flushed swine operations. Large COD removal has direct implication on odor emissions from existing lagoons. The proposed technology also provides an attractive alternative to existing liquid manure management methods. It, thus, promotes the transportation of nutrients from nutrient-rich to nutrient-deficient areas and expands options for environmentally sound and sustainable swine production.

ACKNOWLEDGMENTS. Appreciation is given to both Dr. Diana Rashash for helping with manure sampling and to Cytec Industries, Inc. for providing the polymer materials used in the study.

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