Effectiveness of Liquid-Solid Separation for Treatment of Flushed Dairy Manure: A Case Study

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INTRODUCTION

The Lutz Dairy (Sunny Day Farm) located in Chester, South Carolina is home to the highest producing, registered Jersey herd in the world. On the average, 54 cows are milked each day. The cows are housed in a naturally ventilated, two-row freestall barn. A total mixed ration is fed using a drive-by feeding fence located along one side of the building. Generous amounts of organic bedding (about 0.5 m^3 or 18 ft^3 per stall per week) are used in the freestalls and large amounts of feed is available for the cows all of the time. The cows are milked twice each day in a side-opening parlor and manure is flushed from the freestall alleys each time the cows are milked. Fresh water from a farm pond is used for flushing. The flushed manure is collected in a concrete channel along the end of the barn. The manure flows toward a stationary inclined screen separator that has a screen size of 1.6 mm (0.06 in). The mechanical separator was manufactured by AgPro® (Clemson University does not endorse this product over similar products manufactured by other companies). As the separated solids are conveyed from the machine they fall to a concrete storage pad where they can form a pile that can be as high as 3.0 m (10 ft) tall. The separated liquid (or effluent) is transferred by pipe to a two-cell settling basin. The outlet pipe of the second gravity settling chamber discharges liquid manure to an anaerobic lagoon. The outflow of each cell of the settling basin can be controlled by stacking boards to form a variable height weir. The steps in the manure treatment and handling system are shown in Figure 1.

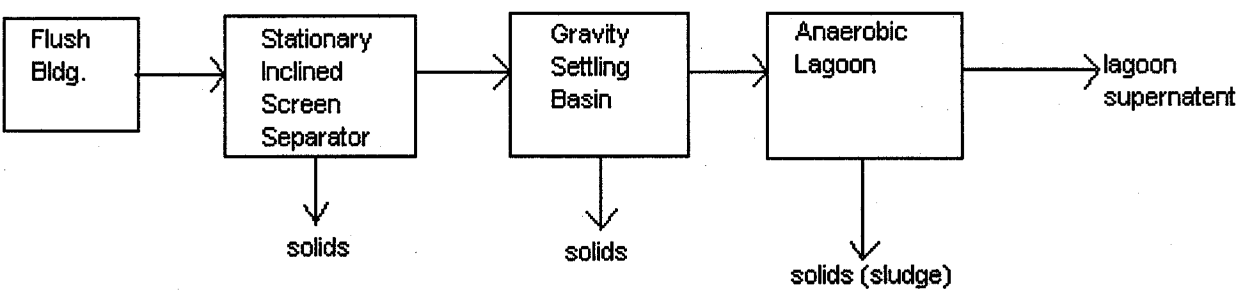

Figure 1. Flow chart of the system used to treat and store flushed dairy manure.

The anaerobic lagoon was constructed before the liquid-solid separation system was installed. Therefore, much of the sludge in the bottom of the lagoon accumulated before the liquid-solid separation system was completed.

In May 1998, a Clemson University Extension in-service training class (Reducing the Impact of Animal Agriculture on the Environment) met at the farm to learn about the manure handling system, and collect manure samples for analysis. In particular the objectives of the study were to:

- determine the solids and plant nutrient content of the: flushed manure, effluent from the separator, effluent from the settling basin, mechanically separated solids, gravity separated solids, lagoon supernatant (surface water), and lagoon sludge,
- determine the amount of solids and plant nutrients removed from the flushed manure by the components of the liquid-solid separation system,
- determine the solids and nutrient removal of the entire system (liquid-solid separation and lagoon), and
- determine how a polymer or alum can be used to enhance the solids and nutrient removal of the separation system.

EXPERIMENTAL METHODS

The dairy producer agreed to clean all separated solids from below the stationary screen separator the day before the measurements were taken. Samples were collected from the morning flush. The pile of solids below the mechanical separator represented 29 hours of solids accumulation from an evening and morning flush.

The time required to flush a freestall alley was about 15 seconds. The feed and stall alleys were flushed independently. The mechanical separator required about 30 minutes to process each flush. Samples were collected for each flush.

Teams of 4 to 5 people were placed at the following sampling locations:

1. at the point where the flushed manure fell from the floor into the collection channel,
2. at the effluent pipe of the stationary screen separator (which is the inlet to the gravity settling basin),
3. at the outflow point of the first cell of the gravity settling basin, and
4. at the outflow point of the second cell of the gravity settling basin.

Each team used long-handled sampling cups that held 500 to 1,000 ml to continuously sample from their respective location throughout the flow period. The large samples were collected in 18.9 L (5 gal) buckets. The team that sampled the flush water had the most difficult job since the duration of flow was only 15 seconds. However, at least one of the team members drew a sample almost every second during the flow.

The samples that were collected from each flush were combined together while being well agitated. A paint stirrer powered by a cordless drill was used to agitate the large samples. Well-mixed samples were removed from the buckets using the sampling cups. At least 4 L of sample was bottled from each sampling location, put on ice, and was transported to Clemson University for analysis. In addition, approximately 10 L of flushed manure and effluent from the stationary screen separator were transported on ice to the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center where gravity settling experiments and a portion of the sample analyses were performed.

All of the separated solids from the mechanical separator were weighted using 18.9 L (5 gal) buckets and a digital scale. Samples from several locations in the pile were placed in a plastic bag after the pile was turned during the weighing process. A large, well-mixed sample of the solids from the settling basin, obtained from several locations, was also collected and placed in a plastic bag. All samples were stored on ice while being transported to Clemson University for analysis.

Lagoon Samples

Four samples of the lagoon supernatant were collected using long-handled cups (3.66 m or 12 ft long) and small plastic buckets on a rope. The two teams that used the long handled cups sampled the surface water from several locations around the perimeter of the lagoon. The samples were mixed in a bucket and 2 liters were stored on ice for analysis. The two teams that used the plastic buckets on a rope threw the bucket out into the lagoon and quickly pulled the bucket back to shore with the rope. Several samples were taken, and mixed in a large bucket. About 2 liters were poured into plastic bottles, and stored on ice.

Lagoon sludge was sampled by using a metal bucket that had a piece of steel riveted onto one side to serve as a weight. A rope was tied to the handle of the bucket. The bucket was thrown out into the lagoon, allowed to sink to the bottom, and then was pulled in slowly with the rope. This was repeated several times, and 8 well-mixed liters were stored on ice in plastic bottles.

Quantities Measured

The samples that were transported to Clemson University were analyzed to measure the concentrations of the following variables: total solids (TS), total volatile solids (VS), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4^+- N), total phosphorus (expressed as P_2O_5), and total potassium (expressed as K_2O), Ca, Mg, S, Zn, Cu, Mn, and Na. Organic nitrogen (organic-N) was calculated as the difference of TKN and NH_4^+- N. Plant nutrient analyses were provided by the Agricultural Service Laboratory at Clemson University. Two replicate plant nutrient analyses were performed for each sample.

Measurements of TS, and VS, were measured in the Agricultural, Chemical, and Biological Research Laboratory in the Department of Agricultural and Biological Engineering at Clemson University. Each sample was poured into a large beaker or bucket and was well mixed using a magnetic stirrer or a paint stirrer. Two 30 to 40 ml subsamples were taken of each sample and were decanted into pre-weighted porcelain dishes. Free water was evaporated from the samples by placing them on a steam table for 12 to 16 hours. The samples were dried completely by holding them in a drying oven for 24 hours at a temperature of 105 C. The mass of TS was determined after the samples were allowed to cool in a desiccator. The mass of the fixed solids was determined by incinerating the dried solids in a furnace that was maintained at 600 C for 1.5 to 2 hours, and allowing the samples to cool in a desiccator. The mass of VS was simply the difference between the total and fixed solids. The TS and VS concentrations were calculated by dividing the mass in mg by the sample volume in L.

Gravity Settling Experiments

Large (10 L) samples of the flushed dairy manure and the effluent from the stationary inclined screen separator were collected, stored on ice, and transported to the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center in Florence, SC. Experiments were conducted to determine the amount of total solids (TS), total suspended solids (TSS), suspended volatile solids (SVS), TKN, organic-N, ammonium-N, total phosphorous, inorganic phosphorous, COD, total potassium, copper, and zinc that can be removed by gravity settling with and without chemical enhancement. The total suspended solids, and suspended volatile solids are measurements of the nonsoluble total and volatile solids that are removable by separation. The soluble fractions can be obtained by difference. The experiments were conducted using 1 L Irmhoff settling cones. The procedures defined by APHA (1995) were followed for all of the measured parameters.

Settling experiments were performed for the unscreened flushed manure and the effluent from the stationary screen separator (screened manure). Three replications of the following treatments were applied to the unscreened and screened dairy manure:

- 30 minutes of settling,
- 60 minutes of settling,
- 60 minutes of settling after mixing in a cationic polyacrylamide polymer with a 20% charge density (PAM) at concentrations of 250, 300, 350, and 400 mg/L, and
- 60 minutes of settling after mixing with 3,194 mg/L (approximately a 1.5 Al/P molar ratio) of liquid aluminum sulfate ($AL_2(SO_4)_3$ 12 H_2O).

The percent of the solids, COD, nitrogen, phosphorous, potassium, copper, and zinc removed was calculated from the difference in the average concentration of solids or nutrients in the manure poured into the settling cone (influent or initial) and the concentration of solids or nutrients in the decanted liquid (or supernatant).

RESULTS FOR THE MANURE TREATMENT SYSTEM

The samples collected at the dairy farm were analyzed to determine the nutrient and solids concentration of the influent and effluent for each step in the manure treatment system (Figure 1). The amount of solids and nutrients removed by each component, and the entire system (including the lagoon) were determined. The solids and nutrient content of the separated solids were also measured.

Solids and Nutrient Content of Flushed Manure and Removal by the Stationary Inclined Screen Separator

The solids and nutrient content of the flushed and screened manure, and the percent removed by the inclined stationary screen separator are shown in Table 1. The total solids content of the flushed manure was 38,258 mg/L or 3.83 % TS, and is much higher than found on most flush dairies. Flushed dairy manure is typically in the range of 1 to 2% solids. The higher solids content in this case is attributed to the large amounts of organic bedding used (0.5 m^3 or 18 ft^3 per stall per week) and the large amount of wasted feed present in the manure. The total suspended solids accounted for 77.3% of the TS, and 83.9% of the total solids were volatile. On the average, 87.7% of the volatile solids were suspended and are removable by physical means. The TKN concentration in the flushed manure was 1,433 mg/L and was 53.9% organic-N.

The removal of all of the constituents in dairy manure by the inclined stationary screen separator is given in the table. In particular, the results indicate that 60.9% of the total solids, 62.6% of the suspended solids, 62.89% of the VS, 66.5% of the COD, 45.7% of the ammonium-N, 52.2% of the organic-N, and 53.1% of the phosphorous was removed by the mechanical separator. The

Table 1. Removal of solids, COD, plant nutrients, and minerals from flushed dairy manure by an inclined stationary screen separator (to convert from mg/L to lb / 1,000 gal divide by 119.826).

	Flushed Manure	After Inclined Stationary Screen	Amount Removed
	-------- mg/L -------		%
Total Solids	38,258	14,959	60.9
Total Suspended Solids [a]	29,575	11,051	62.6
Volatile Solids	32,073	11,937	62.8
Suspended Volatile Solids [a]	28,137	9,760	65.3
Chemical Oxygen Demand [a]	60,096	20,136	66.5
Ammonium-N	661	359	45.7
Organic-N	772	369	52.2
TKN	1,433	729	49.2
P_2O_5 [b]	930	436	53.1
K_2O [c]	921	453	50.8
Ca	953	488	48.8
Mg	337	168	50.2
S	179	104	41.6
Zn	14	7	50.0
Cu	11	12	0
Mn	12	6	50.0
Na	288	140	51.2

[a] Computed from data obtained from the Coastal Plains Soil, Water, and Plant Research Center, USDA-ARS. All other sample analysis performed at Clemson University.
[b] Total phosphorous expressed as P_2O_5.

[c] Total potassium expressed as K_2O.

concentration in copper was not significantly changed, and as result the percent removed was zero.

The only unexpected result was the large removal of ammonium-N. Ammonium-N is in solution and can not be screened. In addition, the procedures to measure ammonical-N used by most laboratories typically convert all NH_3^--N to NH_4^+-N. Therefore, the data includes the concentrations of both ammonical forms of N. Flushing dairy manure is a turbulent flow process and the mixing that occurs can promote the conversion of NH_4^+ to NH_3^-. Also, the manure was held in a long open channel for 30 min as it was processed by the mechanical separator. The lifting and spreading of the slurry on the screen would be expected to enhance volatilization of ammonia. Therefore, the large amount of ammonium-N shown as removed by the separator was attributed to enhanced volatilization.

The amount of solids removed by the separator was measured by weighing all of the solids separated from an evening and morning flush. All of the solids in the pile were weighted using 5 gal buckets and a portable digital scale. The separator produced 1360 kg (2999.5 lb) of solids from 54 cows in 29 hours. Therefore, 20.9 kg (46 lb) of solids with a moisture content of 79.7% was removed from the flushed manure per cow per day.

The separated solids were composed of manure solids, stall bedding, and wasted feed. The amount of solids produced per cow per day was estimated based on fresh manure production data, bedding requirements, and an estimate of feed wastage (Bickert et al., 1995). The solids produced in the dairy barn, on a dry matter basis, included: 4.67 kg (10.3 lb) manure solids, 1.18 kg (2.6 lb) of bedding, and 0.68 kg (1.5 lb) of feed. Therefore, the total amount of solids produced per cow per day on a dry matter basis was estimated to be 6.53 kg (14.4 lb). The quantity of solids removed by the mechanical separator on a dry matter basis was 4.24 kg (9.34 lb) per cow per day. Therefore, the mechanical separator was estimated to remove 65% of the solids. This value is only 6.6% higher than the values calculated based on the influent and effluent concentrations, and is on the same order of magnitude as the sampling error (the coefficient of variation for TS measurements ranged from 7 to 11%).

Removal of Solids and Nutrients by the Gravity Settling Basin

The second step in the manure treatment system used on the Lutz Dairy is to a two-cell settling basin. The two chambers are separated by a concrete wall with a variable height weir located near the center of the wall. The liquid level of each chamber is controlled by the number of boards that are stacked in the steel slots that form the weir.

The reduction in solids and plant nutrients from the settling basin was lower than expected. The boards that control the outflow of the effluent from the gravity settling basins were too low and channelized flow was observed between the inlet and outlet of each chamber. An additional board should have been added to provide longer detention time and would have allowed more time for settling to occur. The data indicated that the concentrations of solids and nutrients in the effluent from each chamber of the settling basin were the same within experimental error.

Therefore, the solids and nutrient data for the effluent from each chamber was averaged and are given in Table 2.

Table 2. Removal of solids and plant nutrients by a settling basin following the stationary inclined screen separator (to convert from mg/L to lb / 1,000 gal divide by 119.826).

	Concentrations After Gravity Settling	Amount Removed By the Settling Basin	Amount Removed by the Inclined Screen and Settling Basin
	mg/L	%	%
Total Solids	11,470	23.3	70.0
Volatile Solids	8,705	27.1	72.9
Ammonium-N	399 (379)	0	42.7 [c]
Organic-N	304	17.5	60.6
TKN	703	3.5	50.9
P_2O_5 [a]	373	14.6	59.9
K_2O [b]	508 (481)	0	47.8 [c]
Ca	423	13.3	55.6
Mg	158	5.7	53.0
S	86	17.2	51.7
Zn	5	25.0	62.5
Cu	7	45.0	38.9
Mn	5	10.0	55.0
Na	151 (146)	0	49.3 [c]

[a] Total phosphorous expressed as P_2O_5.

[b] Total potassium expressed as K_2O.

[c] Concentrations of these nutrients were higher in the effluent from the settling basin than in the effluent from the inclined screen, but were within experimental error. Removal was calculated using the average concentration in the effluent from the inclined screen separator and the effluent from the settling basin.

The amount of solids and nutrients removed by the settling basin were calculated using the constituent concentrations for the effluent of the inclined screen as the influent values (Table 1). The combined treatment provided by the two-stage separation process (screening followed by settling) was determined using the constituent concentrations of the flushed manure as the influent values.

The tabulated results indicate that the settling basin removed 23.3% of the TS, 27.1% of the VS, no ammonium-N, 17.5% of the organic-N, 14.6% of the total P (expressed as P_2O_5), and none of the potassium. The two-stage separation process removed 70.0% of the TS, 72.9 % of the VS, 42.7% of the ammonium-N, 60.6% of the organic-N, 59.9% of the total P (expressed as P_2O_5), and 47.8% of the potassium. Significant percentages of Cu, and Zn were removed, but the initial concentrations were low.

Sludge is composed of the fixed solids that settle to the bottom and the volatile solids that degrade very slowly. The fixed solids can be calculated as TS-VS. From the data given in Tables 1 and 2 it can be determined that the two-stage separation system removed 55.3% of the fixed solids. The majority of these fixed solids would contribute to sludge build-up. Furthermore, a large portion of the VS removed would be expected to be the large particles that are very slow to degrade.

Removal of Solids and Nutrients by the Complete System

The final treatment of dairy manure occurs in the anaerobic lagoon. An anaerobic lagoon treats liquid manure in the following ways: (1) dilution, (2) settling, (3) anaerobic decomposition of the volatile solids, and (4) volatilization of ammonia-N. A large fraction of the solids that settle to the bottom of the lagoon are destroyed by the anaerobes. The solids that degrade very slowly or not at all form the sludge layer. As the solids are decomposed, organic nitrogen is converted to ammonia that is lost from the surface through volatilization.

The reduction in solids and nutrients was estimated as the difference in concentration between the effluent from the settling basin and the supernatant. The overall treatment of the flushed dairy manure by the two-stage separation process, and the lagoon was calculated from the concentrations of the fresh manure and the lagoon supernatant. The constituent concentrations found in the lagoon supernatant, the reduction in plant nutrients and solids by the lagoon, and the treatment provided by the complete system are given in Table 3.

The different methods used to measure the lagoon supernatant (bucket and rope vs. long-handled dip cup) were not significantly different. Therefore, all replications of solids and nutrient analyses were averaged for the lagoon supernatant.

With respect to the supernatant, a large amount of treatment was provided by the lagoon for all solids and plant nutrients. The lagoon reduced the concentration of TS by 76.8%, VS by 83.8%, organic-N by 77.3%, and P_2O_5 by 65.4%. The complete system removed 93.0% of the TS, 95.6% of the VS, 54.2% of the ammonium-N, 91.1% of the organic-N, and 86.1% of the P_2O_5.

Obviously the minerals, phosphorous, and potassium removed from the liquid was moved to the separated solids, and solids that settled to the bottom of the lagoon. Ammonium-N can be lost by volatilization. Biological degradation of the organic-N yields NH_4^+-N that can also be lost to the atmosphere by volatilization of ammonia. Removal of a large fraction of the organic-N prior to the lagoon would greatly reduce ammonia losses to the atmosphere. In this case, 60.6% of the organic-N did not enter the lagoon.

Solids and Nutrient Content of Separated Solids and Sludge

The total solids (%TS) and nutrient content of the screened solids, solids from the settling basin, and lagoon sludge are given in Table 4. The separated solids from the stationary screen separator had a solids content of 20.3%, piled easily, and had low odor. The solids from the settling basin had a higher moisture content (10.9% TS), and were richer in nitrogen and phosphorous than the mechanically separated solids. The concentrations of potassium and minerals were similar.

Table 3. Concentrations of solids and plant nutrients in the lagoon supernatant, and the amount removed by the lagoon and the complete system (to convert from mg/L to lb / 1,000 gal divide by 119.826).

	Concentrations In the Lagoon Supernatant	Reduction By the Lagoon	Amount Removed By the Complete System
	mg/L	%	%
Total Solids	2,665	76.8	93.0
Volatile Solids	1,410	83.8	95.6
Ammonium-N	303	20.1 [c]	54.2
Organic-N	69	77.3	91.1
TKN	373	46.9	74.0
P_2O_5 [a]	129	65.4	86.1
K_2O [b]	367	23.7 [c]	60.2
Ca	185	56.3	80.6
Mg	90	43.0	73.3
S	26	69.8	85.5
Zn	1	80.0	92.9
Cu	1	85.7	90.9
Mn	1	80.0	91.7
Na	115	23.8	60.1

[a] Total phosphorous expressed as P_2O_5.
[b] Total potassium expressed as K_2O.
[c] Concentrations of these nutrients were higher in the effluent from the settling basin than in the effluent from the inclined screen, but were within experimental error. Removal was calculated using the average concentration in the effluent from the inclined screen separator and the effluent from the settling basin.

Table 4. Plant nutrients in separated dairy solids and lagoon sludge (to convert to lb/ton divide by 500).

	Solids From Stationary Screen	Solids From Settling Basin	Lagoon Sludge (Scraped from bottom)
Total Solids (%)	20.3	10.9	7.0
	---------------- mg/kg, wet basis ----------------		
Ammonium-N	100	200	1,840
Organic-N	2,370	2,885	8,950
TKN	2,470	3,085	10,790
P_2O_5	1,530	2,010	11,945
K_2O	930	485	2,465
Ca	2,515	2,755	13,235
Mg	610	325	1,895
S	385	555	3,510
Zn	30	95	300
Cu	50	70	305
Mn	20	35	500

Na	235	120	515

Organic nitrogen accounts for 96% of the total nitrogen in the mechanically separated solids and 94% of the nitrogen in the solids from the settling basin.

All of the major and minor plant nutrients are concentrated to some extent in the sludge. The nutrients that are the most concentrated in the sludge are organic-N, P_2O_5, and Ca. Organic-N constitutes 83% of the total nitrogen in the sludge. Potassium was not concentrated to as great an extent as phosphorous.

RESULTS FOR THE GRAVITY SETTLING EXPERIMENTS

Large samples (10 L) of the flushed dairy manure (unscreened) and the effluent from the inclined screen separator (screened) were used to conduct settling experiments with and without flocculents. One goal of these experiments was to determine if settling with a flocculent could yield a single-step separation process that would equal or exceed the combination of mechanical and gravity separation currently used on this farm. The other goal was to determine the amount of flocculent needed to significantly enhance the constituent removal of the two-stage process by enhancing the settling of screened manure. The flocculents considered were a cationic polymer (PAM) and liquid aluminum sulfate.

Gravity Settling of Unscreened and Screened Dairy Manure

The amount of solids, COD, and plant nutrients that were removed from the unscreened flush manure after 30 and 60 minutes of settling is shown in Table 5. Settling of dairy manure with a solids content of 3.83% for 30 minutes removed 55% of the TS and VS, 61% of the COD, 26% of the organic-N, and 27.8% of the total phosphorous. Increasing the settling time to 60 min removed 5.8% more TS, 17.1% more organic-N, and 10% more total P. Settling did not remove any of the inorganic-P, only trace amounts of potassium, and only a small amount of ammonium-N. Gravity settling for 60 min removed 71.5% of the total suspended solids and 74.1% of the suspended volatile solids. The copper and zinc concentrations in the manure were low, and 60 min of settling removed 40% of the Zn and 33% of the Cu.

Comparison of the removal of solids and nutrients by 60 min of settling with the results shown for the inclined screen separator (Table 1) indicates that the two processes removed essentially the same amounts of total (TS) and volatile solids (VS). Gravity settling removed about 9% more of the suspended total and volatile solids (TSS and SVS). However, the inclined screen was more effective at removing total P (53.1% vs. 37.7%), TKN (49.2% vs. 24.0%), organic-N (52.2% vs.43.3%), and K_2O (50.8% vs. 0.4%).

Gravity settling of dairy manure that had passed through a 1.6 mm screen for 30 min was not very effective. Only 15.6% of the TS were removed in 30 minutes. This was not unexpected since the screen removed 62.6% of the suspended solids. Settling of screened dairy manure for 60 min gave slightly better results and the data are presented in Table 6. The laboratory experiments yielded a TS removal of only 18.1% by settling for 60 min. The data taken on-farm, Table 2, indicate that the two-chambered settling basin removed slightly more of the total solids

Table 5. Removal of solids, COD, and plant nutrients from flushed dairy manure after 30 and 60 minutes of settling (to convert from mg/L to lb / 1,000 gal divide by 119.826).

		After Settling for 30 Minutes		After Settling for 60 Minutes	
	Influent mg/L	Effluent mg/L	% Removed	Effluent mg/L	% Removed
TS	41,763	18,784	55.0	16,376	60.8
TSS	32,955	13,032	60.5	9,378	71.5
VS	34,957	15,640	55.3	12,652	63.8
SVS	30,113	10,796	64.1	7,808	74.1
COD	66,416	25,994	60.9	24,193	63.6
NH_4^+-N	541	426	21.3	589	0
Organic-N	923	681	26.2	524	43.3
TKN	1,464	1,107	24.4	1,113	24.0
P_2O_5 [a]	1,061	766	27.8	661	37.7
Elemental-P	467	337	27.8	291	37.7
Inorganic-P	136	138	0	137	0
K_2O [b]	958	952	0.6	954	0.4
Zn	15	11	26.7	9	40.0
Cu	6	4	33.3	4	33.3

[a] Total phosphorous expressed as P_2O_5.

[b] Total potassium expressed as K_2O.

Table 6. Removal of solids, COD, and plant nutrients from screened dairy manure after 60 minutes of settling (to convert from mg/L to lb / 1,000 gal divide by 119.826).

		After Settling for 60 Minutes	
	Influent mg/L	Effluent mg/L	% Removed
TS	11,962	9,795	18.1
TSS	7,468	7,321	2.0
VS	9,626	8,579	10.9
SVS	6,255	5,208	16.7
COD	12,789	8,793	31.2
NH_4^+-N	254	274	0
Organic-N	390	360	7.7
TKN	644	634	1.6
P_2O_5 [a]	370	320	13.5
Elemental-P	163	141	13.5
Inorganic-P	50	47	6.0
K_2O [b]	526	531	0
Zn	7	7	0

Cu	8	8	0

[a] Total phosphorous expressed as P_2O_5.

[b] Total potassium expressed as K_2O.

(23.3% vs. 18.1%), and about twice as many volatile solids (27.1% vs. 10.9) than indicated by using settling cones. The removal of P_2O_5 was about the same.

Enhanced Settling of Flushed Dairy Manure Using PAM

The amount of solids, COD, and plant nutrients removed from unscreened dairy manure by settling for 60 minutes with and without the addition of PAM is compared in Table 7. The amount of polymer added (PAM) ranged from 250 to 400 mg/L. The polymer was added to the manure, stirred well to enhance the exposure of suspended solids to the polymer, and then was allowed to settle for 60 min. Preliminary experiments indicated that at least 250 mg PAM/L was required to achieve a significant color change in the supernatant. Therefore, 250 mg PAM/L was used as the lower limit. Enhanced settling with PAM did not effect the concentration of inorganic P or ammonium-N significantly. Each treatment was replicated 3 times.

The data shown in the table indicate the following.

- The removal of solids, COD, and all plant nutrients increased as the amount of PAM applied was increased from 250 to 400 mg/L.
- The most significant increase in the removal of manure constituents was achieved for a PAM application rate of 250 mg/L. At this level of treatment, the removal of TSS was increased from 71.5% to 89.9%, or an increase by a factor 1.26 as compared to settling alone. The removal of SVS was increased by a factor of 1.22, and corresponded to a removal of 90.7%. The enhanced removal of TSS by application of 250 mg PAM/L also provided a 62% increase in the removal of organic-N and a 55% increase in the removal of P_2O_5.

Table 7. Removal of solids, COD, and plant nutrients from flushed dairy manure by settling for 60 minutes with and without application of PAM.

Constituent	Initial Concentration	AMOUNT OF PAM ADDED, mg/L 0	250	300	350	400
	mg/L	Percent Removed				
TS	41763	60.8	72.9	76.1	78.0	80.1
TSS	32955	71.5	89.9	92.6	96.2	98.0
VS	34957	63.8	78.1	80.3	83.1	84.7
SVS	30113	74.1	90.7	93.2	96.5	98.3
COD	66416	63.6	79.3	80.8	84.5	86.5
TKN	1464	24.0	43.8	45.7	50.9	53.6
ORGANIC-N	923	43.3	70.3	72.3	81.1	84.4
P_2O_5	1061	37.7	58.6	61.8	64.9	66.8
K_2O	958	0.4	2.6	3.5	4.4	5.2
Zn	15	40.0	79.8	82.0	93.1	96.7
Cu	6	33.3	80.0	82.8	92.8	96.7

- Increasing the PAM concentration by 50 mg/L, from 250 to 300 mg PAM/L, increased the removal of TSS by 3.0%. Adding another 50 mg PAM/L to give a concentration of 350 mg/L gave an additional TSS removal of 3.9% as compared to the results for 300 mg PAM/L. Finally, increasing the PAM concentration to 400 mg/L yielded only a 1.9% improvement in TSS removal. Therefore, increasing PAM concentrations in increments of 20% above 250 mg PAM/L yielded an additional removal of 2.9% on the average. The diminishing benefits of increased PAM concentrations indicates that the maximum practical PAM concentration for flushed dairy manure with a TS of 3.83% is 300 mg/L based on the removal of suspended solids (TSS). The enhancement in the removal of SVS diminished with increases in PAM concentration in a similar manner.
- Enhancing the removal of suspended total and volatile solids is not the only objective for the use of PAM with gravity settling. Removal of nitrogen, phosphorous, and potassium is of great concern in light of new regulations, which may limit the application of animal manure based on, phosphorous. The settling process can remove organic-N and the organic fraction of the total P (71% of total P is organic, Table 5). Addition of 250 mg PAM/L resulted in an increase in the removal of organic-N and P_2O_5 by a factor of 1.62, and 1.55 respectively. Gravity settling with PAM did not improve the removal of K_2O to a great extent. Increasing the PAM concentration to 300 mg/L increased the removal of total P by 5% and organic-N by 3%. Therefore, the removal of total-P and organic-N followed the same pattern as TSS, and the nutrient data support a maximum practical PAM concentration of 300 mg/L. However, a 30% increase in TSS removal, at 300 mg PAM/L, yielded a 64% increase in the removal of P_2O_5 and a 67% increase in the removal of organic-N.
- Although the concentrations of zinc and copper in the flushed dairy manure were low (15 and 6 mg/L respectively), addition of 300 mg PAM/L removed about 82% of these elements.
- Enhancing gravity settling with the addition of 300 mg PAM/L increased the removal of COD by a factor of 1.27.

Enhanced Settling of Screened Dairy Manure Using PAM

The influence of adding 250 to 400 mg PAM//L prior to settling of screened manure for 60 min is shown in Table 8. It should be noted that the removal of plant nutrients in this table is based on the concentration that entered the settling process, that is the effluent from the inclined screen. While settling of untreated screened manure (0 mg PAM/L) removed only a small amount of the suspended solids and plant nutrients the addition of PAM greatly enhanced the effectiveness of settling. For example, addition of 250 mg PAM/L increased the removal of SVS by a factor of 4.13, and increased the removal of P_2O_5 by a factor of 3.55. However, increasing the PAM concentration from 250 to 300 mg/L resulted in a 23% increase in the removal of P_2O_5 and a 28% improvement in the TSS reduction. Addition of more than 300 mg PAM/L gave only a modest increase in the removal of TSS (2.6%). Therefore, the maximum practical PAM concentration was the same as for the unscreened manure (300 mg PAM/L).

Table 8. Removal of solids, COD, and plant nutrients from screened dairy manure by settling for 60 minutes with and without application of PAM.

Constituent	Initial Concentration	AMOUNT OF PAM ADDED, mg/L 0	250	300	350	400
	mg/L	-------------------	Percent Removed	-------------------		
TS	11962	18.1	64.1	73.6	74.7	77.9
TSS	7468	2.0	68.1	87.4	89.7	94.6
VS	9626	10.9	44.7	56.7	57.8	60.8
SVS	6255	16.7	68.9	87.2	89.0	93.5
COD	12789	31.2	57.2	66.2	75.2	80.0
TKN	643	1.0	25.2	34.1	38.9	41.9
ORGANIC-N	390	0.9	39.9	62.4	62.3	73.9
P_2O_5	370	13.7	48.7	59.9	65.4	68.3
K_2O	526	0.0	3.7	0.2	4.4	4.3
Zn	7	0.0	70.0	82.9	89.5	96.2
Cu	8	0.0	59.2	80.8	87.5	96.7

The combined effects of the two-stage separation process, screening followed by settling with and without PAM is shown in Table 9. It should be noted that the removal of solids, COD, and plant nutrients in this table is based on the solids and nutrients present in the flushed manure. The data indicate that most of the removal using this two-stage approach is achieved using 300 mg PAM/L. Settling with 300 mg PAM/L following a 1.6 mm inclined screen resulted in the removal of 97.1% of the TSS, 97.3% of the SVS, 93.5% of the COD, 84.1% of the organic-N, 86.0% of the P_2O_5, and 50% of the K_2O.

Table 9. Removal of solids, COD, and plant nutrients from flushed dairy manure using a two-stage process that includes initial separation by an inclined stationary screen separator (1.6 mm) followed by settling for 60 minutes with and without application of PAM.

Constituent	Initial Concentration	AMOUNT OF PAM ADDED, mg/L 0	250	300	350	400
	mg/L	-------------------	Percent Removed	-------------------		
TS	41763	76.5	89.7	92.4	92.8	93.7
TSS	32955	77.8	92.8	97.1	97.7	98.8
VS	34957	75.5	84.8	88.1	88.4	89.2
SVS	30113	82.7	93.5	97.3	97.7	98.7
COD	66416	86.8	91.7	93.5	95.2	96.1
TKN	1464	54.9	67.1	71.1	73.1	74.5
ORGANIC-N	923	58.2	74.6	84.1	84.1	89.0
P_2O_5	1061	69.9	82.1	86.0	87.9	88.9
K_2O	958	49.9	52.3	50.5	52.6	52.5
Zn	15	53.3	86.0	92.0	95.1	98.2
Cu	6	0.0	45.6	74.4	83.3	95.6

Comparison of the Inclined Screen Separator with Settling of Unscreened Manure with 300 mg PAM/L, and the Two-Stage Separation Process

The removal of solids, COD, and major plant nutrients for the inclined screen separator, gravity settling with 300 mg PAM/L, and a two-stage process that includes screening followed by gravity settling with 300 mg PAM/L are compared in Figure 2. Gravity settling for 60 min with 300 mg PAM/L removed significantly more of the solids, COD, organic-N, and P_2O_5 than the inclined screen (1.6 mm). However, the screening process enhanced the volatilization of ammonia-N and as a result provided a greater reduction in TKN (Table 1). The other advantage of the mechanical
separator over enhanced settling alone was a significant removal of K_2O (50% vs. 3.5%).

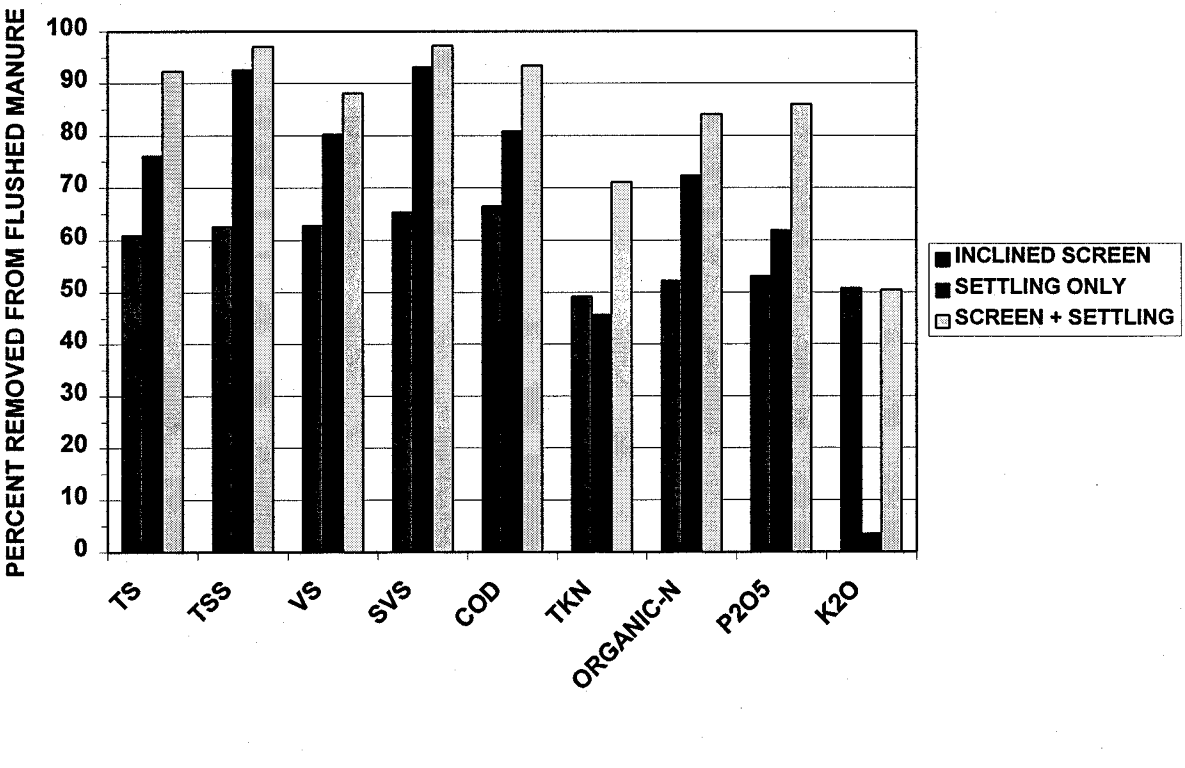

Figure 2. Comparison of the performance of the inclined screen separator with settling for 60 min with 300 mg PAM/L, and a two-stage process that includes the inclined screen followed by 60 min of settling with 300 mg PAM/L.

The greatest removal of solids, COD, and plant nutrients was achieved by the two-stage process that included mechanical separation followed by gravity settling with 300 mg PAM/L. The two-stage process removed 92% of the TS, 97% of the TSS, 88% of the VS, 97% of the SVS, 94% of the COD, 71% of the TKN, 84% of the organic-N, 86% of the P_2O_5, 51% of the K_2O, 92% of the Zn, and 74% of the Cu. The solids and nutrient removal provided by the two-stage separation process was very close to or exceed the treatment provided by the complete on-farm separation and lagoon system as described in Table 3. The effluent could be recycled through the flush system with very little additional treatment. If additional treatment for ammonium-N is desired then aerobic processes such as a trickling filter, aerobic lagoon, or aerated tank could be used.

All three separation techniques provide a significant removal of solids and plant nutrients. Large removals of VS, P, and N would greatly reduce the required treatment volume for an anaerobic lagoon, and the rate of sludge build-up. Removing a large portion of the VS would make lagoon design at lower loading rates more economical and would reduce the potential for strong odor. Large reductions in P and N in the liquid fraction of the manure would allow for better management of P. All of the removed P is concentrated in the separated solids. However, the higher TS content and lower volume of the separated solids would be more economical than liquid manure to transport to remote crop, pasture, or forage land that could utilize the large amounts of organic-N, and P. Separated dairy solids could be composted if additional biomass is added to reduce the moisture content and improve the carbon-nitrogen ratio. The amount of nutrient removal that is needed will depend on how much land application area is available close to the dairy farm and the market opportunities for using the separated solids for compost or as an untreated soil amendment.

Use of Aluminum Sulfate to Enhance Settling of Dairy Manure

Settling experiments were performed using 3,194 mg of liquid alum per liter of unscreened and screened dairy manure. A large fraction of the solids in the unscreened flushed manure floated and did not settle. It was concluded that aluminum sulfate was not feasible to use with unscreened dairy manure. Settling with alum performed well with screened dairy manure. Therefore, the same two-stage separation process can also be used substituting 3,194 mg/L of alum for PAM to enhance the gravity separation stage. The use of 300 and 400 mg PAM/L, and 3,194 mg alum/L to enhance the two-stage process is compared in Figure 3. The application of alum removed slightly less TS but almost all of the suspended total and volatile solids. The two-stage separation process enhanced with alum removed 99.6% of the P_2O_5 and 93.0% of the organic-N. The greater removal of phosphorous was due to the fact that aluminum sulfate precipitated a large portion of the soluble phosphorous. Application of 400 mg PAM/L was required to obtain COD and TKN removals that were equivalent to the performance of alum.

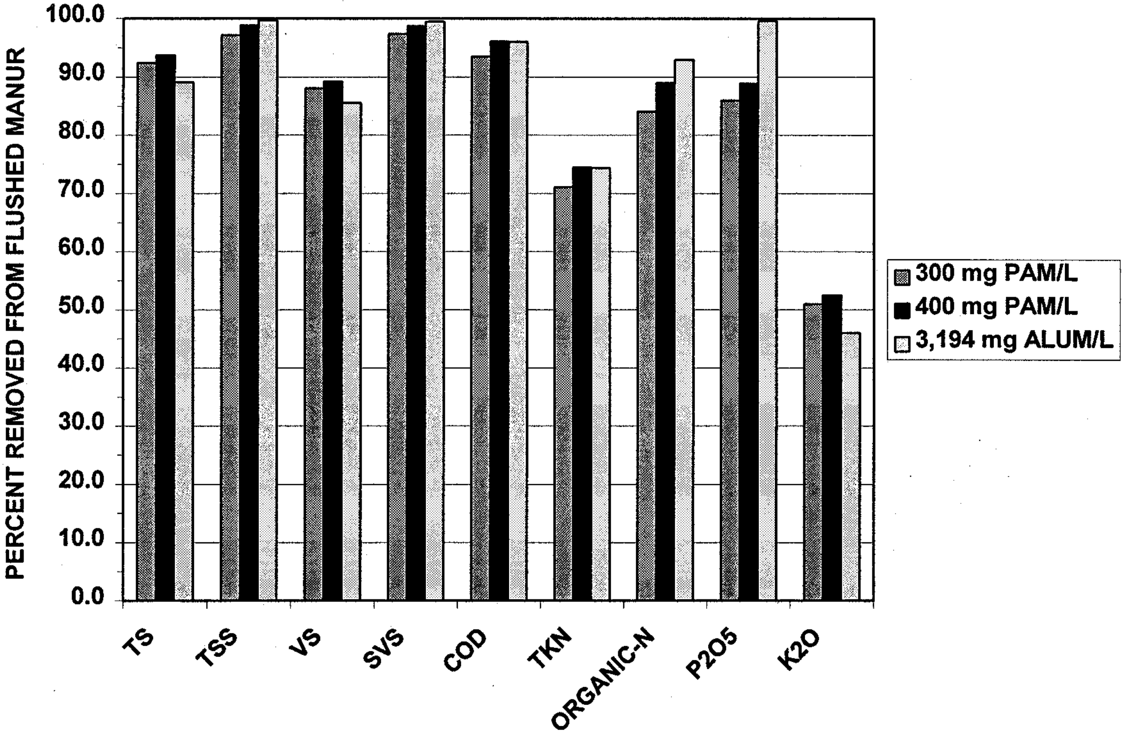

Figure 3. Removal of total solids, COD, and major plant nutrients from flushed dairy manure using a two-stage system composed of mechanical separation followed by gravity settling with 300 and 400 mg PAM/L, and 3,194 mg alum/L.

CONCLUSIONS

The manure handling and treatment system at the Sunny Day farm is composed of the following: fresh water flush of the freestall barn, mechanical separation using an inclined stationary screen separator (1.6 mm screen openings), a settling basin, and an anaerobic lagoon. Samples were collected and analyzed to characterize the removal of total (TS) and volatile solids (VS), nitrogen, phosphorous, potassium, copper, and zinc by each treatment step and the complete system. Large samples of the flushed manure and the effluent from the inclined screen were transported to a laboratory and settling experiments were carried out to determine the effectiveness of gravity settling of unscreened and screened dairy manure with and without addition of a cationic polyacrylamide polymer (PAM) and liquid aluminum sulfate ($AL_2(SO_4)_3$ 12 H_2O). In addition to the major plant nutrients, TS, and VS, these samples were also analyzed to determine the removal of the suspended total (TSS) and volatile solids (SVS), and the chemical oxygen demand (COD). Summaries of the most important observations are listed below.

- The inclined stationary screen separator removed 61% of the total solids, 63% of the volatile solids, 67% of the chemical oxygen demand, 46% of the ammonium-N, 52% of the organic-N, 53% of the total phosphorous, 51% of the total potassium, 50% of the zinc, and none of the copper from dairy manure with a solids content of 3.83%.
- The effluent from the inclined screen flowed into a settling basin. The combination of the inclined screen and the settling basin removed 70% of the TS, 73% of the VS, 43% of the NH_4^+-N, 61% of the organic-N, 60% of the total P, 48% of the total K, 63% of the Zn, and 39% of the Cu.
- The effluent from the settling basin flowed by gravity into a lagoon. Comparison of the constituent concentrations of the flushed manure and the lagoon supernatant indicated that the complete manure treatment system removed 93% of the TS, 96% of the VS, 54% of the NH_4^+-N, 91% of the organic-N, 74% of the total P, 86% of the total K, 93% of the Zn, and 91% of the Cu.
- Samples of the screened solids, settled solids, and lagoon sludge indicated that organic-N, total P, Cu, Zn, and to some extent total K was concentrated to a great extent in the sludge.
- Settling of unscreened manure with a TS of 41.8 g/L (4.18%) for 60 min without the addition of a polymer or alum removed 61% of the TS, 64% of the VS, 64% of the COD, 43% of the organic-N, 38% of the total P, only 0.4% of the total K, 40% of the Zn, and 39% of the Cu. Most of the solids and nutrients were removed in the first 30 min of settling.
- Settling of screened manure (TS = 12.0 g/L) for 30 min only removed about 16% of the TS. Increasing the settling time to 60 min removed 18% of the TS.
- Addition of 250 to 400 mg PAM/L to screened and unscreened dairy significantly increased the removal of suspended total and volatile solids, COD, organic-N, total P, Cu and Zn. The minimum amount of PAM that can be recommended for dairy manure is 250 mg/L. The optimum amount of PAM to add was 300 mg/L for screened and unscreened manure.
- Settling of flushed dairy manure after mixing it with 300 mg PAM/L removed 93% of the TSS and SVS, 81% of the COD, 72% of the organic-N, 62% of the total P, 82% of the Zn, and 83% of the Cu.
- A two-stage separation process that combines an inclined screen followed by settling of the separator effluent for 60 min after mixing with 300 mg PAM/L removed 97% of the TSS and SVS, 94% of the COD, 84% of the organic-N, 86% of the total P, 51% of the total K, 92% of the Zn, and 74% of the Cu.
- Settling of unscreened dairy manure containing 41.8 g TS/L for 60 min with the addition of 3,194 mg alum/L was not very effective. Many of the precipitated solids floated and removals were hard to quantify.
- Alum was very effective for enhancing the settling of the effluent from the inclined screen separator. The defined two-stage separation process that substituted 3,194 mg alum/L for PAM removed 99.7% of the TSS, 99.4% of the SVS, 96.0% of the COD, 93.0% of the organic-N, 99.6% of the total P, and 45.8% of the total K.
- The two-stage liquid-solid separation system (mechanical followed by settling with 300 mg PAM/L or 3,194 mg alum/L) provided similar TS, VS, N and P removals as the liquid-solid separation and lagoon system installed on the farm. Therefore, the effluent from this system may be stored in a tank and recycled through the flush system without concern about significant odor.

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