



United States
Department of
Agriculture

Natural Resources Conservation Service

Part 637 Environmental Engineering
National Engineering Handbook

Chapter 4

Solid-Liquid Separation Alternatives for Manure Handling and Treatment

Issued August 2019

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Acknowledgments

The author of this chapter was Dr. John P. Chastain, Professor and Extension Agricultural Engineer, Clemson University, through an agreement with the Piedmont South Atlantic Cooperative Ecosystem Studies Unit (CESU).

Chapter 4 was prepared under the direction of Noller Herbert, Director, Conservation Engineering Division (CED), NRCS, Washington, DC. Review of the chapter was provided by Jeff Porter, Animal Manure and Nutrient Management Team (AMNMT) Leader, East National Technology Support Center (ENTSC), NRCS, Greensboro, NC. Additional review was performed by Bill Reck, National Environmental Engineer, CED, NRCS, Washington, DC; Glenn Carpenter, National Animal Husbandry Leader (Retired), Ecological Sciences Division (ESD), NRCS, Washington, DC; Cherie LaFleur, Environmental Engineer, Central National Technology Support Center (CNTSC), NRCS, Ft. Worth TX; Harbans Lal, Environmental Engineer, National Water Quality and Quantity Team, West National Technology Support Center (WNTSC), NRCS, Portland, OR; Sally Bredeweg, Environmental Engineer (Retired), WNTSC, NRCS, Portland, OR; Greg Zwicke, Air Quality Engineer, National Air Quality and Atmospheric Change Team, WNTSC, NRCS, Fort Collins, CO; and Sandy Means, Environmental Engineer, AMNMT, ENTSC, NRCS, Greensboro, NC. It was finalized under the guidance of Bill Reck, National Environmental Engineer, CED, NRCS, Washington, DC.

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Chapter 4

Solid-Liquid Separation Alternatives
for Manure Handling and Treatment

Contents	637.0400 Introduction	4-1
	637.0401 Methods of solid-liquid separation	4-2
	(a) Solid-liquid separation by density difference	4-2
	(b) Solid-liquid separation based on particle size	4-5
	(c) Combinations of presses with other separation methods	4-9
	(d) Filter fabrics.....	4-10
	(e) Flocculation and coagulation	4-11
	637.0402 Influence of manure characteristics and handling methods on selection of a solid-liquid separation process	4-11
	(a) Overview of animal housing methods as related	4-12
	to solid-liquid separation	
	(b) Benefits of solid-liquid separation	4-16
	637.0403 Fundamentals of solid-liquid separation	4-30
	(a) Screening.....	4-30
	(b) Particle settling.....	4-37
	(c) Hindered settling of animal manure	4-47
	637.0404 Measures of solid-liquid separation performance	4-57
	(a) Concentration reduction	4-57
	(b) Mass removal efficiency	4-57
	(c) Mass balance on a two-stage solid-liquid separation system	4-61
	(d) Mass balance on gravity settling	4-64
	637.0405 High-rate solid-liquid separation	4-66
	(a) Coagulants and flocculants	4-66
	(b) Advanced final treatment technologies for high-rate systems	4-94
	637.0406 Unique applications of solid-liquid separation technology	4-98
	(a) Sand-laden dairy manure.....	4-98
	(b) Guidelines for design of a weeping wall settling basins.....	4-108
	(c) Geotextile filtration.....	4-114
	(d) Sand bed filtration	4-120
	(e) Belt solid-liquid separation system for swine manure	4-121
	637.0407 Design considerations	4-123
	(a) Single-stage primary treatment for recycle systems.....	4-124
	(b) Multiple-stage primary treatment for recycle systems.....	4-131
	(c) Primary treatment using flocculants and coagulants for	4-133
	recycle systems	

	(d) Gravity settling prior to anaerobic digestion	4-135
	(e) Use of solid-liquid separation to dewater sludge	4-137
	(f) Solid-liquid separation on farms that use manure storages	4-141
	(g) Considerations for storage of mechanically separated.....	4-142
	solids and sand	
	(h) Cost-benefit considerations	4-145
637.0408	References	4-147
Appendix A	Nomenclature	4A-1
Appendix B	Additional Solid-Liquid Separation Performance Data	4B-1
Appendix C	Demonstration Projects Funded by FPPC that Include Liquid-Solid Separation	4C-1
Appendix D	Guidelines for Evaluating Coagulant and Polymer Dose	4D-1
Figure 4-1	Settling basin to provide primary treatment for feedlot runoff	4-2
Figure 4-2	Two settling basins arranged in series treating liquid dairy manure with adjustable-height weirs (Clemson University Extension)	4-3
Figure 4-3	Settling basins arranged in parallel to provide primary treatment for liquid manure	4-3
Figure 4-4	A decanter centrifuge	4-4
Figure 4-5	Schematic of a hydrocyclone (Shutt et al. 1975)	4-4
Figure 4-6	Schematic of a stationary inclined screen separator	4-5
Figure 4-7	A stationary inclined bar screen and frame	4-6
Figure 4-8	An in-channel flighted conveyor separator and solids stacking area	4-7
Figure 4-9	A small in-channel flighted conveyor separator installed above the solids stacking area	4-7
Figure 4-10	A rotating screen separator treating dairy manure	4-7
Figure 4-11	Two different designs of screw presses used to treat slurry manure	4-8
Figure 4-12	Belt press	4-9

Figure 4–13	Combination of an in-channel flighted conveyor screen and a small screw press to treat liquid swine manure	4–9
Figure 4–14	Solid-liquid separator that employs three techniques: fine stationary inclined screen (0.020 in), screw press, and an inclined flighted conveyor screen	4–10
Figure 4–15	Combination of sedimentation and a dewatering press with a fine screen	4–10
Figure 4–16	Geotextile tube dewatering dairy lagoon sludge	4–11
Figure 4–17	Components of a manure storage structure	4–17
Figure 4–18	Components of an anaerobic treatment lagoon	4–18
Figure 4–19	Variation of odor frequency observed near treatment lagoons and manure storages (adapted from Humenik et al. 1981)	4–23
Figure 4–20	Comparison of TS removal by screening manure from dairy cows, beef cattle, poultry, and swine in the laboratory (as excreted manure (no bedding or recycle flush water, 1 in = 25.4 mm)	4–31
Figure 4–21	Impact of differences feed composition on TS removal by screening for dairy manure (no bedding or recycle flush water, 1 in = 25.4 mm)	4–31
Figure 4–22	Comparison of simple screening effectiveness for manure from calves, heifers, and cows (fresh manure, no bedding or recycle flush water, 1 in = 25.4 mm)	4–31
Figure 4–23	Comparison of simple screening effectiveness for manure from swine of different ages (fresh manure, no bedding or recycle flush water, 1 in = 25.4 mm)	4–32
Figure 4–24	Variation in separated solids consistency with respect to screen size for a variety of mechanical separators treating swine manure	4–37
Figure 4–25	Variation in separated solids consistency with respect to screen size for mechanical separators treating dairy manure	4–37
Figure 4–26	The four types of settling observed for dilute mixtures	4–38
Figure 4–27	Free-body diagram of the forces acting on a settling particle	4–39
Figure 4–28	Drag coefficients for discrete settling of spherical particles and non-spherical sediments for particle Reynolds Numbers greater than 0.5	4–40
Figure 4–29	Particle size distribution for dairy manure	4–40
Figure 4–30	Particle size distribution for swine, poultry, and beef manure	4–43
Figure 4–31	Schematic of particle settling in an ideal basin	4–44

Figure 4-32	The three hindered settling zones for liquid animal manure (TS ≥ 0.5%)	4-48
Figure 4-33	Determination of interface settling velocities, U_i , using a 1,000 mL graduated cylinder	4-49
Figure 4-34	Available settling data for dairy manure	4-50
Figure 4-35	Settling data for liquid swine manure	4-50
Figure 4-36	Available settling data for lagoon water-sludge mixtures	4-50
Figure 4-37	Variation of the settling velocity during linear hindered settling (LHS) with respect to TS for dairy and swine manure	4-50
Figure 4-38	Variation of the settling velocity during compression settling (CS) with respect to TS for dairy and swine manure	4-51
Figure 4-39	Schematic of the settling and storage areas for a horizontal flow settling basin used to treat flushed manure on a swine farm	4-54
Figure 4-40	Concentration reduction for a solid-liquid separator.	4-57
Figure 4-41	Mass flows for a solid-liquid separator	4-58
Figure 4-42	Mass flows for a two-stage solid-liquid separation system	4-63
Figure 4-43	Mass flows for a settling basin at the end of the defined solids accumulation period	4-66
Figure 4-44	Effect of alum dose on supernatant aluminum content following sedimentation of liquid dairy manure	4-70
Figure 4-45	Variation in the fraction of total ammoniacal nitrogen (TAN = $\text{NH}_4^+ - \text{N} + \text{NH}_3 - \text{N}$) in ammonia form for liquid and slurry animal manure	4-70
Figure 4-46	Large organic and grain particles captured with sand in a sand lane	4-99
Figure 4-47	Dual sand lanes used to remove sand from dilute, flushed dairy manure	4-100
Figure 4-48	Short baffle used to dissipate energy and spread influent to a sand lane	4-102
Figure 4-49	Effluent from a sand lane falling directly into a settling basin	4-102
Figure 4-50	Sand trap positioned on the end of a flushed, two-row freestall barn	4-103
Figure 4-51	Sketch of the sand beach concept	4-104
Figure 4-52	Recovered sand storage and concrete access ramp used with a sand beach	4-105

Figure 4–53	Operational diagram of the McClanahan sand-manure separator	4–106
Figure 4–54	Sand recovered from a McClanahan sand-manure separator stacked on a conditioning pad	4–106
Figure 4–55	The Tru-Grit [®] Manure Sand Saver manufactured by Parkson Corporation	4–107
Figure 4–56	Closeup of the sand from a cyclone sand-manure separator, note the large amount of feed grains and other organic matter mixed with the sand	4–107
Figure 4–57	A cyclone separator used to remove fine sand from the effluent of a SMS	4–107
Figure 4–58	Cross section of a two-chambered, porous-wall settling basin evaluated by Fulhage	4–108
Figure 4–59	Swine nursery flooring panels used to provide the 8 ft. wide porous sections bar spacing is about 3/8 of an inch	4–108
Figure 4–60	Full settling chamber	4–109
Figure 4–61	Schematic of the two-chambered weeping wall settling basin	4–111
Figure 4–62	A large, multichambered primary weeping wall settling basin	4–111
Figure 4–63	Vertical concrete slotted panels provide 1-inch-wide vertical openings	4–111
Figure 4–64	Test-scale geotextile tubes	4–114
Figure 4–65	Thickened lagoon sludge and fresh dairy solids as removed from the geotextile bags Dried solids accumulated on the inside of the fabric and wet, thick solids that accumulated near the bottom of the tubes	4–115
Figure 4–66	Geotextile tubes used to dewater dairy lagoon sludge mixtures in Georgia and Texas	4–118
Figure 4–67	Agitation of a lagoon with a centrifugal chopper pump to remove sludge	4–118
Figure 4–68	Unloading a small geotextile tube used to dewater dairy lagoon sludge	4–120
Figure 4–69	Use of an MS to reduce the organic loading on a treatment lagoon to yield treated wastewater for manure removal	4–125
Figure 4–70	Use of a settling basin or pond to reduce organic loading on a treatment lagoon and to eliminate sludge accumulation in a treatment lagoon	4–128

Figure 4-71	Use of a gravity settling basin (GS) to settle and thicken solids prior to a high-removal mechanical separator (MS)	4-130
Figure 4-72	Combination of a mechanical separator (MS) and a two-chambered weeping wall settling basin to provide a high-rate of primary treatment for a flush dairy that uses composted or dried solids as bedding	4-132
Figure 4-73	Combination of sand lanes and a two-chambered weeping wall settling basin to provide a high-rate of primary treatment for a flush dairy that uses recycled sand to reduce sand bedding costs.	4-132
Figure 4-74	Combination of mechanical sand-manure separator and a two-chambered weeping wall settling basin to provide a high rate of primary treatment for a flush dairy that uses recycled sand to reduce sand bedding costs.	4-132
Figure 4-75	Use of coagulants and flocculants to enhance removal efficiencies for a two-chambered gravity settling basin	4-133
Figure 4-76	Use of coagulants and flocculants to enhance solids and plant removal efficiencies for single-stage mechanical separation (EMS)	4-133
Figure 4-77	Use of (GS) to reduce chemical costs for enhanced removal of solids and plant nutrients using a mechanical separator (EMS)	4-134
Figure 4-78	Use of gravity settling (GS) to concentrate volatile solids prior to loading a heated anaerobic digester. Digester effluent is not stored in the treatment lagoon to maintain a high level of treatment for the water that is recycled for manure removal	4-135
Figure 4-79	Use of chemically enhanced gravity settling (EGS) to concentrate 80% or more of the volatile solids prior to loading a heated anaerobic digester and to provide a high level of treatment prior to the lagoon. Digester effluent is not stored in the treatment lagoon to maintain a high level of treatment for the water that is recycled for manure removal	4-136
Figure 4-80	Use of chemically enhanced mechanical separation (EMS) to remove the majority of the solids from digester effluent prior to storing liquids in a treatment lagoon. Gravity settling (GS) is used as primary treatment prior to digestion	4-136
Figure 4-81	Use of a reception pit and mechanical separator (MS) to dewater sludge from a treatment lagoon. If flocculation is desired to enhance removal efficiencies, inject chemicals between the reception pit and the mechanical separator	4-137
Figure 4-82	Use of geotextile tubes to dewater sludge from a treatment lagoon	4-138
Figure 4-83	Use of flocculants and geotextile tubes to dewater sludge from a covered lagoon digester	4-138
Figure 4-84	Use of chemically enhanced mechanical solid-liquid separation (EMS) to dewater effluent from a heated anaerobic digester	4-139

Figure 4–85	Separation without chemical enhancement using a mechanical separator (MS) with small screen openings	4–139
Figure 4–86	Mechanical separation of slurry using chemical enhancement (EMS)	4–139
Figure 4–87	Use of a sand-manure separator prior to slurry storage pond on a dairy farm that uses sand for freestall bedding	4–140
Figure 4–88	Use of high-rate liquid solid separators downstream from a sand-manure separator	4–140
Figure 4–89	Temporary storage of mechanically separated solids in a conical pile below a stacking conveyor with windrows for longer term storage in the background	4–141
Figure 4–90	Angle of repose of a pile of granular material that forms a circular cone. The angle of repose, α , is a property of the material, H is the height of the cone, and the radius of the circle that forms the base is r	4–141
Figure 4–91	Dimensions used to calculate the volume of a triangular windrow of separated solids or sand with two halves of a cone on each end	4–143
Figure 4B–1	Concentration reduction of solids, COD, and major plant nutrients following 60 min of gravity settling of liquid swine manure. (Chastain and Vanotti, 2003)	4B–16
Table 4–1	Relative performance of major types of solid-liquid separators treating fresh animal manure	4–12
Table 4–2	Impact of climate and solid-liquid separation performance on treatment volume (TV) of a lagoon used to treat swine manure from growing and finishing animals	4–19
Table 4–3	Impact of climate and solid-liquid separation performance on treatment volume (TV) of a lagoon used to treat manure from lactating dairy cows	4–19
Table 4–4	Sludge accumulation rate (SAR) estimates for anaerobic lagoon design	4–20
Table 4–5	Impact of solid-liquid separation performance on sludge SV of a lagoon used to treat swine manure from growing and finishing animals	4–21
Table 4–6	Impact of solid-liquid separation performance on sludge SV of a lagoon used to treat manure from lactating dairy cows	4–21
Table 4–7	Examples of major and minor plant nutrient contents in liquid and slurry swine and dairy manure (as sampled or wet basis)	4–25
Table 4–8	Whole plant nutrient removal of common grains	4–26

Table 4–9	Plant nutrient removal of common hay and silage crops	4–26
Table 4–10	Impact of solid-liquid separation performance on the ratio of plant available nitrogen to phosphate (PAN:P ₂ O ₅) of liquid swine and dairy manure assuming manure is incorporated following land application	4–27
Table 4–11	Impact of solid-liquid separation performance on the relative volatile solids content (VS/TS) and proportion of dissolved vs (DVS/VS) in liquid swine and dairy manure	4–28
Table 4–12	Examples of separated and settled solids composition volatile solids content (VS/TS) and proportion of dissolved vs (DVS/VS) in liquid swine and dairy manure	4–29
Table 4–13	Contribution of recycled lagoon water to the solids and major plant nutrients observed on two swine farms in South Carolina	4–33
Table 4–14	Comparison of solids removed by the same brand of inclined screen separator on two dairies with different bedding practices, flush water sources and management	4–33
Table 4–15	Comparison of actual and theoretical removal of TS (TSR) for screens and presses treating swine manure	4–34
Table 4–16	Comparison of observed and theoretical removal of TS (TSR) for screens and presses treating dairy manure	4–35
Table 4–17	Effect of manure feed rate (gpm/ft ²) and screen size on TS removal and consistency of separated solids (data from a vibrating screen treating liquid swine manure)	4–36
Table 4–18	Median particle diameters for animal manure	4–40
Table 4–19	Size ranges for sand	4–41
Table 4–20	Particle sizes and d ₅₀ values observed for commonly used freestall bedding sands	4–41
Table 4–21	Comparison of theoretical, discrete particle settling velocities for sand and manure	4–42
Table 4–22	Empirically determined settled volume fractions and interface velocities for liquid dairy manure and milking center wastewater	4–51
Table 4–23	Empirically determined settled volume fractions and interface velocities for liquid swine manure	4–52
Table 4–24	Empirically determined settled volume fractions and interface velocities for dairy lagoon sludge and supernatant mixtures	4–52
Table 4–25	Equations to estimate the settled volume fraction at the end of the three hindered settling zones for dairy manure included in the present study	4–53

Table 4–26	Equations to estimate the settled volume fraction at the end of the three hindered settling zones for swine manure included in the present study ($0.86\% \leq \text{TS} \leq 2.63\%$)	4–53
Table 4–27	Comparison of design overflow rates, U_o , for animal manure and primary treatment of municipal wastewater (ft/hr)	4–53
Table 4–28	Performance of a roller press treating scraped dairy manure, screen size unknown (data from Gooch et al. 2005)	4–60
Table 4–29	Performance of a screw press treating anaerobically digested dairy manure and food waste; screen size = 2.25 mm	4–61
Table 4–30	Performance of a screw press treating effluent from a plug-flow anaerobic digester on a dairy farm; screen size = 0.5 mm	4–62
Table 4–31	Mean concentration and flow data for a two-stage separation system used to treat flushed dairy manure	4–65
Table 4–32	Mass of solids and plant nutrients fed to and removed by a two-stage separation system used to treat flushed dairy manure	4–65
Table 4–33	Influent and outfall concentrations for a settling basin treating flushed swine manure	4–67
Table 4–34	Performance of a settling basin treating flushed swine manure	4–68
Table 4–35	Some properties of metallic salts and precipitates	4–69
Table 4–36	Comparison of the effectiveness of using three dose levels of various coagulants to enhance removal of TS and total phosphorus (TPR) from dilute swine manure (TS = 0.24%) from growing pigs by gravity settling	4–71
Table 4–37	Effect of addition of lime, alum, and ferric chloride on the reduction in phosphorus provided by settling of effluent from sand-manure separator on a dairy farm; the TS content of the separator effluent was 2.85% and the initial concentration of TP was 2,831 mg/L and the initial concentration of soluble P (Ortho-P) was 196 mg/L	4–72
Table 4–38	Reduction in supernatant phosphorus concentrations following addition of hydrated lime milk solution to screened and unscreened milking center wastewater	4–72
Table 4–39	Removal of suspended solids and phosphorus from finishing swine manure (TS = 1%) using various doses of aluminum sulfate and ferric chloride to enhance gravity settling (settling time = 4 hr)	4–73
Table 4–40	Effect of adding ferric sulfate and ferric chloride on the removal of total solids and major plant nutrients from liquid dairy manure (TS = 1.0%) by Sedimentation; results from laboratory settling for 20 minutes	4–73

Table 4-41	Enhanced settling of nursery swine manure (TS = 0.18%) by using alum as a coagulant	4-74
Table 4-42	Effect of adding ferric chloride on the removal of total solids, major plant nutrients, and key minor plant nutrients from liquid dairy manure by sedimentation; results from laboratory settling for 20 minutes	4-75
Table 4-43	Effect of adding aluminum sulfate on the removal of total solids, major plant nutrients, and key minor plant nutrients from liquid dairy manure by sedimentation; results from laboratory settling for 20 minutes	4-76
Table 4-44	On-farm batch settling of flushed dairy manure following primary sedimentation and screening with and without injection of alum; settling time = 24 hours	4-77
Table 4-45	On-farm continuous flow settling of flushed dairy manure following primary sedimentation and screening with and without injection of alum; flow through tank, Q= 23 L/min (6 gpm) and detention time, DT = 91.3 minutes	4-78
Table 4-46	Primary treatment of finishing swine manure (TS = 1.52%) using a gravity settling pond with and without alum	4-79
Table 4-47	Variation in optimal dose of ferric chloride with respect to influent TS concentration to enhance settling of swine and dairy manure	4-79
Table 4-48	Centrifuge treatment (5,000 rpm, 40 to 60 L/min feed rate) of flushed swine manure and lagoon sludge mixture with and without addition of lime	4-80
Table 4-49	Enhancement of nursery swine manure (TS = 0.18%) settling by using cationic, neutral, and anionic charged PAM polymers; polymer dose was 10 mg PAM /L for all three chemicals	4-81
Table 4-50	Removal of solids, COD, and plant nutrients from flushed dairy manure by settling for 60 minutes with and without addition of PAM; optimum dose was about 300 milligrams PAM per liter	4-82
Table 4-51	Removal of solids, COD, and plant nutrients from flushed dairy manure by an inclined stationary screen separator (1.5 mm) followed by settling for 60 minutes with and without application of PAM; optimum dose was about 250 mg PAM/L	4-84
Table 4-52	Removal of solids, N, P and COD, from flushed swine manure by flocculation with a cationic polymer with a 20% charge density followed by screening (1 mm openings); optimal PAM dose was about 100 mg PAM/L based on TSS reduction	4-85
Table 4-53	Removal of solids, COD, and nitrogen liquid swine manure by a 0.25 mm screen following flocculation with a cationic PAM with 30% charge density; optimal PAM dose was about 80 mg/L	4-86

Table 4-54	Removal of solids, N, P, COD, and BOD from pit-recharge swine manure by flocculation with a cationic polymer with a 35% charge density followed by screening (1 mm openings); optimal PAM dose was about 110 mg PAM/L	4-87
Table 4-55	Variation of optimal PAM dose and PAM use efficiency for primary treatment of swine manure removed from a recharge pit; manure was flocculated with a cationic PAM with a 35% charge density and then passed through a screen with 1 mm openings	4-87
Table 4-56	Correlations for primary treatment of liquid swine manure using a cationic PAM with a 35% charge density as a flocculant followed by separation with a 1 mm screen	4-88
Table 4-57	Performance of a screw press treating thin dairy slurry (TS = 4%) with and without the use of a coagulant and flocculant; screw press had a wedge wire screen that was 100 mm in diameter, 343 mm long, and had 0.38 mm openings; the press was operated with 3 kg weights on the discharge pressure plate and rotated at 24 rpm	4-89
Table 4-58	Effect of combinations of FeCl ₃ and PAM on removal of solids) and major plant nutrients by screening (0.8 mm openings) from flushed dairy manure (TS = 0.5%)	4-90
Table 4-59	Centrifuge treatment (5,000 rpm, 40 to 60 L/min feed rate) of flushed swine manure and lagoon sludge mixture following addition of a coagulant, flocculant, and lime	4-90
Table 4-60	Removal of Solids, N, and P from liquid dairy manure by screening following mixing with chitosan (a natural flocculant)	4-91
Table 4-61	Variation in optimum chitosan (a natural flocculant) dose to be used with screening of liquid dairy manure	4-92
Table 4-62	Comparison of dynamic viscosities (μ) for liquid manure and water	4-93
Table 4-63	Empirically determined optimal mixing parameters for coagulation and flocculation of dilute manure using bench-top mixing equipment	4-93
Table 4-64	Summary of mixing procedures used for laboratory studies (jar test) of the effectiveness of coagulants and flocculants for enhancing solid-liquid separation of animal manure; all of the studies used bench-top mixers with six-blade paddles or impellers	4-93
Table 4-65	Description of mixing methods used for field trials of enhancing solid-liquid separation of manure using coagulants and flocculants	4-94
Table 4-66	Phosphorus removal from swine lagoon supernatant using a cone-shaped fluidized bed struvite crystallizer with different levels of Mg supplementation and pH adjustment (field study, adapted from Bowers and Westerman 2005); the influent lagoon water had an average pH of 7.71 and contained 82 to 93 mg TP/L, 38 to 46 mg ortho-P/L, 53 to 67 mg Mg/L, and 176 to 197 mg TAN/L	4-95

Table 4-67	Removal of phosphorus from liquid swine and dairy manure by Struvite precipitation and sedimentation	4-95
Table 4-68	General classifications of membrane filtration	4-97
Table 4-69	Variation of dilution ratio with respect to number of full-barn flushes for SLDM; four-row freestall barn with drive-through feeding; the two alleys were 12 ft wide and the two stall alleys were 10 ft wide	4-98
Table 4-70	Guidelines for sizing of sand lanes and sand traps	4-101
Table 4-71	Summary of two-chambered, porous wall settling basin performance measurements	4-110
Table 4-72	Comparison of normalized basin sizing parameters from field studies of weeping wall settling basins	4-112
Table 4-73	Solids concentration reduction by a weeping wall settling basin used to treat flushed manure on a California dairy; freestalls were bedded with dried separated manure solids	4-113
Table 4-74	Solids and plant removal using a weeping wall settling basin to treat flushed manure on a Texas dairy that used sand bedding that was removed prior to the basin	4-113
Table 4-75	Composition of the dewatered solids removed from a weeping wall settling basin	4-113
Table 4-76	Performance of geotextile bags used to treat lagoon sludge and milking center wastewater	4-116
Table 4-77	Volume reduction and composition of the separated solids removed from test-scale geotextile bags	4-117
Table 4-78	Results of field trials of using geotextile filtration to dewater agitated dairy lagoon sludge with and without addition of a coagulant and PAMs	4-119
Table 4-79	Performance belt separator located below perforated flooring for finishing swine	4-122
Table 4-80	Results from a bench scale study of conversion of organic-N to TAN in liquids obtained from a belt separation system	4-122
Table 4-81	Approximate throughput rates for several types of mechanical solid-liquid separators	4-126
Table 4-82	Advantages and disadvantages of using draining settling basins and settling ponds for single-stage primary treatment	4-129
Table 4-83	Angle of repose, α , for separated manure solids and sand	4-142

Table 4–84	Dry matter bulk density, ρ_{DB} , of noncompacted separated solids and lagoon sludge	4–142
Table 4–85	Variation of radius, r , and volume of a circular cone, V_{CONE} , as a function of cone height, H , and angle of repose, α	4–143
Table 4–86	Cost and benefit categories to consider when planning a solid-liquid separation system	4–146
Table 4B–1	Summary of separation efficiency data for incline screen separators (static and in-channel flighted conveyor) treating beef and swine manure (concentration reduction)	4B–1
Table 4B–2	Summary of separation efficiency data for rotating screen separators (concentration reduction)	4B–1
Table 4B–3	Summary of separation efficiency data for incline screen separators (static and in-channel flighted conveyor) treating dairy manure (concentration reduction)	4B–2
Table 4B–4	Removal of solids, COD, plant nutrients, and minerals from flushed dairy manure using a 1.5-mm inclined stationary screen separator	4B–3
Table 4B–5	Performance of an inclined screen and settling basin in series treating flushed dairy manure ($T_{SIN} = 3.8\%$, $CR =$ concentration reduction)	4B–4
Table 4B–6	Summary of separation efficiency data for roller and belt presses (concentration reduction)	4B–5
Table 4B–7	Summary of separation efficiency data for vibrating screen separators (concentration reduction)	4B–6
Table 4B–8	Summary of separation efficiency data for screw presses (concentration reduction and mass removal efficiency)	4B–7
Table 4B–9	Summary of separation efficiency data for centrifuges and hydrocyclones (concentration reduction)	4B–8
Table 4B–10	Performance of gravity settling treating flushed dairy manure with $T_{SIN} = 4.2\%$	4B–9
Table 4B–11	Plant nutrients in separated dairy solids and lagoon sludge	4B–9
Table 4B–12	Performance of gravity settling treating milking center wastewater with $T_{SIN} = 0.7\%$ detention time = 60 min and $SVF = 0.093$	4B–10
Table 4B–13	Performance of gravity settling treating milking center wastewater with $T_{SIN} = 1.7\%$ detention time = 60 min, and $SVF = 0.254$	4B–11
Table 4B–14	Composition of settled solids following 30 and 60 minutes of settling of milking center wastewater	4B–12

Table 4B-15	Performance of gravity settling treating a mixture of Dairy Lagoon Sludge and Supernatant With $T_{\text{SIN}} = 1.9\%$ Detention Time = 7 hr, and SVF = 0.385	4B-13
Table 4B-16	Performance of gravity settling treating a mixture of dairy lagoon sludge and supernatant with $T_{\text{SIN}} = 3.98\%$ (adapted from Chastain and Darby 2000) Detention Time = 7 hr, and SVF = 0.423	4B-14
Table 4B-17	Solids and plant nutrient content in thickened dairy lagoon sludge	4B-15
Table 4B-18	Influent and supernatant concentrations of liquid finishing swine manure treated by 60 min. of gravity settling	4B-16
Table 4C-1	Solids and nutrient removals (concentration reduction, %) observed using a centrifuge to separate polymer flocculated lagoon water and manure (from Agricultural Waste Solutions)	4C-2
Table 4C-2	Concentration reductions (%) of solids and major plant nutrients provided by addition of ferric sulfate and polymer followed by dewatering with a geotextile tube	4C-3
Table 4C-3	Costs for using chemicals and geotextile tubes to treat pit swine manure and lagoon sludge	4C-4
Table 4C-4	Summary of concentration reductions and component costs for a multistage dairy manure treatment system in Florida	4C-5
Table 4D-1	Selected opening sizes for standard screens	4D-3

Chapter 4

Solid-Liquid Separation Alternatives for Manure Handling and Treatment

637.0400 Introduction

Solid-liquid separation can be used in animal manure systems to achieve a variety of objectives. Traditionally, solid-liquid separation systems have been used to exclude large solids from a storage structure or lagoon, to improve pumping characteristics, to reduce organic loading on a treatment lagoon, and to treat runoff from outdoor feedlots. Over the last decade new equipment and applications have been developed that provide extensive primary treatment using flocculants to remove the majority of the total (TS) and volatile (VS) solids and plant nutrients, such as nitrogen and phosphorus.

Many solid-liquid separation options have been developed or improved over the last 15 years. Solid-liquid separation options can be divided into two general categories: those that use the density difference between the solids particles and water, and those that remove solids based on particle size. Methods that exploit particle density differences include gravity settling, centrifuges, and hydrocyclones. Solid-liquid separators that are based on particle size include stationary inclined screens, in-channel flighted conveyor screens, rotating screens, screw presses, belt presses, and rotary presses. Some of the best performing solid-liquid separation options use a combination of methods or multiple stages. For example, some manufacturers combine a conveyor screen with small openings with a rotary or screw press. The small screen allows small manure particles to be captured, but the separated solids are too wet to stack in a pile. The secondary press provides additional solids dewatering to allow separated solids to be stored in a conical pile or windrow. Other options include using gravity settling to yield thick slurry that can be more effectively treated by a screw press while allowing the liquids from the settling step to flow to a lagoon.

Performance of all of the solid-liquid separation options can be enhanced by addition of coagulants or flocculants. Some of the common coagulants that have been used are the metal salts of aluminum, iron, and calcium. The flocculants that have been shown to enhance the removal of solids and phosphorus include cationic polyacrylamide polymers and a natural polymer made from shellfish waste called chitosan. In some cases, the optimal performance is provided

when various metal salts and polymers are combined prior to screening, pressing, or settling. Determine the optimal dose of the chemical or chemicals to be used and provide a practical and effective means to mix the chemicals in the manure adequately prior to solid-liquid separation. Chemical enhancement of solid-liquid separation can provide high removal of suspended solids (90% or more) and plant nutrients (80 to 90% of P), if desired. The key is to determine the amount of removal that is needed for a particular livestock facility to meet nutrient management, facility management, and regulatory goals in the most cost-effective manner.

Removal of solids and plant nutrients following anaerobic digestion and separation of sand and soil from dairy manure represent new applications that are currently being deployed across the United States. Several options exist that rely on settling and hydrocyclones to provide 75 to almost 100 percent separation of sand and manure. These novel sand-manure separation methods are important on dairy farms where sand bedding is used.

Most of these advances in solid-liquid separation technology and applications have arisen in response to the need to improve animal manure management systems to protect water and air quality and to comply with local, State, and Federal regulations. The many recent advances in solid-liquid separation have also given rise for the need of a publication to summarize these advances and to provide engineers and other professionals with the information needed to more precisely include these processes in treatment system design. The purpose of this document is to assist in solid-liquid separation technology selection, evaluation of separation performance, and quantifying the impact of solid-liquid separation on manure management. Detailed information is provided on the influence of entrainment on the performance of mechanical separators, design of gravity settling using discrete particle settling and hindered settling theory, efficacy of combining separator methods in a single machine, benefits of using coagulants and flocculants, benefits of solid-liquid separation, a summary of the solid-liquid separation methods that have been used with sand-laden dairy manure, and numerous system design diagrams are also provided to demonstrate the wide variety of ways that solid-liquid separation can be implemented into an animal manure treatment system. This chapter provides 21 detailed examples to illustrate application of the theory in design.

637.0401 Methods of solid-liquid separation

There are many types of solid-liquid separation techniques that can be implemented in animal manure treatment systems. Separation of animal manure is most often accomplished by exploiting differences in particle density or particle size. The objectives of a solid-liquid separation system can vary greatly from farm to farm. Some common objectives for using these technologies are to—

- Remove solids from slurry manure to facilitate handling separated liquids with pumps.
- Reduce organic loading in a lagoon or waste storage pond.
- Reduce sludge buildup in a lagoon.
- Thicken liquid manure prior to anaerobic digestion.
- Generate separated solids for use as an ingredient to make compost, to recycle as bedding on dairy farms, or for use as some other novel value added product.
- Provide treatment to yield reduced-strength wastewater to flush manure from animal housing areas.
- Improve the uniformity of solids and plant nutrients in the separated liquids.
- Remove excess phosphorus from separated liquids.
- Improve the balance of nitrogen and phosphorus in the separated liquids to better match crop requirements.

(a) Solid-liquid separation by density difference

Two of the most common methods of solid-liquid separation that exploit differences between the density of water and the density of suspended material are sedimentation and centrifugation.

(1) Sedimentation

The most common method of solid-liquid separation that exploits the difference between the density of water and the density of suspended material is sedimentation or gravity settling. Gravity settling of suspended solids is an effective mode of treatment for dilute wastewater such as feedlot runoff (fig. 4–1) or flushed manure (figs. 4–2 and 4–3). The main requirements for sedimentation are flow velocities that are slow enough to allow solids to settle (less than 0.5 ft/s), a detention time sufficient to allow capture of the settling solids (generally 20 min. or longer), and sufficient solids storage below the settling zone to maintain settling efficiency.

Settling basins used to treat runoff from outside lots (fig. 4–1) are designed to provide the required detention time for the design storm event and the solids storage volume based on the time interval between solids removal. The solids in the settling basin are often removed using a front-end or skid-steer loader after allowing them to dry down following a storm event. If the solids removed are dry enough to handle as a solid, an additional solids stacking area may be used to provide longer term storage prior to land application or possibly composting. The nutrient-rich liquid effluent that flows out of the basin can be stored

Figure 4–1 Settling basin to provide primary treatment for feedlot runoff (Iowa State University Extension)



in a pond, treated in a lagoon or digester, or, in some cases, applied to a vegetative filter strip. In all cases, the nutrients in the liquid flowing from a settling basin need to be incorporated into a proper nutrient management plan.

Settling basins used to treat liquid manure from the animal housing area can be configured in a variety of ways depending on the needs and goals of a particular operation. Generally, these types of settling basins are designed to provide the required detention time for the daily flow of liquid manure from the animal buildings and to provide the maximum solids removal possible. The liquid effluent is stored in a pond or treated in a lagoon prior to land application.

The simplest type of settling basin used to treat liquid manure provides means to receive influent manure, a volume to allow for settling and storage of the solids, an outlet that retains settled solids while allowing the liquid effluent (supernatant) to flow out to a lagoon or storage structure, and a means to remove the settled solids.

An example of two simple settling basins configured in series is shown in figure 4–2. Liquid manure flows into the first basin through a pipe that discharges the flow onto a concrete ramp to dissipate the flow energy. The

flow out of each of the basins is controlled by simple variable height weirs. The height of the weirs can be raised by adding pressure treated boards to two slots. Adding boards will increase the height of the stored manure. The boards can be seen stacked on the concrete block walls in figure 4–2. This simple design does not allow the solids to drain dry. As a result the solids are removed using a front-end loader as a semisolid or thick slurry.

Settling basins can also be arranged in parallel as shown in figure 4–3. The advantage of such a design is that it allows the solids to dry prior to removal in one basin until it can be handled as a solid while another basin provides primary treatment.

(2) Centrifuges and hydrocyclones

Centrifuges and hydrocyclones use the same principle to remove suspended solids from liquid manure as settling basins. In centrifugation, the acceleration of the particles in suspension is increased to a value higher than gravity by application of an external force. As a result, a greater fraction of the suspended material can be removed by centrifugation than sedimentation.

A centrifuge is a mechanical separator that exploits density differences to achieve removal of suspended material. Particle acceleration is increased by rotating

Figure 4–2 Two settling basins arranged in series treating liquid dairy manure with adjustable-height weirs (Clemson University Extension)



Figure 4–3 Settling basins arranged in parallel to provide primary treatment for liquid manure (Mukhtar et al. 1999)



the manure about a fixed axis and is a function of the speed and radius of rotation. One type of centrifuge is called a decanter centrifuge (fig. 4-4). The decanter centrifuge uses an auger that rotates inside a rotating cylinder (3,500 to 5,000 rpm). The influent slurry is pumped into the center of the cylinder and centrifugal forces separate the suspended solids and liquids into two layers. The auger rotates at a higher speed than the cylinder which presses the solid fraction toward the conical end where it is discharged. The liquids are decanted out the opposite end.

A hydrocyclone (fig. 4-5) is a cone-shaped apparatus that has no moving parts except for the high-pressure booster pump that is used to spray the influent into the cone. Liquid manure is pumped into the top of the cone against the wall at high speed. The strong swirling motion pushes the solids to the outside wall of the cone where they slide down the wall by gravity and are removed from the cone. The separated liquid forms an inner vertical spiral that exits the top of the cone through a pipe.

Figure 4-5 Schematic of a hydrocyclone (Shutt et al. 1975)

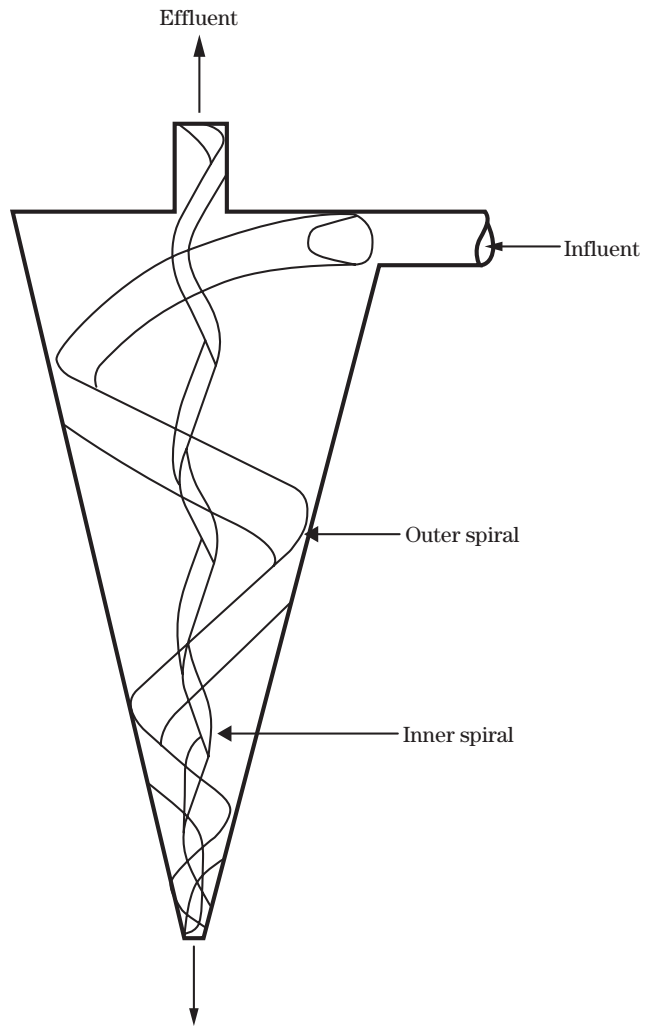
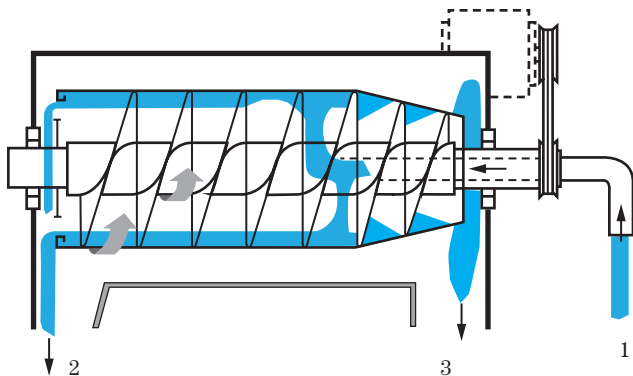


Figure 4-4 A decanter centrifuge (Glerum et al. 1971)



- 1 influent
- 2 effluent
- 3 separated solids

(b) Solid-liquid separation based on particle size

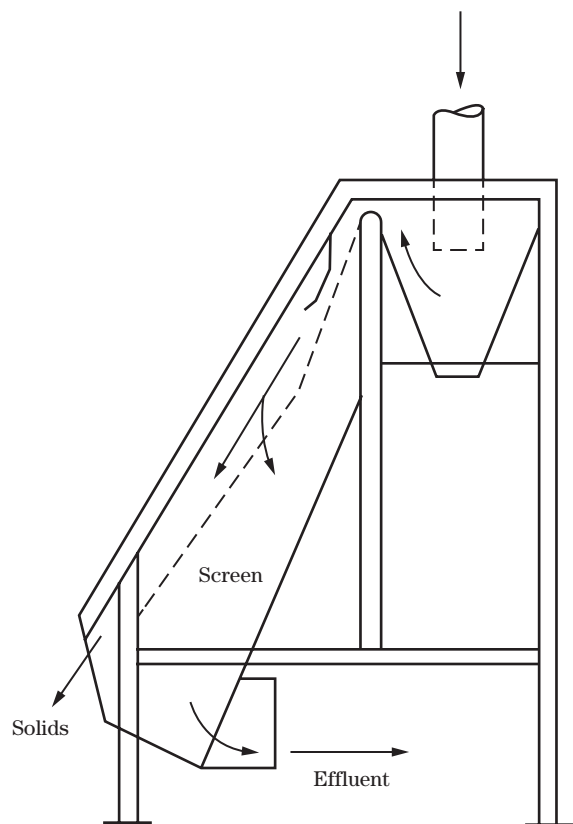
Screens and presses are examples of separation techniques that exploit differences in particle size to remove suspended material. Separation by screening occurs when liquid manure is passed over a mesh of sufficient size to allow capture of a portion of the suspended manure particles while allowing the liquids and small particles to pass through. Mechanical separators are available that use stationary inclined screens, vibrating screens, and rotating screens. All types of screen separators rely on gravity to force the liquid through the screen.

(1) Stationary inclined screen

A stationary inclined screen separator is one of the simplest mechanical separators available (figs. 4–6 and 4–7). The separator consists of a sloped and curved bar or wedge-wire screen, a frame to support the screen, a channel to distribute the influent across the top of the screen, and a collection channel and pipe to collect and transfer the liquid effluent. The only moving part is the pump that lifts the influent to the top of the machine.

Stationary screen separators are designed to use gravity to cause the liquids to pass through the screen while the solids slide down the screen. The separated solids thicken as they accumulate on the bottom half of the screen and are deposited on a collection pad or onto a stacking conveyor or auger. This type of mechanical separator is used in a variety of configurations to remove large fibrous particles from liquid dairy manure.

Figure 4–6 Schematic of a stationary inclined screen separator (Shutt et al. 1975; Virginia Polytechnic Institute, Virginia Cooperative Extension)



The advantages of a stationary inclined screen separator are the lack of moving parts and the low energy requirements (influent pump). The primary disadvantage is that the screen requires periodic cleaning with a high-pressure spray to keep the screen from clogging which requires additional labor, returns fine solids to the manure stream, and adds fresh water to the system.

(2) In-channel flighted conveyor screen

This type of separator employs a flat inclined screen (perforated or wedge-wire), and a chain and flight conveyor. The machine is placed in an open channel that is sized to hold the wastewater while it is being processed (fig. 4-8). Manure is not pumped to the top of the screen to load the separator. Instead, a chain pulls flights, or horizontal bars, up the screen lifting solids and a portion of the liquids onto the screen. As the solids travel up the conveyor the liquid passes through the screen and is collected in a channel at the bottom of the machine. A pipe is used to transfer the liquid effluent to the next treatment process or to storage. The

separated solids continue to dewater as they travel to the top of the screen where they are deposited onto a concrete collection pad. The length and angle of the inclined screen determines the height of the solids storage pile unless topography allows the machine to be installed above the storage area (fig. 4-9).

The uses of an in-channel screen are similar to those of the stationary inclined screen separators. The advantage of the in-channel screen is that agitation and pumping is not required and liquid manure can be transferred to the separator by gravity. The main disadvantage is that the chain-flight conveyor and drive system may require more maintenance since moving parts are exposed to corrosive and abrasive materials. However, use of high-quality, non corrosive metal can greatly reduce these concerns. The only energy required to operate the machine is the drive motor for the conveyor.

(3) Rotating screen

This type of mechanical separator uses a perforated or wedge-wire screen that is attached to a frame to form a large porous drum (fig. 4-10). The drum slowly rotates horizontally around its axis in a manner similar to a clothes dryer. Manure is pumped into the machine and is distributed evenly on the top of the rotating screen at a rate that is compatible with the rotational speed of the drum and screen size. The liquids pass through the drum and are collected in a hopper below the screen. The separated solids on the outside of the screen are removed as it rotates past a scraper. The solids are channeled away from the screen and fall to the solids collection area.

Rotary screen separators can be used for a wide variety of applications depending on screen opening size and the screen cleaning system. Screens with relatively large openings can be used to remove the largest particles from liquid dairy or swine manure. The scraping blade and simple brushes provide adequate cleaning to maintain separator performance. Complex designs are also available that use precision made wedge-wire screens with small openings. These are used to remove fine particles from wastewater and require more complicated spray and backwash systems to maintain separator performance.

Figure 4-7 A stationary inclined bar screen and frame (courtesy of US FARM Systems, Tulare, CA)



Figure 4–8 An in-channel flighted conveyor separator and solids stacking area (Mukhtar et al. 1999)



Figure 4–9 A small in-channel flighted conveyor separator installed above the solids stacking area (Clemson University Cooperative Extension)



Figure 4–10 A rotating screen separator treating dairy manure (Iowa State University Cooperative Extension)



The advantage of the rotary screen separator is the relatively compact design that requires less space than many other options. The disadvantage is that energy is required to pump manure to the machine and to operate the separator. This may require more maintenance than a stationary inclined screen or in-channel flighted conveyor screen.

(4) Vibrating screen

A vibrating screen separator uses a flat circular screen mounted in a circular housing. The housing is mounted on heavy springs and an electric motor is used to drive a mechanism that rapidly vibrates the housing and the screen. Liquid manure is pumped at a controlled rate in the center of the screen. The liquid passes through the screen and is collected and removed. The solids are moved to the edge of the screen where they are allowed to drop to the storage area. The vibrating motion of the screen helps to reduce clogging of the screen.

Vibrating screen separators tend to be small and are not very useful for the large liquid manure volumes generated on modern farms. They are mostly used in the food processing industry and to remove solids from small flows.

(5) Presses

A press uses a roller or a screw to exert a substantial amount of pressure against a screen or perforated belt

to remove liquids from slurry manure or separated solids. Presses are generally not an effective primary treatment option for liquid manure or thin slurries (TS less than about 3%) because the pressure generated will force many of the solids through the screen with the liquids. As a result, presses are best used to provide primary treatment for dairy and swine manure that is handled as slurry with a TS content of five percent or more. The other common use of a press is to dewater solids from a screen separator or a settling basin that is too wet to handle as a solid.

Common types of presses are screw presses, roller presses, and belt presses. The design and configuration of the presses available vary greatly between manufacturers depending on the desired application. However, the basic principle of operation is the same and is the focus of what follows.

A screw press separator is a machine that uses a large screw to force manure through a tube and past a cylindrical screen (fig. 4–11). A plug of manure solids is formed at the end of the tube and the flow of separated solids is controlled by a set of pressure plates. The resulting internal pressure within the tube forces the liquids out through the screen. The amount of force exerted by the pressure plates affects the moisture content of the separated solids and depends on the amount of weight that is suspended on the pressure plate arms. An appropriate amount of weight needs to

Figure 4–11 Two different designs of screw presses used to treat slurry manure (Virginia Polytechnic Institute, Virginia Cooperative Extension)



be used to yield a desirable moisture content for the separated solids.

A roller press employs two concave screens, rotating brushes, and rotating rollers with brushes. Manure slurry is initially discharged on the first screen and is pressed against the screen with four brushes that rotate like a Ferris wheel. The rotation of the first set of brushes cleans the solids off the first screen and deposits them on the second concave screen. Two rotating rollers apply a greater amount of pressure against the screen to remove additional moisture from the solids and two rotating brushes clean the solids off the second screen and to the solids collection area.

A belt press consists of a flat, perforated fabric belt that runs horizontally between two rollers (fig. 4–12). The inlet to the press discharges slurry onto the belt and the rollers squeeze the liquid fraction through the porous belt. The dewatered material remains on the belt and is expelled into the solids collection area. The liquid fraction is collected and transferred to storage or additional treatment.

Figure 4–12 Belt press (Texas A&M AgriLife Extension Service)



(c) Combinations of presses with other separation methods

The goal of most modern mechanical solid-liquid separators is to remove the maximum amount of solids from liquid manure while producing separated solids that can be stacked and handled as a solid. To capture a large fraction of solids, the size of the openings in the screen must be made very small. However, the openings that provide the maximum solids removal produce separated solids with the consistency of slurry or a semisolid. A screw press can be added as a second step to provide additional dewatering to yield stackable separated solids. The machine shown in figure 4–13 is an in-channel flighted conveyor used to treat liquid swine manure. A small screw press was added to the end of the conveyor to dewater the solids from the screen.

Figure 4–13 Combination of an in-channel flighted conveyor screen and a small screw press to treat liquid swine manure (Clemson University Extension)



The mechanical solid-liquid separator shown in figure 4–14 was designed to provide high rates of solids removal using a fine stationary inclined screen (0.020 in openings). The machine employed three separation and dewatering steps. Primary treatment was provided by two large stationary screens. The slurry from the screens was fed into a screw press to provide the majority of the solids dewatering. The screw press discharged the solids onto an inclined flighted conveyor screen that allowed liquids to drain from the solids while being moved to the stacking area. The solids from this machine stacked well and had an average moisture content of 77 percent (23% TS).

Gravity settling can be combined with a press to provide high rates of solids removal and separated solids dry enough to be stacked (fig. 4–15). The initial settling step must be designed to allow for solids to settle and thicken to the consistency of slurry. Settled solids are pumped from the bottom of the basin, without agitation, into a press with a fine screen for additional dewatering. The liquid effluents from both steps are transferred to final treatment and storage. One of the advantages of this type of combination is that a much smaller portion (10 to 25%) of the daily flow of wastewater must be treated by the press. This saves energy and accommodates the slow processing rate (gal/h) of a press with a fine screen.

(d) Filter fabrics

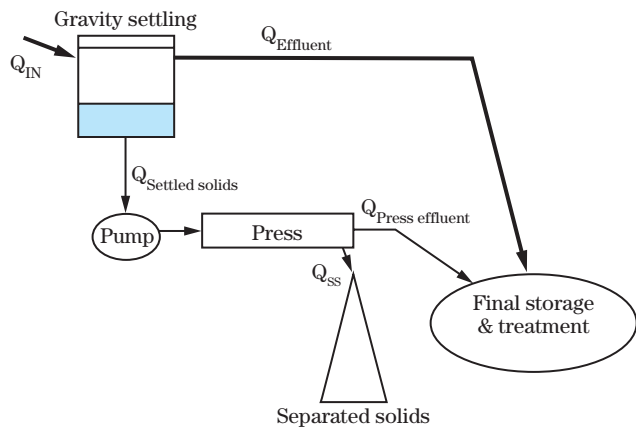
Filter fabrics are woven polypropylene fabrics of different weaves (based on thread count) that can provide apparent opening sizes ranging from 5 to 100 microns. These fabrics are used in a variety of pressurized or vacuum filter presses to dewater slurries and sludge. High rates of solid removal and dewatering may be obtained, but addition of chemical flocculants is generally required. These types of machines can use filter fabrics stretched over a drum, as a belt or on compression plates. These types of machines can capture very fine manure particles and pack them into filter cake with a water content of 65 percent or less. These types of machines are not widely used in animal waste treatment applications. However, filter presses combined with addition of polymers to aid dewatering have been investigated in recent years. The main disadvantage of using a filter press for animal waste treatment is the cost of the chemical flocculants and the cost of replacing the filter fabric (about every 6 months).

Geotubes are large tubes made of woven geotextile with apparent opening sizes ranging from 0.4 to 0.6 mm (Baker 2002) and have been used to statically dewater lagoon sludges (fig. 4–16). The fabric acts as a coarse filter fabric. The large tube is pumped full of agitated lagoon sludge to a maximum height that is defined by the diameter of the bag and the strength

Figure 4–14 Solid-liquid separator that employs three techniques: fine stationary inclined screen (0.020 in), screw press, and an inclined flighted conveyor screen (courtesy of US FARM Systems, Tulare, CA)



Figure 4–15 Combination of sedimentation and a dewatering press with a fine screen.



of the fabric. Initially, liquids flow through the pores and then drain slowly as the solids thicken to form a cake. The liquid effluent is collected and drained back to the lagoon. The only pressure to drive flow through the pores is gravity. If the fabric becomes clogged then dewatering will stop and the only way moisture will be removed is by evaporation. Addition of chemical flocculants may be required to reduce clogging of the fabric pores.

(e) Flocculation and coagulation

Addition of coagulants and flocculants to manure can enhance the performance of all types of solid-liquid separation methods. Use of a coagulant or flocculant to enhance separation performance requires addition and mixing of the chemical into the manure prior to separation. Therefore, chemical enhancement can only be used with manure that contains enough dilution water to allow complete mixing and pumping. In general, chemical enhancement of solid-liquid separation is most effective for manure with a TS of 6 percent or less.

Examples of coagulants include aluminum sulfate, ferrous sulfate, ferric sulfate, and ferric chloride. All of these compounds react chemically to form precipitants that are typically heavier and larger than a significant proportion of the suspended particles. Polymers are long-chain, high-molecular-weight molecules that can have a neutral (nonionic), positive (cationic), or negative (anionic) charge. Addition of a polymer will result in the formation of large, dense, fragile flocs that can enhance removal of solids and plant nutrients using most separation techniques.

Figure 4–16 Geotextile tube dewatering dairy lagoon sludge (University of Georgia Cooperative Extension)



637.0402 Influence of manure characteristics and handling methods on selection of a solid-liquid separation process

The first step in selection of a separation method is to develop an understanding of the animal production facilities that the manure treatment system must support. The designer must understand the features of the animal housing system that will impact the volume and characteristics of the waste stream. Features to consider are the animal species, amount and type of bedding used, amount of water added to the manure, method used to collect manure from the housing area, method used to remove manure from the facility, method used to treat and store manure, and the manure utilization options available on or near the site.

The information provided in the following section is only a general guideline. In some cases the designer will need to visit the client's farm, or a similar farm, to determine the characteristics of the manure that will be the influent to the separation process. Make plans to collect a representative sample of the manure that is removed from the buildings during the site visit. Have the sample analyzed by an approved laboratory to determine the concentrations of TS, VS, total Kjeldahl nitrogen (TKN), ammoniacal N ($\text{TAN} = \text{NH}_4^+ - \text{N} + \text{NH}_3^- \text{N}$), organic-N, total phosphorus (typically expressed as P_2O_5), total potassium (typically expressed as K_2O), and any other constituents that may be required by local, State, or Federal regulations or permits.

The critical manure characteristic that can be used to develop a short list of possible separation alternatives is the TS concentration of the manure that is removed from the animal housing area. The amount of water and bedding added to the manure will be reflected in this value and will be used to classify manure as a solid, slurry, or liquid.

A general summary of the relative performance of common solid-liquid separation methods that have been used to treat animal manure is provided in table 4.1. Use this table as a starting point in the selection process. Greater detail on separator performance and the full range of methods will be provided in later sections of this publication.

The number of the symbols (+) shown in the table provide an indication of how separator performance is influenced by TS. For example, gravity settling works well for TS concentrations less than three percent. If the manure has a TS greater than three percent, the applicability of sedimentation becomes questionable. Above a TS of four percent, gravity settling should not be considered in most cases because of the small supernatant volume. A centrifuge generally decreases in effectiveness as the TS content of the influent manure increases in a similar manner as gravity settling. However, a centrifuge is able to achieve greater solid-liquid separation in the TS range of three to five percent because the acceleration of manure particles is greater than gravity. Screen-type separators have the lowest performance as compared to gravity settling or a centrifuge for treatment of very diluted manure (TS < 2%). However, screen-type separators are preferred if TS of influent manure will typically be between two and four percent. Presses are not effective for primary treatment of dilute manure, but are one of the best options if the TS of the influent manure will be greater than five percent most of the time.

(a) Overview of animal housing methods as related to solid-liquid separation

The amount of water added to manure to remove it from the animal housing is a dominant factor that influences the concentration of TS and the applicability of solid-liquid separation in a manure management system.

(1) Dairy

Many types of housing systems are used for dairy cows across the United States, and the methods used to handle manure and wastewater will impact the opportunities for application of solid-liquid separation technology. The designer needs to be familiar with the various housing types so that a set of reasonable choices for a particular site can quickly be decided.

(i) Pastures and open feedlots

Many dairy cows are kept outside either on pastures or on feedlots. In both cases, the majority of the manure from the milking herd will either not be collectable or will be handled as a semi-solid or solid (TS ≥ 10%). The main difference between these two systems is the stocking rate or area per cow.

Table 4–1 Relative performance of major types of solid-liquid separators treating fresh animal manure

Type of separator	Total solids of influent manure (%)							
	≤ 1	2	3	4	5	6	8	10
Gravity settling	++++ ^{1/}	+++	++	+	NR ^{2/}	NR	NR	NR
Centrifuge	++++	++++	+++	+++	++	++	+	NR
Screen separators								
stationary	+	++	+++	++++	++++	NR	NR	NR
vibrating	+	++	+++	++++		NR	NR	NR
rotary	+	++	+++	++++	++++	NR	NR	NR
Press								
screw press	NR	NR	++	+++	+++	++++	++++	++++
belt press	NR	NR	++	+++	+++	++++	++++	++++

1/ The greater the number of plus signs, the more effective the separator will be for a given value of TS.

2/ NR = not recommended based on available data or no data exists in the literature.

The stocking rates of pasture systems are low enough (1.5 to 6 ac/cow) to allow stands of forage to be maintained to provide feed for the animals and manure from the cows is deposited on the pasture as they graze. The actual stocking rate that will be successful will depend on the quality of the pasture, and the level of rotational grazing that is implemented.

In many cases, a covered or uncovered feeding area is used to provide supplemental feed for the cows following each milking. On small grazing dairies, this feeding area may be a bunk that is moved around the pasture to avoid bare spots. In such cases, this manure will not be collected. Distribution of manure will be facilitated by movement of the bunk. On larger dairies, the supplemental feeding area will be a feeding fence with an open concrete or dirt lot. Manure from these types of areas must be periodically scraped and runoff must be managed so as to prevent contamination of surface water. Provision of a covered feeding area, often called a feeding barn, will reduce the amount of runoff that must be collected, treated, and stored.

For both pasture and feedlot dairy farms, the only types of manure that could be potentially treated using solid-liquid separation includes manure and wastewater from the milking center and runoff from outside lots and lanes. Settling basins are a common separation method used to remove solids from runoff from outside lots and feeding areas. The liquid effluent still contains large amounts of suspended solids and plant nutrients and will require further treatment. Manure that is scraped from lots and lanes will be in a thick slurry to semisolid (TS = 8 to 15%), and is typically not treated using solid-liquid separation.

Milking center wastewater contains all manure wash water from the holding pens and the parlor room, wash water from the pipelines, liquid waste from the milk room, and varying amounts of waste milk. The TS content of milking center waste can be as low as 0.5 percent but is rarely greater than 3 percent. Therefore, sedimentation and screening are the most common methods of solid-liquid separation. If a screen separator is used it may need to be combined with sedimentation and or some sort of coagulant or flocculant to achieve maximum solids and nutrient removal. Runoff from outside lots and lanes is best treated by gravity settling, and it can be included with the milking center waste in many cases. The waste volume and concentration of TS in these waste streams will vary greatly

by season of the year from less than 0.5 to about 3 percent. Therefore, the solid-liquid separation system must be capable of handling large variations in volume and consistency

(ii) Freestall systems

The most prevalent type of dairy housing system in the United States is the freestall barn. In these types of barns the cows are free to lie down, stand, move around, or eat and drink. In addition, lanes are provided to move groups of cows to and from a milking center two to three times a day for milking. Manure must be removed two to three times each day from freestall barn alleys and at least once a day from lanes.

The consistency of the manure that is removed from a freestall barn will depend on the amount and type of bedding used for stalls, the method used to remove manure from the alleys, the amount of water added to the manure from waterer wastage, and water added from sprinkler cooling systems. However, all freestall facilities can be divided into two broad categories, scrape or flush.

Scrape—The most common method for scraping manure from freestall alleys and lanes is to use a skid-steer loader with a scraping blade made from an old tractor tire or with a metal bucket. The tire scraper is preferred since it does not damage the concrete surface and its concave shape works well with manure of a variety of moisture contents.

The other method that is used to scrape manure from freestall alleys is a mechanical alley scraper. This machine drives reciprocating scrapers that are attached to cables or chains that are recessed in the alley floor. Therefore, small amounts of manure are removed from the alleys at intervals throughout the day. Mechanical alley scrapers are not used to clean lanes that are used to move cows or from floors in the milking center.

Manure that is scraped from alleys and lanes is deposited in reception pits at the end of the alley. Manure is transferred to storage or the primary treatment system by either gravity or pumping.

The consistency of scraped dairy manure will vary with the amount and type of stall bedding used and with the amount of drying that occurs before it is removed from the animal housing area. While the TS content will vary, it is typically in the range of 10 to 14 percent if organic bedding is used. Therefore, solid-liquid separation is not often used to treat scraped manure from a freestall barn. However, a screw or belt press may be applicable in some situations.

If sand is used as stall bedding, the manure will still have the consistency of thick slurry but will have a TS on the order of 18 percent and is not a good candidate for treatment using any method of solid-liquid separation unless sand is removed first.

In most cases, wastewater from the milking center is transferred to the reception pit that receives manure from the freestall barn. Mixing of these two waste streams will reduce the TS of the manure that is fed to the solid-liquid separation system to the range of 5 percent to 8 percent. As a result, a press tends to work best on dairy farms that mix manure scraped from the housing area with milking center wastewater.

If sand bedding is used in the freestall barn, adding milking center waste to sand-laden manure will reduce the TS content and cause sand to readily settle in the reception pit or in gravity flow pipes. For this reason, it is generally best to keep sand-laden freestall manure and milking center wastewater separate unless a sand-manure separator will be used.

Flush—A flush system uses a large quantity of water released quickly to remove cow manure from the alleys of freestall barns, holding pens, lanes, and cow platforms in the milking parlor. The actual amount of water required for cleaning the floors by flushing depends on alley width and slope. As a result, the TS of flushed manure is typically low. The TS content of flushed dairy manure can range from less than 0.5 percent for a flushed milking center to as high as 3.5 percent for a freestall barn that contains stalls that are heavily bedded with wood shavings. Most flushed dairy manure has a TS on the order of 1 percent to 2 percent.

A flush system is a convenient method to remove manure from dairy freestall barns and milking centers but yields a high volume of liquid manure that must be treated each day. As a result, gravity settling and

screen separators that can handle high flow rates are preferred. The use of a screw or belt press for flushed manure will require multiple units or other means to provide the required manure throughput rate.

Sand bedding is also used in many flushed freestall buildings. These types of systems require higher flush flow velocities and implementation of some means of sand removal prior to solid-liquid separation. Sand can be removed from dilute manure by means of specially designed settling basins, sand traps, sand lanes, or a mechanical sand-manure separator. Details concerning these specialized treatment processes are provided in NEH637.0406 of this handbook.

(iii) Tie-stall and stanchion barns

Tie-stall and stanchion barns are not a popular housing option on most dairy farms. However, they are still used on older farms in the Midwest and the Northeast for herd sizes of 80 cows or less. Each cow is kept in her own stall that has a water bowl and a feed manger. The cow is kept in the stall by a neck chain (tie-stall) or a movable metal yoke called a stanchion.

The stall surface is finished concrete and may be covered by a rubber mat or rubber filled mattress. Large amounts of organic bedding are added to the stalls to provide a clean, dry, and comfortable place for the cow to lie down. The bedding is kicked out of the stalls by the cows and collects in a gutter behind the cows with manure. The result is semisolid to solid manure with a TS in the range of 15 to 20 percent. If milk house wastewater is included with the barn manure in a reception pit, then the manure will be a slurry (TS ranging from 8 to 12%). Solid-liquid separation is rarely used to treat stall barn manure.

In some cases, the milk house wastewater is handled separately from the barn manure and has a solids content less than 0.5 percent. Gravity settling is the primary solid-liquid separation option to consider for milk house waste. Addition of a coagulant or flocculent can enhance treatment effectiveness.

Many tie-stall barns have an outside lot next to the barn that is used only a few hours each day (2 to 4 h). Sedimentation may be used as primary treatment for lot runoff as is common for other types of feedlots.

(2) Swine

Most swine housing systems are designed around liquid or slurry manure handling systems and bedding is not used. The solid-liquid separation options that are applicable for dairy farms can also be applied on swine farms. However, the mass removal of solids and other constituents is less for swine than dairy manure due to the differences in ration (ground feeds versus forages) and the resulting smaller particle size of the solids in swine manure as compared to dairy manure.

Not all types of swine facilities can easily use solid-liquid separation. Some small swine farms use heavily bedded pens, and manure is handled as a solid. Solid-liquid separation is not applicable on these farms. There is also a growing trend in cold climates to collect slurry manure in a deep pit below fully slotted floors. In most cases, slurry manure from deep pit buildings is used directly on nearby cropland to offset fertilizer needs. However, situations may exist where it would be advantageous to separate solids from the liquids to facilitate composting or movement of plant nutrients to a remote facility. In such a case, the solid-liquid separation technologies that work well with slurry swine manure would be the most applicable.

(i) Slurry

A common type of slurry manure handling system used in swine housing facilities is the gravity drain gutter. This method of manure collection includes perforated or slotted flooring in the animal pens. Manure drops through the floor and collects in one or more shallow channels below the pigs. Every 5 to 7 days, the manager pulls a plug, and the manure with an average TS content in the range of 3 to 6 percent flows either to storage or primary treatment. After manure is removed from the barn, a 3- to 4-inch layer of fresh water is added to the pit to provide enough dilution water to ensure manure will flow properly.

In some swine facilities, the floor is partially slotted. The solid floor of the animal resting area is sloped to a manure collection gutter that is covered by a slotted floor (concrete slats). Most of these buildings are designed so as to encourage animals to defecate in the slotted floor area (called the dunging area). However, the facility manager will periodically wash down the resting area with a high-pressure hose. The collection gutter is emptied once a week using a pull plug. Depending on the amount of water used to wash down

the pens, the TS content of the manure from this type of building will range from 3 to 6 percent.

The other source of dilution water for both types of gravity drain gutter is waterer wastage. It is not uncommon for swine to add significant amounts of water to the slurry pit by playing with the nipple waterers.

Gravity settling is the only solid-liquid separation technique that should not be considered if swine manure is collected as slurry. In many cases, some sort of press is the best separator choice.

(ii) Liquid

The two primary liquid manure handling methods used in swine facilities are flush and pit-recharge systems. The volume of manure that must be collected and handled varies greatly depending on the frequency of barn cleaning and the weight of animals housed.

Most flush swine facilities have completely slotted or perforated floors that allow manure to fall through the floor onto a sloped, concrete channel. Manure is flushed from below the slotted floor 2 to 12 times each day depending on the type of flush control used. An independent flush tank is used to clean manure from each row of pens. Most flush tanks are sized to release 250 to 500 gallons of water per flush. Flushed manure is collected in a cross channel and is conveyed to a 6- to 8-inch pipe that is used to transfer manure by gravity to primary treatment or a treatment lagoon. Lagoon surface water (supernatant) is typically recycled back to the flush tanks.

Older swine buildings may use an open flush gutter for finishing swine or breeding stock. Flushing schedules can range from twice each day using a manual dump tank to a continuous stream. The resting and feeding area is a solid concrete floor that is manually scraped or cleaned with a high-pressure hose.

The TS content of flushed swine manure can vary greatly from farm to farm depending on frequency of cleaning and the amount of water used. The TS content can range from about 0.5 to 1.5 percent. The best solid-liquid separation techniques for flushed manure is gravity settling or a screen that can handle a moderate to high flow rate.

Many new swine facilities in the southern United States use a variation of the pit-recharge manure handling system (Barker and Driggers 1985). A pit-recharge manure handling system consists of an under-floor pit with an average depth of 24 to 30 inches. The floor of the pit is generally sloped 1 inch per 20 feet toward a collection gutter that conveys manure to a drain that is located in a sump outside the building. The drain is plugged using a removable standpipe that is typically made of PVC. A slot is cut in the side of the standpipe to set the liquid depth in the building. The level is set so that the highest part of the pit floor is covered by 3 to 6 inches of water. In most cases, the pit is filled with recycled lagoon supernatant and the pit is typically emptied every 5 to 7 days. The manure is transferred to the separation system or a treatment lagoon by gravity.

The TS concentration from a recharge pit can vary from 1.5 to 2.5 percent due to variations in pig weight from 50 to 260 pounds. As a result, the best solid-liquid separation techniques for manure from pit-recharge buildings are gravity settling and screen type mechanical separators. If maximum solids and plant nutrient removal is required, a coagulant or flocculant will be needed.

(3) Beef

Beef cattle are produced on a variety of farms. The production chain begins on pasture-based cow-calf farms. The product of these farms is stocker calves. Stocker calves are sold to another beef producer to be fed high-quality forage or pasture to prepare them for finishing (back-grounding). Feeder cattle are then placed in feedlots where they are fed a high-grain diet to produce choice or prime grade finished beef.

The only types of beef farms that could have an application for solid-liquid separation are feedlots that produce either feeder or finished cattle. Gravity settling is a common treatment option for runoff from outside lots (TS in the range of 0.5 to 2%). Solids that remain on the lot are periodically scraped and removed. In some cases, beef manure is handled as a liquid or slurry (TS of 2 to 8%) and a screen or press may satisfy the treatment objective for a particular farm.

(4) Poultry

Manure is handled as a solid on the majority of poultry farms in the United States and as a result solid-liquid separation is typically not used.

The primary exception is egg producing farms that flush manure from beneath the cages or scrape manure from a pit as slurry. Liquid poultry manure (TS content < 3%) could be treated by sedimentation or screening. If the manure has the consistency of a slurry (TS of 6 to 8%) a press may be a viable option.

(5) Other animals

There are many other types of animal farms including veal, horse, sheep (meat and dairy), goats (meat and dairy), rabbits, quail, and squab. In all but a few situations, animals on these farms are either kept on pasture or in well-bedded pens or barns. Therefore, solid-liquid separation is generally not applicable.

The primary exception is veal facilities. In a veal barn, calves are kept in individual stalls. They are fed primarily a liquid diet of fortified milk replacer. Since the calves are not fed solid food, the manure has the consistency of slurry but with a TS content of about two percent. Manure is often removed by flushing below a slotted floor, which will reduce the TS content to well below one percent. Solid-liquid separation is not common on veal farms and performance data are not readily available. However, it is likely that gravity settling would be the only feasible option since the veal calf manure is so low in large particles.

Manure from dairy goats and dairy sheep is typically handled as a well-bedded solid. However, waste from the parlor and milk room will be similar to that found on bovine dairy farms. As a result, solid-liquid separation options that are suitable for milking centers on cow dairies may have some appropriate applications.

(b) Benefits of solid-liquid separation

Most swine and dairy production facilities in the United States, Canada, and Europe use liquid or slurry manure handling systems to facilitate the mechanization of collection, transfer, storage, and land application of manure. In cold climates, slurry manure is often stored until conditions are favorable for land application in lined earthen basins, below or above ground storage tanks, or in pits below slotted floors.

In temperate and warm climates, it is common to treat and store swine manure in anaerobic or facultative lagoons. Solid-liquid separation via gravity settling has been used extensively to reduce the solids content in runoff from outdoor beef, swine, and dairy feedlots.

Solid-liquid separation has traditionally been viewed as a method to improve the pumping and irrigation characteristics of liquid manure, to generate solids for composting, or land application. More recently, solid-liquid separation has been used to facilitate implementation of secondary biological treatment, reduce sludge build-up in lagoons, facilitate better nutrient management practices, and facilitate the use of the organic portion of manure as an energy source.

(1) Manure storage benefits

Manure storages are sized to store all of the manure, waterer wastage, and wash-down water for a defined storage period. Additional depth is also provided for net rainfall (precipitation—evaporation) during the wettest months of the year, the 25-year, 24-hour storm, and a minimum freeboard of 12 inches (fig. 4–17). The entire storage contents are agitated and land applied one or more times per year. In warm climates, manure storages are often sized to contain 120 to 180 days of manure since grains and forages can be grown much of the year. In cold climates, storage periods of 1 year are common. It is important that the storage structure be sized to provide adequate storage when land application cannot occur.

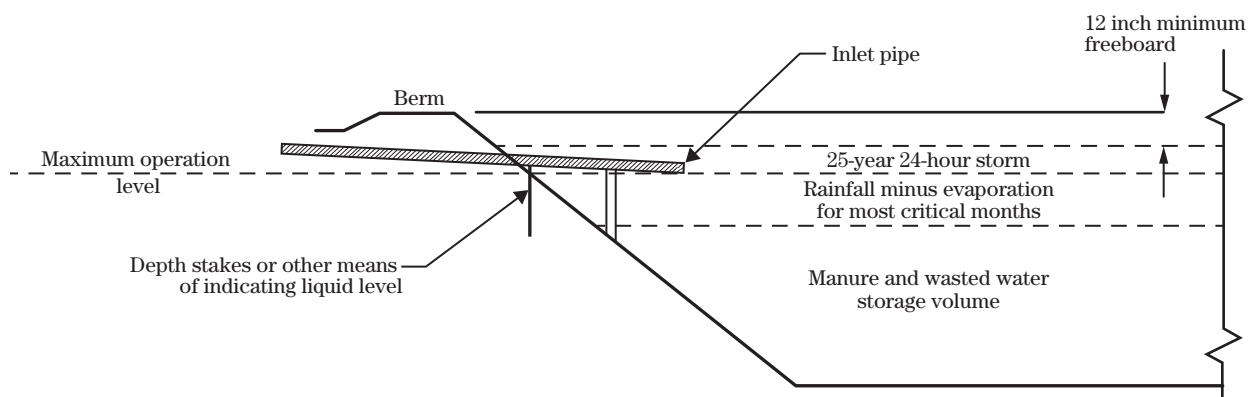
Surface water from a storage structure should not be used as a source of recycle water for flushing manure

from a barn, since manure storages are not designed to provide the necessary treatment to reduce solids content, ammonia, and pathogens. If surface water from a storage pond or tank is used in a recycle flush system, higher odor and ammonia levels would be expected in the buildings. Use of poorly treated water for manure removal has resulted in a decline in animal health. Corresponding increases in the amount and cost of antibiotics needed to maintain animal health have been observed.

Manure storage structures can be made of a variety of materials. The most common is the lined earthen basin or storage pond. However, above and below ground concrete or glass-lined steel tanks can also be used.

The benefits of providing solid-liquid separation of manure prior to storage include improved pumping and handling characteristics of the manure, reduction in agitation requirements, and reduction in storage volume. Swine and dairy facilities that store manure as a thick slurry (TS = 6 to 10%) must expend a significant amount of time and energy agitating the storage prior to and while pumping manure into a tank-type manure spreader. Proper agitation is needed to homogenize the plant nutrients in manure prior to land application and provide maximum removal of solids from the storage. The tractor horsepower and the agitation time requirements prior to land application are influenced by the solids content. Thick slurry, such as well-bedded dairy manure, will form a thick crust on the surface of the storage. While the undisturbed crust will reduce odor emissions, it will also require 6 to 10 hours of continuous agitation with a large tractor (100

Figure 4–17 Components of a manure storage structure



to 150 hp) to break up the crust and mix it with the storage contents prior to loading the spreader. Agitation is also required as the storage is emptied and the contents are spread on cropland. Constant agitation is needed if fields are near the storage. Intermittent agitation will be sufficient to maintain the nutrient and solids content of the slurry if manure is hauled to distant fields. Agitation requirements of large manure storages with thick slurries require substantial amounts of fuel for the tractors and labor to operate agitation and land application equipment. Using a mechanical separator, such as a screw press that can remove 20 to 40 percent of the total solids, would reduce or prevent crust formation. The remaining lighter, smaller manure particles would be easier to maintain in suspension by agitation. This would reduce power and time requirements for agitation and pumping manure into a spreader. Providing solid-liquid separation prior to storage will reduce the required manure storage volume to some extent. The volume reduction that results from mechanical separation of manure depends on the animal species, bedding practices, and percentage of the solids that are removed. Storage volume reductions provided by mechanical separators can range from only 1.2 percent at a total solids removal of 7 to 22 percent at a total solids removal of 42 percent. If manure from a storage structure is to be used to provide recycled plant nutrients to large land areas, one of the most fuel and labor efficient methods of land application is medium to large bore irrigation systems (e.g., traveling, big gun, or 0.25-inch nozzle impact sprin-

klers). Such systems are combined with a buried main pipeline and a system of hydrants to avoid the need for large tractors in the fields and the associated fuel and labor costs. Mechanical solid-liquid separation can be used to remove large ($d > 1$ mm) and medium ($d > 0.25$ mm) sized particles that would clog nozzles or pipes. Therefore, a key benefit of solid-liquid separation is to facilitate the use of irrigation as a fuel and labor saving land application technique.

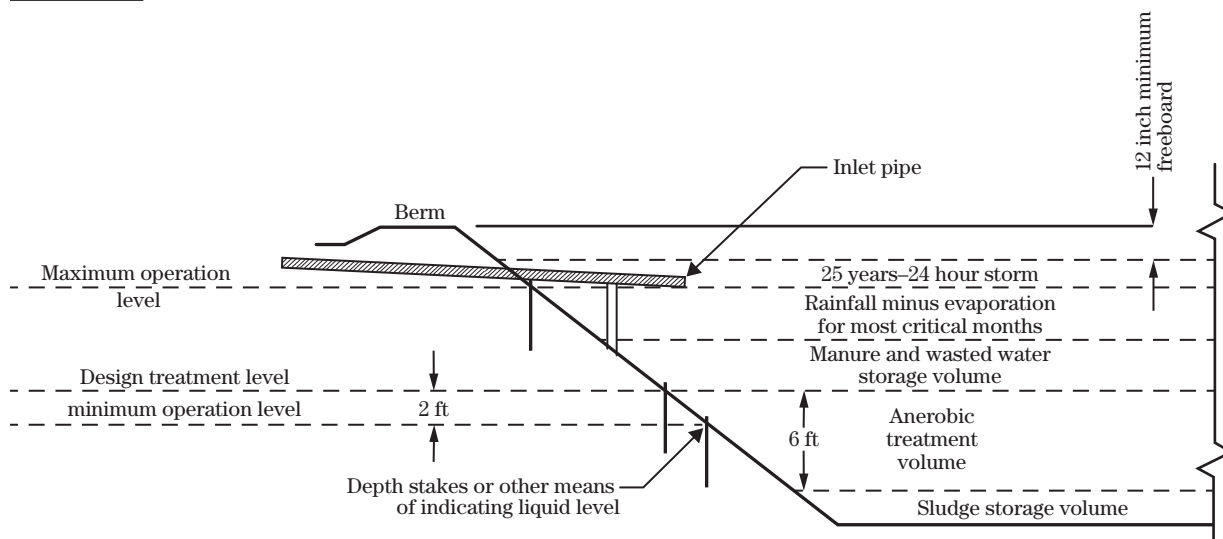
(2) Treatment lagoon benefits

Lagoons are the most common biological method used to treat and store liquid manure from animal facilities. Most lagoons are constructed as a lined earthen basin and, as a result, lagoons look similar to a storage pond. However, a treatment lagoon is designed based on anaerobic and/or facultative treatment principles. A lagoon is sized to provide storage for manure and net precipitation like a storage pond, but additional volume is provided to allow for controlled biological treatment (treatment volume) and the accumulation of sludge (sludge storage volume). The volumes used to size an anaerobic lagoon are shown in figure 4–18. The lagoon operator must maintain these volumes and depths for the lagoon to function properly.

(i) Treatment volume

The treatment volume of a lagoon is determined based on the design VS loading rate (lb VS/1,000 ft³-day). As a result, the treatment volume (TV, ft³) can be calculated as $TV = 1,000 (MVS/LR)$, where the mass of VS added

Figure 4–18 Components of an anerobic treatment lagoon (based on ANSI/ASAE EP403.4, 2011)



to the lagoon each day (MVS, lb VS/day) depends on the animal species, stage of growth, productivity, and number of animals. The design loading rate (LR) depends on the climate. Larger loading rates can be used in warm climates rather than in cold climates, since cold temperatures reduce growth rates of the microbes that breakdown the VS. For example, in the coastal plains of South Carolina, the maximum loading rate that should be used for a treatment lagoon is 5.0 pounds VS per 1,000 cubic foot-day. However, in a colder climate like Iowa, the maximum loading rate is 3.5 pounds VS per 1,000 cubic foot-day.

Providing primary treatment using solid-liquid separation will reduce a significant fraction of the TS and VS solids that will enter a lagoon. As a result, the treatment volume in the lagoon will be reduced in direct proportion to the fraction of the VS removed (f_{VSR}). The reduction in lagoon treatment volumes following solid-liquid separation are summarized for finishing swine manure in table 4–2 and for dairy cow manure in table 4–3.

Table 4–2 Impact of climate and solid-liquid separation performance on treatment volume ($TV^{1/}$) of a lagoon used to treat swine manure from growing and finishing animals^{2/}

Loading rate (LR) lb VS/1,000 ft ³ -day	Percent VS removed by solid-liquid separator ($100 \times f_{\text{VSR}}$)							
	0%	20%	30%	40%	50%	60%	70%	80%
----- Treatment volume, ft ³ /1,000 lb of live animal weight -----								
3.0 (Southern Minnesota) ^{3/}	1,670.0	1,336.0	1,169.0	1,001.0	835.0	668.0	501.0	334.0
3.5 (Iowa)	1,431.4	1,145.1	1,002.0	858.9	715.7	572.6	429.4	286.3
4.0 (Kansas)	1,252.5	1,002.0	876.8	779.3	626.3	501.0	375.8	250.5
4.5 (North Carolina)	1,113.3	890.7	779.3	668.0	556.7	448.0	334.0	222.7
5.0 (Central Georgia)	1,002.0	801.6	701.4	601.2	501.0	400.8	300.6	200.4
5.5 (Central Texas)	910.9	728.7	637.6	546.5	455.5	364.4	273.3	182.2
6.0 (Central Florida)	715.9	572.6	501.0	429.4	357.9	286.3	214.7	143.1

1/ $TV = 1,000 (MVS (1-f_{\text{VSR}})) / LR$, where f_{VSR} = fraction of volatile solids removed by the solid-liquid separator

2/ Solids production of growing and finishing swine was $MTS = 6.5 \text{ lb TS}/1,000 \text{ lb live animal weight}/\text{day}$, and $MVS = 5.01 \text{ lb VS}/1,000 \text{ lb live animal weight}/\text{day}$.

3/ Representative climates for the loading rate shown (based on fig. 2 in ANSI/ASAE EP403.4, ASABE R2015).

Table 4–3 Impact of climate and solid-liquid separation performance on treatment volume ($TV^{1/}$) of a lagoon used to treat manure from lactating dairy cows^{2/}

Loading rate (LR) lb VS/1,000 ft ³ -day	Percent VS removed by solid-liquid separator ($100 \times f_{\text{VSR}}$)							
	0%	20%	30%	40%	50%	60%	70%	80%
----- Treatment volume, ft ³ /1,000 lb of live animal weight -----								
3.0 (Southern Minnesota) ^{3/}	3,933.3	3,146.7	2,753.3	2,360.0	1,966.7	1,573.3	1,180.0	786.7
3.5 (Iowa)	3,371.4	2,697.1	2,360.0	2,022.9	1,685.7	1,348.6	1,011.4	674.3
4.0 (Kansas)	2,950.0	2,360.0	2,066.0	1,770.0	1,475.0	1,180.0	885.0	590.0
4.5 (North Carolina)	2,622.2	2,097.8	1,835.6	1,573.3	1,311.1	1,048.9	786.7	524.4
5.0 (Central Georgia)	2,360.0	1,888.0	1,652.0	1,416.0	1,180.0	944.0	708.0	472.0
5.5 (Central Texas)	2,145.5	1,716.4	1,501.8	1,287.3	1,072.7	858.2	643.6	429.1
6.0 (Central Florida)	1,685.7	1,348.6	1,180.0	1,011.4	842.9	674.3	505.7	337.1

1/ $TV = 1,000 (MVS (1-f_{\text{VSR}})) / LR$. Where f_{VSR} = fraction of volatile solids removed by the solid-liquid separator.

2/ Solids production of lactating dairy cows was $MTS = 14.4 \text{ lb TS}/1,000 \text{ lb live animal weight}/\text{day}$, and $MVS = 11.8 \text{ lb VS}/1,000 \text{ lb live animal weight}/\text{day}$.

3/ Representative climates for the loading rate shown (based on figure 2 in ANSI/ASAE EP403.4, ASABE, R2015)

In cold Midwestern States, such as southern Minnesota and Iowa, swine manure is rarely treated in a lagoon because the cold climate would require construction of an extremely large, lined earthen basin that is often prohibitively expensive. However, pork producers in warmer climates often use treatment lagoons to provide solids reduction and to yield effluent that has been sufficiently treated to allow it to be recycled through flush or pit-recharge manure removal systems. Implementation of solid-liquid separation system that removes 30 to 40 percent of the VS would allow pork producers in the Midwest to use similar lagoon treatment volumes as pork producers located in North Carolina or central Georgia.

The large amount of solids produced by high-producing dairy cows results in treatment volumes that are 2.36 times larger than for the equivalent weight of finishing swine. As a result, solid-liquid separation is recommended for any flush dairy facility that uses lagoon supernatant to flush freestall alleys. Even in warm climates, VS removals in the range of 40 to 60 percent are needed to yield treatment volume requirements that are similar to swine finishing farms.

(ii) Sludge storage volume

The other component of a treatment lagoon that is not included in a storage pond is the sludge storage volume (SV). Engineers have defined sludge that accumulates in a lagoon in a variety of ways. In some of the initial studies, the entire settled layer in a lagoon was defined as sludge (Sweeten et al. 1980). By the early 1980s, a more detailed view of sludge in a treatment

lagoon began to emerge. Fulhage (1980) suggested that lagoon sludge consists of only the nondegradable VS and the fixed solids (FS) that accumulate at the bottom of a treatment lagoon. His sludge accumulation estimate for swine lagoons included an estimate of the VS destruction rate and the fraction of the TS added to the lagoon that would settle to the sludge layer. Smith (1980) presented a two-layer concept to describe sludge accumulation. The lower layer was called the sludge bed and included all recalcitrant VS and FS. An active layer called the sludge blanket covered the sludge bed. Five years later, Barth and Kroes (1985) presented a complex lagoon sludge accumulation model that included inert sludge composed of FS, nondegradable VS, and an active sludge layer. More recently, Chastain (2006) provided a review of the available data concerning lagoon sludge accumulation rates and proposed a mass balance approach that expanded on ideas presented by Fulhage (1980) and Barth and Kroes. Engineers continue to use the term sludge to describe solids from a primary settling basin, and fully or partially biologically stabilized manure. Such mixed use of the term has led to a great deal of confusion.

The international standard on lagoon design recommends the use of the sludge accumulation rates (SAR) given in table 4–4 for calculation of the sludge storage volumes for anaerobic treatment lagoons.

The sludge storage volume is calculated as the product of the SAR and the mass of TS added to the lagoon over a defined sludge storage period. The benefit provided by a solid-liquid separation system is that the

Table 4–4 Sludge accumulation rate (SAR) estimates for anaerobic lagoon design (ANSI/ASAE EP403.4, ASABE, 2011)

	m ³ /kg TS added	ft ³ /lb TS added
Poultry (layer or pullet)	0.00202	0.0324
Swine	0.00137	0.0219
Dairy (Value does not include contribution of soil or bedding.) ^{1/}	0.00455	0.0729

^{1/} There is no value available for beef animals. However one might expect it to be less than the dairy value due to the lower fiber percentage of most beef diets.

solids added to the lagoon are reduced, which will reduce sludge accumulation. A significant reduction in sludge accumulation will allow a much smaller lagoon to be used to treat manure from a given number of animals. If solid-liquid separation is added to remove a significant amount of TS prior to an existing lagoon,

the amount of time before sludge accumulation becomes excessive will be increased, and the useful life will be extended. Sludge storage volume estimates and the reduction provided by solid-liquid separation are provided for swine and dairy manure in tables 4–5 and 4–6.

Table 4–5 Impact of solid-liquid separation performance on sludge SV^{1/} of a lagoon used to treat swine manure from growing and finishing animals^{2/}

Sludge storage period Years	Percent TS removed by solid-liquid separator (100 × f _{TSR})							
	0%	20%	30%	40%	50%	60%	70%	80%
----- Sludge storage volume, ft ³ /1,000 lb of live animal weight -----								
1	52.0	41.6	36.4	31.2	26.0	20.8	15.6	10.4
2	103.9	83.1	72.7	62.3	52.0	41.6	31.2	20.8
3	155.9	124.7	109.1	93.5	77.9	62.3	46.8	31.2
4	207.8	166.3	145.5	124.7	103.9	83.1	62.3	41.6
5	259.8	207.8	181.9	155.9	129.9	103.9	77.9	52.0
10	519.6	415.7	363.7	311.7	259.8	207.8	155.9	103.9
15	779.4	623.5	545.6	467.6	389.7	311.7	233.8	155.9

1/ $SV = SAR \times MTS (1 - f_{TSR}) \times t_{SP}$ Where SAR = the sludge accumulation rate, f_{TSR} = fraction of total solids removed by the solid-liquid separator, and t_{SP} = the sludge accumulation period in days. From ANSI/ASAE EP403.4 (ASABE, 2011) the SAR for swine manure is 0.0219 ft³ of sludge per lb of TS loaded.

2/ Solids production of growing and finishing swine was MTS = 6.5 lb TS/1,000 lb live animal weight/day, and MVS = 5.01 lb VS/1,000 lb live animal weight/day.

Table 4–6 Impact of solid-liquid separation performance on sludge storage volume (SV^{1/}) of a lagoon used to treat manure from lactating dairy cows^{2/}

Sludge storage period Years	Percent TS removed by solid-liquid separator (100 × f _{TSR})							
	0%	20%	30%	40%	50%	60%	70%	80%
----- Sludge storage volume, ft ³ /1,000 lb of live animal weight -----								
1	383.2	306.5	268.2	229.9	191.6	153.3	114.9	76.63
2	766.3	613.1	536.4	459.8	383.2	306.5	229.9	153.3
3	1,149	919.6	804.6	689.7	574.7	459.8	344.8	229.9
4	1,533	1,226	1,073	919.6	766.3	613.1	459.8	306.5
5	1,916	1,533	1,341	1,149	957.9	766.3	574.7	383.2
10	3,832	3,065	2,682	2,299	1,916	1,533	1,149	766.3
15	5,747	4,598	4,023	3,448	2,874	2,299	1,724	1,149

1/ $SLV = SAR \times MTS (1 - f_{TSR}) \times t_{SP}$ Where SAR = the sludge accumulation rate, f_{TSR} = fraction of total solids removed by the solid-liquid separator, and t_{SP} = the sludge accumulation period in days. From ANSI/ASAE EP403.4 (ASABE, 2011) the SAR for dairy manure is 0.0729 ft³ of sludge per lb of TS loaded.

2/ Solids production of lactating dairy cows was MTS = 14.4 lb TS/1,000 lb live animal weight/day, and MVS = 11.8 lb VS/1,000 lb live animal weight/day.

The estimated reductions in the sludge storage volume provided in the tables are conservative since the removal of total solids by the separator was applied uniformly to all solids in the manure. Solid-liquid separation removes mostly suspended solids that would settle to the sludge layer, and, as a result, the estimates given in the tables maybe larger than expected in many cases. Detailed information concerning the performance of a separation system would allow a more precise estimate using a mass balance approach (Chastain, 2006a). However, the values given in the tables are sufficient for lagoon design purposes in most cases.

The estimates given in tables 4.5 and 4.6 indicate that the reduction in sludge storage volume corresponds to the percentage of TS removed by the separator in a similar manner as the reduction in treatment volume provided by VS removal. Therefore, solid-liquid separation systems that remove a large fraction of the TS and VS will reduce the size and cost of a new lined treatment lagoon. Another important benefit is the reduction in the amount of sludge that must be periodically agitated and removed from the lagoon and applied to cropland to maintain the required treatment volume. Therefore, a solid-liquid separation system can reduce the cost to construct a treatment lagoon and reduce the fuel and labor costs to maintain the lagoon.

(3) Odor and ammonia

Manure in most storage ponds or treatment lagoons will be maintained in an oxygen-free condition (anaerobic). Microbes that break down VS anaerobically will release odorous compounds (e.g., phenol, p-cresol, p-ethylphenol, indole, skatole, and many others). Even high-rate solid-liquid separation techniques that provided 52 percent reduction in TS, could only remove 11 percent of key odorous compounds from swine manure (Vanotti et al. 2009). An article by Zhang and Westerman (1997) reviewed the published data on solid-liquid separation techniques and the particle size distributions of animal manure. Their review concluded that large particles in manure take a relatively long time to degrade and do not contribute greatly to odor production. However, the large particles do contribute to the accumulation of sludge in anaerobic lagoons. Over time, the sludge volume can build up and decrease the treatment volume and cause excessive odors. Manure particles with an average diameter of 0.25 millimeters or less are the fastest to biologically degrade and must be removed with coarse particles to

greatly reduce the odor generation potential of liquid manure.

Research has shown that the frequency of odor, or the rate of odor occurrence, near a manure storage structure will vary with the volatile solids loading rate (lb VS/1,000 ft³-day, Humenik, et al. 1981). Generally, manure storages have a much higher loading rate than treatment lagoons. Consequently, the odor frequency and strength for manure storages can be much higher than for treatment lagoons.

The loading rate has a large impact on the amount of odor and the frequency of odor that is detected near a lagoon or storage pond as shown in figure 4.19. At very high loading rates, such as 30 pounds VS per 1,000 cubic foot-day, a significant odor will be produced near a storage pond 80 percent of the time. However, a lagoon sized using a loading rate of 5.0 pounds VS per 1,000 cubic foot-day will have a detectable odor near the lagoon about 33 percent of the time. At very low loading rates (LR < 4.0 lb VS/1,000 ft³-day), a treatment lagoon will generate detectable odor about 20 percent of the time. Therefore, one way to control odor from a lagoon is to use a very small loading rate (LR ≤ 3.0 lb VS/1,000 ft³-day). However, a lagoon sized based on a small loading rate will be large and expensive to construct. Providing primary treatment with a solid-liquid separator prior to a treatment lagoon can make obtaining a lower loading rate more affordable. For example, if a swine lagoon was designed using a loading rate of 5.0 pounds VS per 1,000 cubic foot-day, adding a separator that can remove 25 percent of the VS will reduce the loading rate to 3.75 pounds VS per 1,000 cubic foot-day and will provide a reduction in odor frequency of about 39 percent. A high-rate liquid solid separation system that provides 69 percent VS reduction (Vanotti et al. 2009) would reduce the loading rate to 1.6 pounds VS per 1,000 cubic foot-day. In such a case, the odor frequency and sludge accumulation rate in a treatment lagoon would be minimal. Research on a swine farm in North Carolina has documented that substantial odor reduction can be provided by high rates of total and volatile removal as a result of greatly reduced lagoon loading (Vanotti et al. 2009; Vanotti and Szogi 2008; and Vanotti et al. 2007).

The variation in odor frequency with loading rate given in figure 4–19 also demonstrates that it is critical to maintain the required anaerobic treatment volume in a lagoon. The treatment volume will be greatly reduced if sludge is allowed to build up excessively in a lagoon. The decreased treatment capacity has the same effect as an increase in loading rate and will cause an increase in odor frequency.

The final important consideration related to the loading rates of a treatment lagoon is the quality of recycle water used for manure removal. The loading rate of a lagoon greatly affects the quality of the water that is recycled through the building to remove manure. Inadequately treated lagoon liquid, associated with high loading rates, can increase ammonia levels in the buildings and increase odor from the buildings. An old lagoon with excessive amounts of sludge should not be used as a source of recycle water. The maximum loading rate that should be used if lagoon water is recycled through the building varies by climate and was given in table 4–2 (fig. 2 in ANSI/ASAE EP403.4, ASABE 2011).

(4) Aerobic and facultative treatment

Facultative and aerobic treatment methods are designed so as to add various amounts of oxygen to provide destruction of organics or odor control. Natural aeration (wind) can be used to add just enough air to suppress anaerobic bacteria in the upper layer of a lagoon (facultative layer) resulting in a reduction in odor emission. Low rate, mechanical aerators have

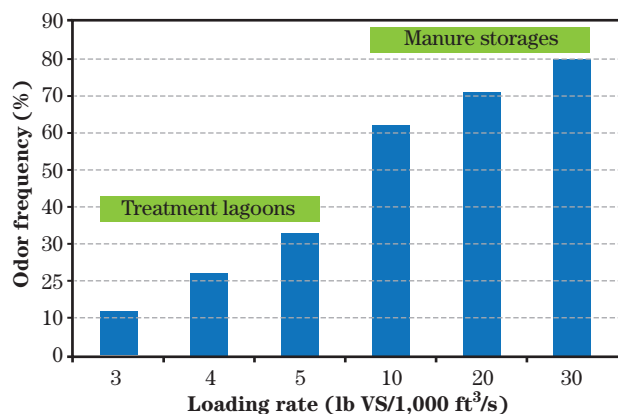
also been used to treat the surface layer of storage ponds and lagoons to provide a more sustained and reliable aerobic or facultative layer to oxidize odors and to break down organics. Full aerobic treatment of manure requires high-rate aeration that is similar to aerated lagoon and activated sludge treatment systems used to treat municipal and food processing waste streams. Solid-liquid separation benefits any type of facultative or aerobic treatment method by reducing the organic load on the system.

The organic loading variable that is most often used for aerated treatment methods is the biological oxygen demand (BOD_5). Loading rates are typically given in terms of pounds BOD_5 per day or pounds BOD_5 per 1,000 cubic meters-day. Furthermore, the oxygen required to remove a given amount of BOD_5 by a mechanical aerator depends on the organic loading rate in terms of pounds BOD_5 per hour. Therefore, any reduction in the BOD_5 provided by a solid-liquid separator provides a corresponding reduction in the organic load. For example, a solid-liquid separator that provides a BOD_5 removal from liquid manure of 30 percent will provide a 30 percent reduction in the organic load on an aerated treatment system. Reduction in organic loading will save construction costs by reducing the size of a facultative or aerobic lagoon and will reduce electrical costs for mechanically aerated systems. The BOD_5 concentration of animal manure is high, and removal of 40 to 60 percent of the BOD_5 by gravity settling or high rate mechanical separation is needed if aerobic treatment is to be implemented. In most solid-liquid separation data sets, BOD_5 removal is not given since aerated treatment methods are not common on animal farms due to high energy costs. However, the percent removal of BOD_5 is approximately equal to the percent removal of total solids. Therefore, a settling basin that will remove 55 percent of the TS will reduce the organic load on an aerated treatment system by about 55 percent.

(5) Uses of separated liquids and solids

Animal manure contains all of the essential major and minor plant nutrients that are used by plants (table 4–7). The major plant nutrients are nitrogen (N), phosphorus (P), and potassium (K). Key minor plant nutrients include calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), copper (Cu), and zinc (Zn). Manure has also been shown to contain small but sufficient amounts of chlorine (Cl), boron (B), iron (Fe), and molybdenum (Mo) that are sometimes deficient in

Figure 4–19 Variation of odor frequency observed near treatment lagoons and manure storages (adapted from Humenik et al. 1981)



soil. Plant nutrients in manure originate from the feed, supplements, medications, and water consumed by the animals. Using animal manure as a fertilizer for crops or trees may provide a portion, or all, of the major and minor plant nutrient requirements. The amount of nutrients provided depends on the nutrient content of the manure (lb of nutrient/1,000 gal of manure or lb/ton) and the amount of manure applied to the land (gal/ac or tons/ac). The amount of manure applied per acre, or application rate, can be based on the N, or P_2O_5 , or K_2O needs of the plant to be grown.

The total amount of phosphorus contained in manure is often expressed as the equivalent amount of phosphate (P_2O_5) to allow comparison with commercial fertilizers and to facilitate use with fertilizer recommendations and soil-test results. Similarly, the total potassium is given as potash (K_2O) to allow manure to be easily used as a source of K. Many studies have shown that the P_2O_5 and K_2O contained in animal manure are available to plants in the same way as commercial sources of these key nutrients. Therefore, the P_2O_5 and K_2O in animal manure can be used to replace purchased commercial fertilizer on a direct or pound-per-pound basis.

The nitrogen in animal manure is in both soluble and organic forms. All of the soluble nitrogen, ammonium-N (NH_4^+ -N) and small amounts of nitrate-N, is available to the crop. Manure that is spread on the soil surface without incorporation will result in a loss of ammonium-N by ammonia volatilization (Chastain 2006b). The amount lost can vary from depending on the moisture content and pH of the manure. Dilute manure results in minimal N-loss due to volatilization since the water in the manure will carry much of the ammonium into the soil as it infiltrates. Typical ammonium-N losses are in the range of 20 to 50 percent. If manure is immediately incorporated, as in the case of direct injection, then none of the ammonium-N will be lost to the air. The organic nitrogen in manure must be mineralized to ammonium-N in the soil before it can be taken up by plant roots with the soil water. The amount of organic-N that will become available to a crop varies by animal species, soil temperature, moisture, pH, and degree of soil contact. Organic-N mineralization rates can vary from 30 to 80 percent with most types of manure providing a conversion of 40 to 60 percent. The amount of nitrogen in the manure that will be available to the crop is called the plant available nitrogen (PAN) and can be estimated using

ammonium-N availability factors and mineralization factors. Estimates of the plant available nitrogen are shown for liquid and slurry manure based on land application methods in table 4–7. The examples provided in the table demonstrate that the PAN is always less than the total-N. Only the plant available portion of the nitrogen in animal can be used to replace purchased commercial fertilizer.

While manure contains the major nutrients needed to grow a crop it does not always contain them in the proportions that are optimal for plant growth. Most grains use 2.2 to 2.5 pounds of nitrogen for every pound of P_2O_5 as indicated in table 4–8. The desired ratio of N to P_2O_5 (N: P_2O_5) for forage crops is in the range of 2.0 to 3.6 (table 4–9). However, animal manure as removed from a housing facility has a plant available-N to P_2O_5 ratio (PAN: P_2O_5) in the range of 0.64 to 1.07, depending on the method of application, species, and moisture content (table 4–7). Untreated, dilute manure such as milking center wastewater with a lower concentration of phosphorus has a PAN: P_2O_5 that more closely matches crop needs especially if nitrogen conserving application methods are used (PAN: P_2O_5 = 2.29). Application of animal manure to provide the nitrogen needs of economically important crops such as grains and forages can result in over application of phosphorus by a factor of 1.6 to 5.7, depending on the N: P_2O_5 of the crop to be grown and the PAN: P_2O_5 of the manure (P over application factor = N: P_2O_5 of the crop ÷ PAN: P_2O_5 of the manure). Overapplication of phosphorus for many years can cause the concentration of plant available P in the top 6 inches of soil to increase substantially. If concentrations of P are high on or near the soil surface, then a potential exists for P to be transported to nearby surface water (e.g., streams, lakes, wetlands) by either soil erosion or dissolved P in runoff water. Elevated levels of P in surface water can lead to increased growth of algae and other aquatic plants, depleted oxygen levels due to large amounts of decaying plant matter, and accelerated rates of eutrophication. Depleted oxygen levels caused by the higher than normal amounts of decaying plant matter in a water body is a common cause of fish kills.

Table 4-7 Examples of major and minor plant nutrient contents in liquid and slurry swine and dairy manure (as sampled or wet basis)

	----- Swine -----		----- Dairy -----		
	Fresh slurry ^{1/}	Manure from building ^{2/}	Manure from building ^{2/}	Slurry	Milking center wastewater
Moisture =	90.8%	98.0%	96.2%	93%	98.3%
Total solids =	9.2%	2%	3.8%	7%	1.7%
Constituent	----- lb/1,000 gal -----				
NH ₄ ⁺ -N	28.6	11.4	5.5	9.4	6.3
Organic-N	22.7	5.6	6.5	13.6	3.8
TKN ^{3/}	51.3	17.0	12.0	23.0	10.1
P ₂ O ₅ ^{4/}	40.4	13.4	7.8	14.0	3.4
K ₂ O ^{5/}	34.5	14.2	7.7	21.0	7.7
Surface-applied PAN ^{6/}	26.0	8.5	5.4	10	4.7
PAN:P ₂ O ₅	0.64	0.63	0.69	0.71	1.38
Incorporated PAN	34.0	12	7.0	13	6.6
PAN:P ₂ O ₅	0.84	0.90	0.90	0.93	1.94
Direct injection PAN	40.0	14	8.1	15	7.8
PAN:P ₂ O ₅	0.99	1.04	1.04	1.07	2.29
Ca	32.6	3.7	8.0	10.0	2.7
Mg	6.9	2.4	2.8	4.8	1.1
Zn	0.49	0.28	0.12	0.21	0.04
Cu	0.12	0.26	0.09	0.05	0.01
Mn	0.19	0.12	0.10	0.18	0.03
S	7.5	1.3	1.5	3.1	0.55
Na	6.6	2.5	2.4	3.2	1.3

- 1/ Nutrient content of manure as excreted (from ASAE Standard D384.1, 1998). All other values based on database compiled by the author.
- 2/ The total solids content from flush and pit-recharge buildings will vary from 1.5 to 2.6% depending on building design and animal weight. A mean value of 2% is shown.
- 3/ TKN = Organic-N + (NH₄⁺-N)
- 4/ Total phosphorus expressed as P₂O₅. To get elemental P multiply by 0.44.
- 5/ Total potassium expressed as K₂O. To get elemental K multiply by 0.83.
- 6/ Plant available nitrogen (PAN) estimates based on review given by Chastain (2006b)

(i) Separated liquids

One of the benefits of any method of solid-liquid separation is that it removes a portion of the plant nutrients from the liquid fraction (effluent) and concentrates them in the much smaller volume of settled or separated solids (5 to 25% of the influent manure volume). Generally, any process that provides a greater removal of solids from the liquid fraction will also remove more phosphorus and organic nitrogen. The practical benefit is that the PAN:P₂O₅ of the liquid effluent will be increased as shown by several examples given in table 4–10. At high rates of TS and P₂O₅ removal, the PAN:P₂O₅ can be increased to values on the order of 1.46 to 3.94. If the value of PAN:P₂O₅ of the effluent is close to the N:P₂O₅ ratio needed for the crop, then overapplication of P can either be greatly reduced or eliminated. High-rate separation techniques (PAN:P₂O₅ = 3.94) can yield a liquid effluent that can

be used to supply the nitrogen needs of a crop while maintaining P₂O₅ application rates near or below plant removal rates. Such a practice would allow producers to more easily comply with Federal and State P application regulations.

Solid-liquid separation also changes the composition of the VS in the separated liquid. VS in animal manure are the fraction that is used by microorganisms in secondary biological treatment. The total mass of VS is composed of dissolved volatile solids (DVS) and suspended volatile solids (VSS) such that VS = VSS + DVS. In most cases, the DVS and fine suspended VS are the most easily degraded by microorganisms. The larger VSS that can be easily settled or screened are much slower to be decomposed by biological treatment. Furthermore, the fraction of VSS that are extremely slow to degrade (over several years) are typically viewed as

Table 4–8 Whole plant nutrient removal of common grains (adapted from Camberato 2001; MWPS 1993)

Crop	N	P ₂ O ₅	K ₂ O	Removal
	lb of nutrient used per bu produced			N:P ₂ O ₅
Corn (total plant)	1.2	0.52	1.2	2.3
Wheat	1.7	0.68	2.0	2.5
Barley	1.1	0.49	0.97	2.2
Oats	0.95	0.44	1.2	2.2

Table 4–9 Plant nutrient removal of common hay and silage crops (adapted from Camberato 2001; MWPS 1993)

Crop	N	P ₂ O ₅	K ₂ O	Removal
	lb of nutrient used per ton produced			N:P ₂ O ₅
Annual ryegrass	43	17	48	2.5
Clover-grass	41	13	39	3.2
Corn silage	7.1	2.5	7.2	2.8
Bermudagrass hay	50	14	42	3.6
Fescue hay	39	19	53	2.0
Sorghum-sudangrass	40	15	58	2.7

part of inert or recalcitrant sludge along with settleable FS. Solid-liquid separation tends to increase the proportion of easily degradable VS in the liquid effluent as indicated by an increase in the ratio of DVS to VS (DVS/VS) as shown by several examples in table 4–11.

The examples indicate that solid-liquid separation primarily removed the suspended volatile solids and the only dissolved VS was removed in the water fraction of the separated solids. As a result, increasing the removal of TS, VS, and VSS always increased the proportion of DVS in the separated liquids. Therefore, high rates of solids removal not only reduce the organic loading on a lagoon or other type of biological treatment process, but it also makes the separated liquid easier to treat.

(ii) Separated solids

Implementation of any type of solid-liquid separation system will yield a stream of separated or settled solids that will often be more concentrated in phosphorus and other plant nutrients than the influent liquid or slurry. However, the separation efficiency will greatly influence the composition of the separated solids. The

solids composition for three different solid-liquid separation methods is compared in table 4–12. The three examples are screening of flushed dairy manure with a 0.020-inch incline screen, screening of liquid swine manure after flocculation with a polymer flocculant (PAM), and gravity settling of liquid swine manure for 60 minutes.

The separated solids from both of the screening methods yielded solids that could be piled and handled as a solid. Use of the flocculant allowed the removal of 66 percent of the total phosphorus from swine manure which was slightly larger than the phosphorus removal that could be provided by gravity settling (61%). The nitrogen and phosphorus content of the solids from the flocculated and screened swine manure were much higher than the screen dairy manure and as a result the PAN:P₂O₅ ratio was much lower (0.27 vs. 1.8). The PAN:P₂O₅ ratio of the settled solids was similar to the flocculated and screened solids (0.27 vs. 0.30). Therefore, the practical benefit of a high-rate screening process (flocculation and screening) is that high P removals can be obtained while yielding stackable separated solids.

Table 4–10 Impact of solid-liquid separation performance on the ratio of plant available nitrogen to phosphate (PAN:P₂O₅) of liquid swine and dairy manure assuming manure is incorporated following land application

Manure type and separation process	Concentration reduction of TS (%)	Concentration reduction of P ₂ O ₅ (%)	PAN:P ₂ O ₅ in liquid effluent
Liquid swine manure	—	—	0.68
Screw press, 0.5 mm	16	16	0.97
Settling for 60 min	44	61	1.46
Addition of 140 mg PAM/L ^{1/} followed by a 1 mm screen	55	74	3.94
Liquid dairy manure	—	—	0.90
Inclined screen, 1.6 mm	61	53	1.17
Settling for 60 min	61	38	1.35
Settling following addition of 400 mg PAM/L ^{1/}	80	67	1.68
Inclined screen + settling following addition of 400 mg PAM/L	94	89	2.65

^{1/} Polyacrylamides

The PAN:P₂O₅ ratio of separated solids can range from 0.27 to 1.8 depending on the efficiency of the separation system and the composition of the influent manure. The volume of settled solids can be in the range of 10 to 30 percent of the untreated manure volume. The volume of mechanically separated solids is small relative to the fresh manure volume (5 to 20% of the influent volume). Therefore, a smaller fraction of the total manure produced would need to be hauled to fields where phosphorus application rates are not limiting.

Flocculants that allow more phosphorus to be removed from liquid manure by screening will also remove more of the total carbon (C_T) relative to the total nitrogen. Therefore, higher rates of P removal yield separated solids with a lower C_T:N ratio. The screened

dairy solids described in table 4–12 had a C_T:N of 26.2 whereas the C_T:N of the flocculated and screened swine solids had a C_T:N of only 7.2. Research studies and on-farm experience has shown that separated manure solids with a C_T:N of 22 or more will readily compost without the addition of additional carbon if solids are allowed to dry to a moisture content of about 60 percent (Chastain et al. 2006). Nutrient-rich solids with a low C_T:N can be combined with carbon sources to raise the C_T:N ratio to 25 to 30 to produce compost products that are rich in plant nutrients (Vanotti 2005). Such compost products would allow manure solids to be more easily used for the production of high-value fruits, vegetables, and ornamental plants (Chastain et al. 2006).

Table 4–11 Impact of solid-liquid separation performance on the relative volatile solids content (VS/TS) and proportion of dissolved vs (DVS/VS) in liquid swine and dairy manure

Manure type and separation process	Concentration reduction of TS (%)	Concentration reduction of VS (%)	Concentration reduction of VSS (%) ^{1/}	VS/TS in liquid effluent	DVS/VS in liquid effluent ^{2/}
Liquid swine manure (Vanotti, et al., 2002)	—	—	—	0.81	0.42
Addition of 60 mg PAM/L followed by a 1 mm screen	39	40	69	0.79	0.70
Addition of 140 mg PAM/L ^{3/} followed by a 1 mm screen	55	55	95	0.79	0.93
Liquid dairy manure (Chastain et al. 2001a)	—	—	—	0.84	0.12
Inclined screen, 1.6 mm	61	53	65	0.80	0.18
Settling for 60 min	61	64	74	0.77	0.38
Inclined screen + settling	77	76	83	0.87	0.39
Settling following addition of 400 mg PAM/L	80	85	98	0.63	0.88

1/ VSS = suspended volatile solids

2/ DVS/VS = [1 – VSS/VS]

3/ polyacrylamides (PAM)

Separated solids with a $C_T:N$ greater than 20 has the potential to be a net immobilizer of soluble nitrogen in the soil. That is, the breakdown of carbon applied to the soil may compete with plants for available nitrogen. Therefore, not all separated solids are well suited for land application to supply N for common grains and forages. It would be best to compost separated solids with a high $C_T:N$, similar to the screened dairy solids in table 4–12, prior to land application or to restrict application to crops with a low demand for nitrogen.

Solid-liquid separation can also be used to facilitate anaerobic digestion of manure. Modern swine and dairy facilities often add large amounts of water to manure to flush manure from barns. As a result, the added dilution will greatly increase the volume of a heated anaerobic digester. Gravity settling can be used to concentrate the majority of the volatile solids in the settled solids thereby reducing the volume pumped into a digester by 75 to 90 percent. In many cases, it is

impossible to use a high-rate, heated digester without first thickening the solids to a slurry consistency by sedimentation. An unheated, covered lagoon is another anaerobic treatment option for liquid swine or dairy manure. Excessive sludge buildup is a primary cause of covered lagoon failure (Chastain and Linville 1999). Removal of a significant portion of the settleable solids by screening will greatly reduce sludge buildup in a covered lagoon, but will result in a decrease in biogas production. Sedimentation prior to a covered lagoon digester will eliminate excessive sludge build-up, and greatly reduce digester size. However, biogas production will be much lower since a large fraction of the volatile solids that could be used by methanogens to produce biogas would be excluded.

Screening of flushed dairy or swine manure can also facilitate the use of manure solids as a source of combustible biosolids. Screened manure solids contain much less ash than whole swine or dairy manure while maintaining the energy content. Ash content (FS/TS)

Table 4–12 Examples of separated and settled solids composition

	Low-rate P removal (20%) screened dairy manure ^{1/} 0.020-inch inclined screen (% wet basis)	High-rate P removal (66%) screened swine manure ^{2/} flocculated and screened (% wet basis)	High-rate P removal (61%) settled solids from ^{3/} flushed swine manure (lb/1,000 gal)
TS	22.75	16.7	261.9 (3.1% TS)
VS	20.44	11.36	179.0
Total-N	0.441	0.888	18.02
Ammonium-N	0.028	0.057	5.42
PAN ^{4/}	0.188	0.461	10.64
P ₂ O ₅	0.104	1.53	39.23
PAN:P ₂ O ₅	1.81	0.30	0.27
K ₂ O	0.130	0.109	6.80
Calcium	0.296	0.386	—
Magnesium	0.089	0.349	—
Sulfur	0.064	0.209	—
Carbon	11.56	6.37	99.45
$C_T:N$	26.2	7.2	5.5

1/ Chastain (2009)

2/ Vanotti (2005)

3/ Chastain and Vanotti (2003)

4/ Estimate of the incorporated plant available nitrogen (Chastain 2006b)

in manure can be in the range of 20 to 37 percent and causes slag to form in combustion chambers. Slag formation is one of the key problems associated with burning manure solids as a biofuel. Screening liquid dairy or swine manure can yield separated solids with ash contents that are 33 to 75 percent lower than untreated manure while maintaining the heating value of the solids (7,000 to 8,000 Btu/dry lb). Natural air or solar drying of separated manure solids to 25 percent moisture or less would be required to allow them to be mixed with coal or other biomass materials for combustion.

With proper composting and/or drying, screened manure solids can be used for freestall bedding and can reduce production costs where bedding is expensive or unavailable. Solar drying of screened dairy manure to a moisture content of 9 to 10 percent and storage in covered windrows has been used successfully in dry western climates (Chastain, 2009). Composting and drying of separated solids has also been shown to yield a good freestall bedding material (Bernard, 2004; Keys et al., 1976). Both methods greatly reduce bacterial population. However, high moisture conditions in the stalls can cause microbial populations to increase again (Britten, 1994). Therefore, maintenance of relatively dry freestalls is essential if dried or composted separated solids are used.

637.0403 Fundamentals of solid-liquid separation

(a) Screening

Many mechanical separators exploit differences in particle size to effect separation. Examples include incline screens and presses. Therefore, a general understanding of the affects of animal species, animal age, and other solids added to manure on screening effectiveness will aid the practitioner in selecting and evaluating a separator.

Several studies have been performed over the last few decades to provide data on manure particle distribution (Chang and Rible 1975; Powers et al. 1995; Zhang and Westerman 1997; Masse et al. 2005; Wright 2005; Meyer et al. 2007). Data was selected from some of the available studies to illustrate the most important results. Each investigator quantified the amount of

manure particles that were trapped on standard size screens in a laboratory. However, each investigator used different screen sizes. To facilitate comparison between different studies, plots were made of the percent of TS that were removed by a particular screen size using the data provided in each study.

(1) Animal species

A significant factor that influences the particle size distribution in animal manure is species. Most monogastric animals, such as swine and poultry, are fed rations that are predominately finely ground corn and soybeans, whereas ruminants are fed a diet high in forages (hay, corn silage, haylage). Consequently, the manure particles in ruminant manure tend to be larger and are more easily removed by screening as indicated in figure 4–20. This is especially true for larger screen sizes.

The data given in the figure indicates that 36 percent of the TS in swine manure will remain on a 0.039 inch (1.0 mm) screen. The corresponding values for poultry, beef, and dairy manure are 24, 31, and 37 percent respectively. If the screen size is reduced to 0.0197 inch (0.5 mm) the solids removal increases to 35 percent for poultry, 40 percent for beef, 46 percent for dairy, and 48 percent for swine. For fine screens, 0.010 inch or smaller, the TS removal is less dependent on species. However, poultry and swine are slightly higher than dairy and beef.

(2) Feed composition

Differences in feed composition, animals, and experimental techniques can also be a source of variation in manure particle size and the amount of TS that can be captured on a screen as shown in figure 4–21. The amount of TS removed from dairy cow manure by a 0.0394 inch (1.0 mm) screen was 42, 37, and 32 percent in the three studies shown. Therefore, on the average 37 percent of the TS were collected on the 0.0394 inch (1.0 mm) screen but the variation between studies was ± 13 percent of the mean.

These data point out that difference in manure characteristics between herds can account for a variation in screening performance on the order of 10 percent. Therefore, caution must be exercised when comparing performance of the same separator on two different farms over a short time period. In many cases, a difference in TS removal of less than 10 percent should not be considered to be of practical significance.

(3) Animal age

On most animal farms, feed rations are formulated to match the needs of growing and lactating animals. Differences in average particle size and digestibility of the ration will affect the characteristics of manure.

The influence of animal age, and the related variations in ration, is demonstrated for dairy cattle in figure 4–22. On the average, 42 percent of the solids in manure from dairy cattle of all ages were retained on a 0.0197 in (0.5 mm) screen. However, a smaller percentage of the manure particles from calves and heifers were retained on the 0.0394 inch (1.0 mm) and 0.0787 inch (2.0 mm) screens as compared to lactating cows. Manure from dairy calves fed milk replacer and from growing heifers fed a high protein ration contained a larger percentage of small particles than manure from lactating cows. Therefore, using screen sizes greater than 0.0197 inch (0.5 mm) were not as effective for young animals as they were for lactating cows.

The only screening data available that compares different stages of animal growth for swine was provided by Gilbertson et al. (1987). There data were from manure collected from grow-finish and farrow-to-wean facilities and is given in figure 4–23. The differences were not great and the mean of their data is show as the black line in figure 4–20.

(4) Other sources of solids in manure

Manure is not the only source of solids in the waste stream from animal production facilities. The “extra” solids added to the waste stream will be greatly influenced by the type of animals housed, design and management of the housing area, and method used to remove manure from the building. These “extra” solids can come from bedding (as in dairy freestall buildings), recycled lagoon water (as in flush systems), wasted feed, and soil.

Figure 4–20 Comparison of TS removal by screening manure from dairy cows, beef cattle, poultry, and swine in the laboratory (as excreted manure, no bedding or recycle flush water, 1 in = 25.4 mm)

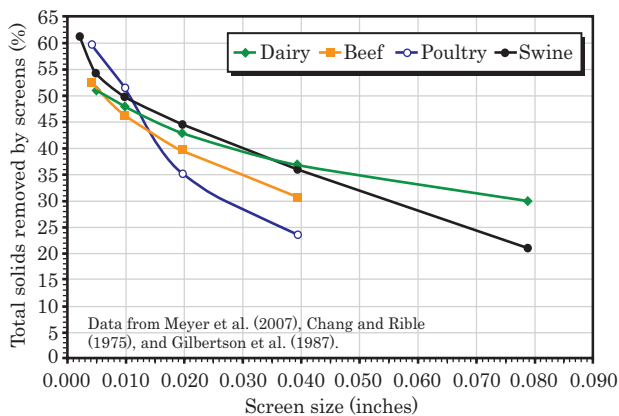


Figure 4–21 Impact of differences feed composition on TS removal by screening for dairy manure (no bedding or recycle flush water, 1 in = 25.4 mm)

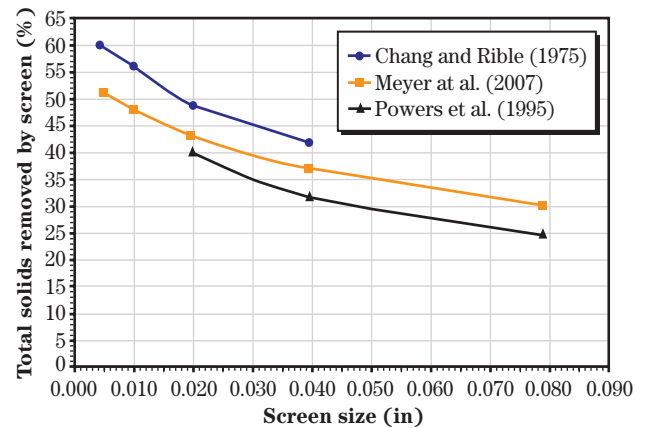
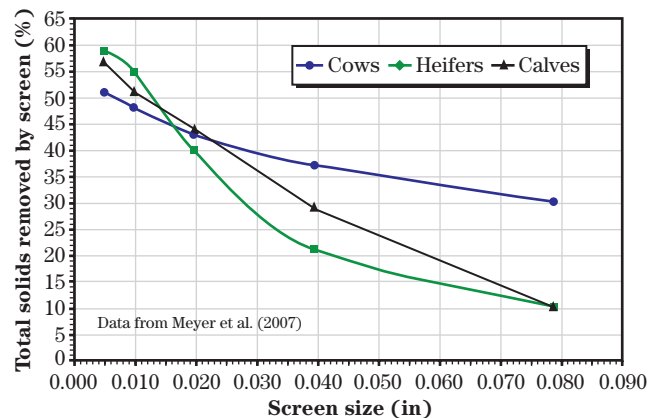


Figure 4–22 Comparison of simple screening effectiveness for manure from calves, heifers, and cows (fresh manure, no bedding or recycle flush water, 1 in = 25.4 mm)



The total mass of solids in the waste stream can be estimated as—

$$MTS = MTS_M + MTS_B + MTS_{WF} + MTS_{RW} + MTS_{SOIL} \quad (\text{eq. 4-1})$$

where—

- MTS = mass of all dry solids added to the manure
- MTS_M = mass of TS from manure
- MTS_B = mass of TS from bedding
- MTS_{WF} = mass of TS from waste feed that is pulled by cows into the feed alley
- MTS_{RW} = mass of TS contained in recycled water used to remove manure from the buildings
- MTS_{SOIL} = mass of soil, sand, or grit that enters the waste stream

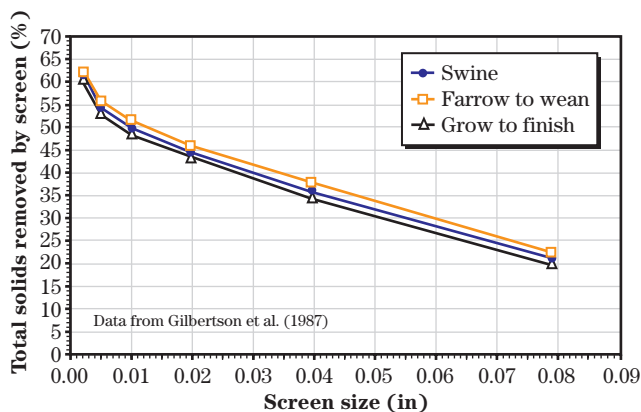
Contribution of recycled lagoon water—Fine suspended material in the lagoon water used to remove manure from dairy and swine facilities can add a significant amount of solids and plant nutrients to the manure that is fed to a solid-liquid separation system. These fine solids generally cannot be removed by screening or settling and will add to the concentration of solids and plant nutrients in the influent manure. As a result, recycled solids and nutrients can confound field evaluation of a separator by decreasing the observed removal by the separator.

The significance of the contribution of solids and plant nutrients from using recycled lagoon water to remove manure from animal buildings is demonstrated for two swine farms in table 4-13. One farm was a swine finishing farm that received pigs at a weight of 45 pounds and marketed them at about 250 pounds. Manure was collected in a recharge pit for one week after filling it with lagoon water that contained 0.5 percent TS. The other farm was a farrow-to-feeder farm that used a flush system that was operated 8 to 12 times per day. The lagoon water on this farm was more dilute and contained only 0.08 percent TS. Therefore, the two cases provided in the table represent an extreme range of conditions.

The results for the pit-recharge buildings indicate that one-fifth to one-quarter of the solids, N and P, that were removed from the buildings and treated by solid-liquid separation were from the recycled lagoon water. Furthermore, the pit water accounted for 80 percent of the volume ($100 \times V_R / V_M$) and was not treatable by simple screening.

The manure removed from the buildings on the farrow-to-feeder farm had a much lower TS content (TS = 0.18%) than the finishing farm (TS = 2.0%). This was the result of frequent flushing with lagoon water with only 0.08 percent TS, and lower manure solids production from the sows and nursing litters. Even with the dilute lagoon water, 42 percent of the solids in the flushed manure was added by recycled lagoon water. The recycled lagoon water also contributed the majority of the N, P, and K that was in the flushed manure.

Figure 4-23 Comparison of simple screening effectiveness for manure from swine of different ages (fresh manure, no bedding or recycle flush water, 1 in = 25.4 mm)



Using lagoon water to flush a dairy freestall barn will also add significant amounts of solids that cannot be removed by a screen. A study in California indicated that recycled lagoon water can account for 25 percent of the TS in flushed dairy manure (Wright 2005).

Bedding use impacts TS removal—No studies were found that provided a direct comparison of the particle sizes found in dairy manure removed from buildings based on bedding practices. However, the TS content of flushed dairy manure can range from 0.7 percent TS if composted manure solids were used as freestall bedding (Wright 2005) to 3.8 percent TS if large amounts of shavings and sawdust were used (Chastain et al. 2001a).

The impact of freestall bedding type on screening of flushed dairy manure is demonstrated using results from two field studies in table 4–14. The same brand of inclined screen separator was used on both farms and both separators were fitted with a 0.060 inch screen.

The primary differences between the two farms were the freestall bedding practices and the water used for

flushing. Large amounts of wood shavings and sawdust were added each week to the freestalls on the South Carolina farm and pond water was used to flush the freestall alleys. On the farm located in Missouri more modest amounts of organic bedding were used in the stalls and recycled lagoon water was used to flush the alleys.

Table 4–13 Contribution of recycled lagoon water to the solids and major plant nutrients observed on two swine farms in South Carolina

	Pit-recharge: finishing farm			Flush: farrow-to-feeder farm		
	Recharge pit manure lb/1,000 gal	Recycled lagoon water lb/1,000 gal	Fraction added from lagoon ^{1/} (%)	Flushed manure lb/1,000 gal	Recycled lagoon water lb/1,000 gal	Fraction added from lagoon (%)
TS	166.9 (2.0% TS)	41.7 (0.5% TS)	20	15.2 (0.18% TS)	6.68 (0.08% TS)	42
TKN	19.9	6.3	25	1.96	1.42	68
Org-N	6.10	2.0	26	0.59	0.4	64
NH ₄ ⁺ –N	13.8	4.3	25	1.37	1.02	70
P ₂ O ₅	14.8	3.6	19	1.74	0.96	52
K ₂ O	NR ^{2/}	NR	— ^{2/}	1.82	1.43	74
	(V _R /V _M) = ^{3/}	0.80			0.946	

1/ Fraction added from lagoon = $100 \times \{[C_{\text{RECYCLE}}]/[C_{\text{MANURE AS REMOVED}}]\}(V_{\text{R}}/V_{\text{M}})$

2/ NR = Data not reported.

3/ (V_R/V_M) = volume of recycled lagoon water ÷ volume of manure removed from buildings

Table 4–14 Comparison of solids removed by the same brand of inclined screen separator on two dairies with different bedding practices, flush water sources and management

	South Carolina dairy ^{1/}	Missouri dairy ^{2/}
Screen size	0.060 in (1.5 mm)	0.060 in (1.5 mm)
Breed	Jersey	Holstein
Milk production level	High	Average
Alley flush water source	Fresh water from a pond	Recycled lagoon water
Bedding use	17.6 ft ³ /stall/week ^{3/} (shavings and sawdust)	Design value ≈ 1.4 ft ³ /stall/week ^{4/} (bedding type not reported)
Influent TS content	3.8%	Not reported, ≈ 2%
TS removed	60.9%	45.5%
Wet solids produced	51 lb/AU-day ^{5/}	23 lb/AU-day
Dry matter content of solids	20.3%	23.1%
Dry separated solids produced	10.4 lb DM/AU-day	5.3 lb DM/AU-day

1/ Chastain et al. (2001a)

2/ Fulhage and Hoehne (1998)

3/ Calculated from farm records

4/ Design value given by Bickert et al. (1995)

5/ AU = animal unit = 1,000 lb of average production live weight

Collection of representative influent samples while the alleys were being flushed was not possible on the Missouri farm. Therefore, the most accurate measurement for comparison of separator effectiveness was the mass of solids dry matter (DM) removed per 1,000 pounds of animal weight (1 AU =1,000 lb) per day. It was determined that using large amounts of wood shavings for freestall bedding increased the amount of solids dry matter (DM) removed by almost a factor of about 2 (1.96).

Obviously, the larger bedding particles were easier to remove by screening, but screening of manure is actually more complex than these results suggest. Large particles in any waste stream will form a mat on the screen and will capture particles that are smaller than the opening size of the screen.

(5) Entrainment

The capture of smaller particles by a mat of larger particles on a screen is called entrainment. As is demonstrated in table 4–14, entrainment can be enhanced when organic bedding is added to manure. However, entrainment is one of the factors that influence the solids removal of all separators that employ a screen.

The importance of entrainment can be demonstrated by comparing the actual total solids removed (TSR) by a separator with the theoretical value obtained from particle size distribution data (fig. 4–20). The compari-

son was made by calculating an entrainment factor (E) as—

$$E = \frac{\text{Actual TSR}}{\text{Theoretical TSR}} \quad (\text{eq. 4-2})$$

Therefore, it is desirable to operate a separator in such a way that the entrainment factor is greater than one.

Most swine housing does not require organic bedding, and the only solids added are from recycled lagoon water and wasted feed. Therefore, any observed entrainment would be due to the matting of large manure and feed particles and not organic bedding as previously observed for dairy manure.

Entrainment factors were calculated for a variety of separator types and screen sizes used to treat swine manure. The studies selected were field trials or laboratory experiments that used swine manure that was representative of farm practice. The results for swine manure are given in table 4–15.

Two basic types of mechanical separator have been included in table 4–15, namely those that apply manure to a screen with or without added pressure. Inclined static screens and vibrating screens use either a pump or conveyor to apply manure to the screen. Belt and screw presses apply manure to a flat (belt press) or

Table 4–15 Comparison of actual and theoretical removal of TS (TSR) for screens and presses treating swine manure

Type	Screen size (in)	Influent TS (%)	Actual TSR (%)	Theoretical TSR ^{1/} (%)	Entrainment factor ^{2/}	Reference
Incline static screen	0.0394	0.5	35	37	0.95	Shutt et al. (1975)
	0.0590	0.5	9	29	0.31	Shutt et al. (1975)
Vibrating screen	0.0041	2.9 ^{3/}	58 ^{3/}	56	1.04	Holmberg et al. (1983)
	0.0092		42 ^{3/}	50	0.84	
	0.0203		36 ^{3/}	45	0.80	
	0.0386		30 ^{3/}	37	0.81	
Belt press	0.0039	3.0	47	56	0.84	Fernandes et al. (1988)
		8.0	59	56	1.05	
Screw press	0.0098	0.89	13	49	0.27	Westerman and Arogo (2005)
	0.0197	5.5	18	45	0.40	Chastain et al. (2001b)

1/ Value from swine data given in figure 4–20

2/ See equation 4–2

3/ Mean values from cited study

cylindrical (screw press) screen, and apply pressure by some means to achieve separation.

The data shown in table 4–15 indicates that most screen-type separators treating swine manure were not able to remove the same amount of solids as observed in laboratory screening experiments. The motion of the vibrating screen increased the flow rate through the screen, but disturbed the buildup of a mat of manure solids that would help capture smaller particles. The high pressure of the screw press and belt press disrupted particle mat formation by forcing larger particles through the screen. Only on 8 percent slurry yielded an entrainment factor greater than 1.0 for the belt press. The incline screen was ineffective with a screen size of 0.0590 inch. The flow rate may have been too great relative to screen slope and forced many particles through the screen. These data point out that efficient screening of swine manure requires selection of a small screen size and application of small forces to prevent the destruction of a particle mat. Entrainment appears to be an important factor in the removal of solids from swine manure by screening.

The effects of entrainment on screening dairy manure are shown in table 4–16. The general trends were the same as observed previously—enhanced entrainment effects help screening performance significantly and presses tend to have less entrainment than simple screens. The mechanical pressure and scraping action

of many presses tend to reduce entrainment by forcing particles through the screen. However, entrainment improved screening of dairy manure much more than for swine manure.

(6) Manure feed rate and screen size

The factors that affect the performance of screens and presses that have been considered are particle size, manure consistency, screen size, and entrainment. Another factor that can influence performance of a separator is the relationship between influent manure flow rate and screen opening size. Press-type separators are designed to limit the flow of manure flow into a screw or set of belts and excess flow is typically returned to the feed tank. Inclined and vibrating screen separators are designed to process the entire flow pumped to the machine. Consequently, the following description applies primarily to screen-type separators that process manure at the influent pumping rate.

The manure flow rate that can be successfully used with a screen-type separator increases with the total screen area. Therefore, the parameter of importance is not the total flow, gallons per minute, but the influent flow rate per unit area of screen, gallon per minute per square foot. The influent flow per unit area of screen is defined as the manure feed rate.

Table 4–16 Comparison of observed and theoretical removal of TS (TSR) for screens and presses treating dairy manure

Type	Screen size (in)	Influent TS (%)	Actual TSR (%)	Theoretical TSR ^{1/} (%)	Entrainment factor ^{2/}	Reference
Incline static screen	0.0219	2.8	68	42	1.62	AWMFH (2012)
	0.0591	NR	45	34	1.32	Fulhage and Hoehne (1998)
	0.0591	3.8	61	34	1.79 ^{3/}	Chastain et al. (2001a)
	0.0661	4.6	49	32	1.53	NRCS (1996)
	0.0787	2.2	26.9	30	0.90	Zhang et al. (2003)
Vibrating screen	0.0289	1.9	70	40	1.75	AWMFH (2012)
	0.0469	5.8	56	36	1.56	AWMFH (2012)
Screw press	0.0197	2.6	24.6	43	0.57	Converse et al. (2000)
	0.0295	10.0	50.5	40	1.26	Gooch et al. (2005)
	0.0940	4.9	33.1	25	1.32	Converse et al. (2000)

1/ Value from dairy data given in fig. 4–20

2/ See eq. 4–2

3/ Included large amounts of organic bedding.

Few studies have been conducted that provide data to observe the effect of manure feed rate on the TS removed from the manure and on the consistency of the separated solids. The best data available was for an 18 inch diameter vibrating screen that was used to treat flushed swine manure from a finishing building (Holmberg et al. 1983). However, the trends observed by Holmberg also apply to most types of gravity fed screens. The results for a fine (0.0041 in) and large (0.0386 in) screen are summarized in table 4–17.

The results summarized in table 4–17 clearly show that the highest solids removal, 66.9 percent, occurred when the fine screen (0.0041 in) was used with a feed rate of 22.4 gallons per minute per square foot per second. However, the separated solids had the consistency of a thin slurry with a TS concentration of only 2.4 percent. Decreasing the feed rate to 5.6 gallons per minute per square foot per second resulted in a decrease in TS removal (50.4%) and the separated solids were a pumpable slurry with a TS of 8.5 percent. The solids removed by this screen could be used to load an anaerobic digester, but they would require additional dewatering to produce solids dry enough to be handled and stacked as a solid. Using a larger screen with an opening size of 0.0386 inch to treat flushed swine manure could provide separated solids with a TS content of about 18 percent for manure feed rates ranging

from 5.6 to 16.8 gallons per minute per square foot per second. However, the TS removal was reduced to 28 percent. Increasing the manure feed rate to 22.4 gallons per minute per square foot per second provided a significant increase in TR removal (35.8 percent), but the separated solids would require additional dewatering or would need to be handled and treated as slurry. These results demonstrate a limitation that occurs for most types of separators that use screens. It is impossible to obtain the highest TS removals using a screen without yielding wet pumpable separated solids. If dry, stackable solids are a system requirement, then a large screen with a lower manure feed rate is required. If a fine screen is used and stackable solids are a design requirement, then a second separator, such as a screw, belt, or roller press, is needed to dewater the slurry from the screen. The second stage of separation will not remove 100 percent of the solids from the slurry and as a result the overall efficiency will be reduced. Examples of mechanical separators that combine a screen with additional dewatering were provided previously in figures 4–13 and 4–14.

Many of the studies available in the literature did not provide information on the manure feed rate (gpm/ft² of screen). Therefore, it is impossible to make comparisons that take into account the effects of flow rate. The available data on the effect of screen size

Table 4–17 Effect of manure feed rate (gpm/ft²) and screen size on TS removal and consistency of separated solids (data from a vibrating screen treating liquid swine manure, adapted from Holmberg et al., 1983)

Manure feed rate, gpm per ft ² of screen	Screen opening size = 0.0041 in		Screen opening size = 0.0386 in	
	TS removed by screen (%)	TS content of separated solids (%)	TS removed by screen (%)	TS content of separated solids (%)
5.6	50.4	8.5	22.7	17.2
11.2	56.9	4.0	32.0	17.6
16.8	59.4	3.0	29.5	18.1
22.4	66.9	2.4	35.8	10.7

on consistency of separated solids for simple, one-stage mechanical separators is shown for swine and dairy manure in figures 4–24 and 4–25. The data in the figures clearly show that presses are the only types of mechanical separators that can yield stackable solids while using small screens.

(b) Particle settling

Settling relies of the force of gravity to remove suspended solids from liquid manure. The size, density, shape, and concentration of the solid particles in liquid manure influence the rate and effectiveness of primary treatment of animal manure by gravitational settling.

Settling behavior of sediment, sand, and manure particles is typically described by using four types or classifications. The type of settling that will occur depends on the initial solids concentration, the tendency of particles to form flocs, and the degree of settling hindrance between particles. The four types are settling are shown conceptually in figure 4–26.

Discrete particle settling (Type 1) occurs when each particle in the mixture falls independently of all other particles. That is, the settling velocity of all particles depends on the density, diameter, and shape of the particle with no interactions with other particles. The settling velocity of discrete particles is constant once they have reached their terminal velocity. Discrete particle settling only occurs for dilute liquid manure (TS << 0.5%, Wedel and Bickert 1996).

As particles settle they may form clumps of smaller particles called flocs. The settling of these relatively large flocs is termed flocculant (Type 2) settling. These flocs may have a lower density than the individual particles, but they often fall faster since a floc may behave as a single particle with a large diameter. As a result, formation of a sufficient number of flocs may result in an increase in settling velocity. Prediction of floc formation is complicated and depends on a variety of factors, including surface charges, chemical composition of the particles, the amount of organic matter in the suspension, and the amount of contact time between particles. A more detailed discussion of flocculation is provided by Hann et al. (1994) and Metcalf and Eddy (1979).

Figure 4–24 Variation in separated solids consistency with respect to screen size for a variety of mechanical separators treating swine manure

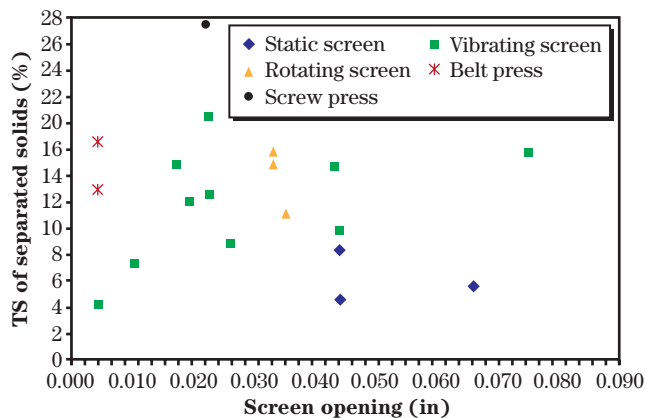
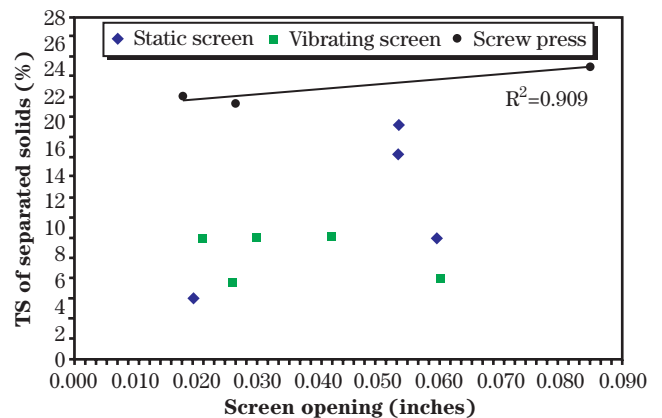


Figure 4–25 Variation in separated solids consistency with respect to screen size for mechanical separators treating dairy manure



As the settling process progresses, the concentration of particles and flocs becomes so great that they no longer settle independently. Instead particles form a blanket of material that falls at the same rate as liquid flows upward through the void spaces between particles. As a result, a distinct interface develops between the supernatant and the settling mass of solids. Settling is hindered (Type 3) when the interface between the supernatant and the settling material can be easily observed. Generally, the settling velocity decreases as settling time increases when hindered settling predominates.

Hindered settling occurs when the TS content is above 0.5 percent. Hindered settling is the primary type of settling found when treating manure from many types of animal facilities.

Near the end of the hindered settling phase, the layer of settled solids forms a well-defined layer on the bottom of the basin. This layer continues to decrease in height due to compression. This type of settling is called compression settling. The settling velocity becomes essentially linear during compression settling until the material reaches an ultimate concentration.

(1) Discrete particle settling theory

The settling of discrete particles is the only type of settling that can be easily approached using analytical methods. Although discrete settling predominates for only dilute animal waste streams (TS < 0.5%), it still provides the physical basis for the design of settling basins for manure and grit traps.

The forces acting on a particle that is falling freely in water is illustrated in figure 4-27. The forces include the weight of the particle, the buoyancy exerted by the fluid, and the drag force. Assuming that the particle has reached its terminal velocity, $U-p$, the force balance can be expressed as—

$$\text{Weight} - \text{Buoyant Force} - \text{Drag Force} = 0 \quad (\text{eq. 4-3a})$$

$$V_p \rho_p g - V_p \rho_f g - C_D A_p \rho_f \frac{(U-p)^2}{2} = 0 \quad (\text{eq. 4-3b})$$

where—

- V_p = particle volume (L^3)
- ρ_p = particle density (m/L^3)
- g = acceleration of gravity (L/t^2)
- ρ_f = fluid density (m/L^3)
- C_D = drag coefficient (from Newton)

A_p = projected particle area in direction of fall (L^2)

$U-p$ = settling velocity of the particle, (L/t)

Solving equation 4-3b for the particle settling velocity gives the following general equation:

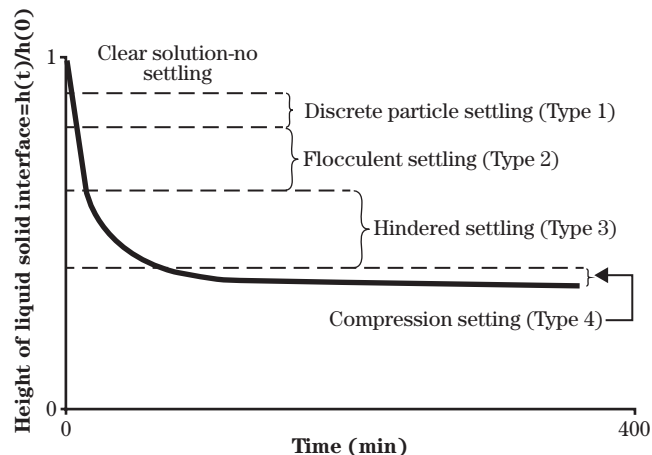
$$U-p = \left[\frac{(2gV_p)(\rho_p - \rho_f)}{C_D A_p \rho_f} \right]^{\frac{1}{2}} \quad (\text{eq. 4-4})$$

In most cases, all particles are treated as spheres with an equivalent diameter, d . Therefore, (V_p/A_p) becomes simply $(2d/3)$. Also water is the fluid in the majority of cases and as a result $(\rho_p/\rho_{\text{WATER}})$ becomes the specific gravity of the particle (SG_p). Using these assumptions equation 4-5 simplifies to—

$$U-p = \left[\frac{(4gd)}{3C_D} (SG_p - 1) \right]^{\frac{1}{2}} \quad (\text{eq. 4-5})$$

The settling velocity of a particle is dependent on the diameter, the specific gravity, and the drag coefficient. The particle diameters that should be considered and the specific gravity depend on the solids in the suspended mixture. However, the drag coefficient for a

Figure 4-26 The four types of settling observed for dilute mixtures (after Haan et al. 1994, chapter 7)



given particle diameter (d) is a function of the particle Reynolds Number.

The defining relationship for the particle Reynolds Number, Re_p , is—

$$Re_p = U_p \frac{d}{\nu} \quad (\text{eq. 4-6})$$

where—

ν = kinematic viscosity of the fluid

(2) Drag coefficients for particle settling

Equation 4-3 provides the relationship that allows the drag coefficient to be determined from settling velocity measurements. Rearranging equation 4-5 gives the following useful relationship:

$$C_D = \frac{\left(\frac{4}{3}gd\right)(SG_p - 1)}{(U_p)^2} \quad (\text{eq. 4-7})$$

Stokes showed that under laminar conditions ($Re_p \leq 0.5$) the drag coefficient for spherical particles can be computed from the following relationship:

$$C_D = \frac{24}{Re_p} \quad (\text{eq. 4-8})$$

In Stokes range ($Re_p \leq 0.5$), the general relationship for U_p (equation 4-5) can be simplified to give—

$$U_p = \frac{1}{18} \left(\frac{gd^2}{\nu}\right) (SG_p - 1) \quad (\text{eq. 4-9})$$

Equation 4-9 generally works well for particle shapes found in municipal and agricultural waste streams (Eckenfelder, 1970; Wedel and Bickert, 1996).

Above Re_p of 0.5 the shape of the particle tends to greatly influence the drag coefficient and flow conditions become turbulent. Eckenfelder (1970) provided the following equation for the drag coefficient for spherical particles for $0.5 < Re_p \leq 500$:

$$C_D = \frac{18.5}{(Re_p)^{0.6}} \quad (\text{eq. 4-10})$$

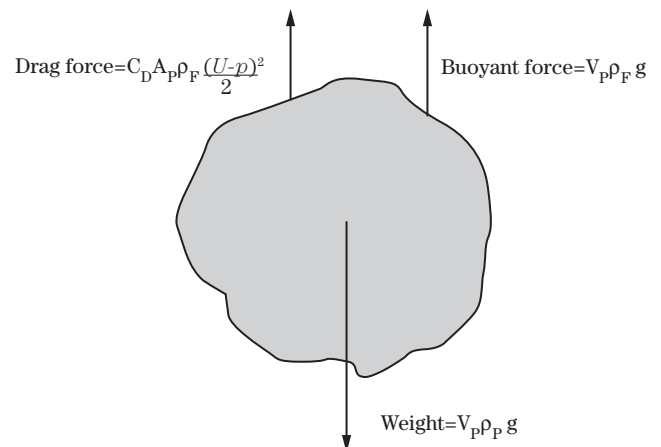
Wilson et al. (1982 as cited by Hann et al. 1994) empirically developed relationships for U_p using sand sediments for Re_p greater than 0.5. Wilson's empirical relationship that related settling velocity (cm/s) to particle diameter (mm) was—

$$\text{Log}_{10}(U_p) = -0.34246(\text{Log}_{10}d)^2 + 0.9812 \text{Log}_{10}d + 1.14613 \quad (\text{eq. 4-11})$$

Equation 4-9 was used with equation 4-5 to determine settling velocities and drag coefficients for sand sediments ($SG_p = 2.65$) for $0.5 < Re_p \leq 200$. The drag coefficients from Wilson's data are compared with the relationship for spherical particles (eq. 4-8) and other data for sediments (Hazen 1904; Richards 1908; and Kivell and Lund 1940; as cited by Wedel and Bickert 1996) in figure 4-28.

The data presented by Wilson provide a realistic prediction of C_D for discrete settling of irregularly shaped particles for Re_p greater than 0.5. The drag coefficients based on Wilson's data were selected to be used for discrete settling of manure for Re_p greater than 0.5 since the shape of manure particles is rarely spherical.

Figure 4-27 Free-body diagram of the forces acting on a settling particle



The following regression equation related Wilson's drag coefficients to the particle Reynolds Number:

$$C_D = \frac{29.93}{(Re-p)^{0.688}}, (0.5 \leq Re-p \leq 200, R^2 = 0.9918)$$

(eq. 4-12)

(3) Particle size distributions for animal manure

Particle size distribution data for animal manure are shown in figures 4-29 and 4-30. None of the data sets used a large enough range of screens to allow calculation of an unbiased mean diameter. However, the median particle diameter (d_{50}) could be determined from the data and is sufficient for estimating settling velocities for most design purposes (Hann et al., 1994).

The median particle diameter is defined as the screen size that allows 50 percent of the particles to pass through (50% finer).

Median particle diameters for dairy, swine, beef, and poultry manure were determined from the available

data and are given in table 4-18. The large variation in median diameters for dairy and beef animals was attributed to differences in feed composition (percent forage content and fineness of grind) and bedding practices in animal housing areas. The average d_{50} for dairy manure was 0.30 millimeter (0.012 in).

The median particle diameter of swine manure was also influenced by the phase of animal growth. The

Table 4-18 Median particle diameters for animal manure

Species	d_{50} (mm)	d_{50} (in)
Dairy		
Cows ^{1/}	0.157	0.0062
Cows ^{2/}	0.450	0.0177
Heifers ^{1/}	0.315	0.0124
Calves ^{1/}	0.276	0.0109
Swine ^{3/}		
Farrow-to-wean	0.294	0.0116
Grow-Finish	0.189	0.0074
Beef ^{2/}	0.150	0.0059
Poultry ^{2/}	0.266	0.0105

1/ Meyer et al. (2007)

2/ Chang and Ribbe (1975)

3/ Gilbertson et al. (1987)

Figure 4-28 Drag coefficients for discrete settling of spherical particles and non-spherical sediments for particle Reynolds Numbers greater than 0.5

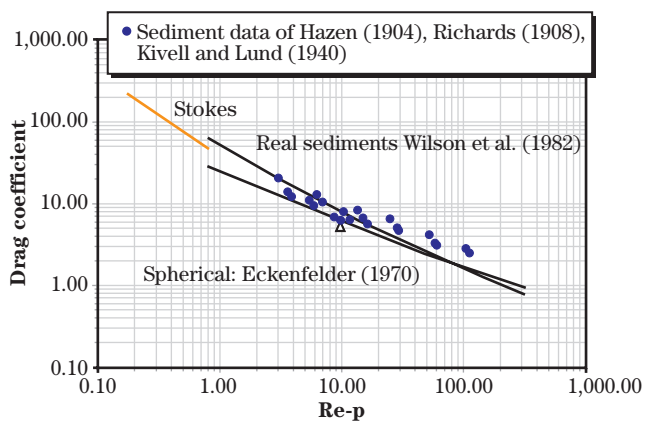
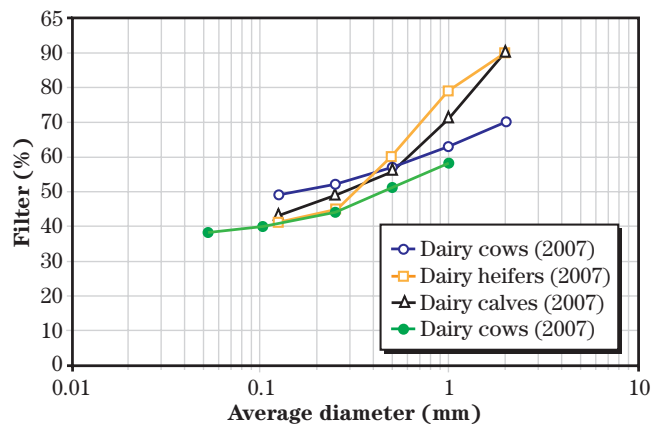


Figure 4-29 Particle size distribution for dairy manure (Meyer et al. 2007; Chang and Ribbe 1975)



d_{50} value ranged from 0.189 to 0.294 millimeter with a mean of 0.24 millimeter (0.009 in).

(4) Particle size of sand

Soils and soil-sand mixtures are typically classified by grain sizes by using standard size sieves. The USDA provides soil textural classifications of sand based on ranges of particle sizes and are given in table 4–19.

While ranges of particle sizes are helpful they do not provide the information needed to classify the sand used for freestall bedding in dairy barns. Wedel and Bickert (1996) measured particle size distributions for three types of sand used for bedding dairy freestalls in Michigan, and Gooch and Wedel (2008) investigated the particle sizes of sand used for freestall bedding in

New York. Sand used for freestall bedding was either purchased from a quarry or was excavated from a field. The three classifications used were coarse, medium, and fine. Coarse sand was described as washed sand used for concrete. Medium sand was described as washed mortar or mason’s sand. Fine sand was typically field sand, but can also refer to beach sand, pit run sand, or quarry fines. The points and the d_{50} values were obtained from the charts given by Wedel and Gooch and are given in table 4–20. The d_{50} values ranged from 0.17 millimeter (0.007 in.) for fine sand to 0.70 millimeter (0.028 in.) for coarse sand. It is obvious from the data shown that coarse sand is the best bedding choice if it is desired to remove sand from manure by settling.

The general recommendation is to use concrete sand with a particle distribution that lies within the requirements to meet ASTM Standard C–33. Sand that meets ASTM C–33 must have no more than 10 percent of the particles pass through a 0.15 millimeter (No. 100) sieve and no more than 3 percent pass through a 0.075 millimeter (No. 200) sieve. Both of the coarse sands shown in table 4–20 appear to meet these criteria.

One of the main purposes of removing sand from liquid manure is to protect pumps and other manure handling equipment. Wedel and Bickert (1996), reported that removal of grit with a mean size of 0.2

Table 4–19 Size ranges for sand (USDA 1979)

Soil textural class	Range in particle diameter	
	(mm)	(in)
Very coarse sand	1.0 to 2.0	0.039 to 0.079
Coarse sand	0.5 to 1.0	0.020 to 0.039
Medium sand	0.25 to 0.5	0.010 to 0.020
Fine sand	0.10 to 0.25	0.004 to 0.010
Very fine sand	0.05 to 0.10	0.002 to 0.004

Table 4–20 Particle sizes and d_{50} values observed for commonly used freestall bedding sands

	Percent finer than 0.1 mm	Percent finer than 0.2 mm	Percent finer than 0.4 mm	Percent finer than 1.0 mm	d_{50} (mm)
Coarse					
Coarse ^{1/}	2	12	30	63	0.70
Washed Concrete ^{2/}	3	11	28	65	0.70
Medium					
Medium ^{1/}	6	28	58	85	0.33
Washed Mason ^{2/}	5	15	32	80	0.56
Fine					
Fine ^{1/}	13	61	94	100	0.18
NY sample #1 ^{2/}	16	62	95	99	0.17
NY sample #2 ^{2/}	16	63	92	98	0.17

1/ Wedel and Bickert (1996)

2/ Gooch and Wedel (2008)

millimeter (0.008 in) or larger was sufficient to protect pumps from heavy wear and to prevent excessive deposition in pipes, and channels. Consequently, sand traps used on dairy farms should be designed based on a sand particle diameter of 0.2 millimeter (0.008 in) if the primary goal is to protect pumps and not just the median value.

(5) Comparison of discrete particle settling velocities of sand and manure

Many times settling basins are designed based on horizontal flow velocity, target detention time, and solids storage, but an estimate of particle settling velocity is often not used. If it is desired to achieve separation of sand and manure, and not just simple settling, then it is impossible to achieve a satisfactory design for

a sand-settling basin without taking into account an estimate of differences in $U-p$ between sand and manure.

Particle settling velocities were calculated for sand and manure particles using equation 4–9 for laminar conditions ($Re-p < 0.5$) and equations 4–5 and 4–12 for turbulent conditions ($Re-p > 0.5$). The specific gravity of sand was 2.65 and the specific gravity of manure was assumed to be 1.1 based on the range of SG for organic matter (Hann et al. 1994) and the means solids densities of manure measured by Baker (2002). The results are compared for particle diameters ranging from 0.05 to 1.1 millimeters in table 4–21.

Flow past falling particles was laminar for mean diameters up to 0.082 millimeter for sand and 0.21 millimeter for manure and as a result Stokes Law was used to

Table 4–21 Comparison of theoretical, discrete particle settling velocities for sand and manure

Mean d (mm)	Sand (SG = 2.65)			Manure (SG = 1.1)		
	U-p (cm/hr)	Re-p	C _d	U-p (cm/hr)	Re-p	C _d
0.05	806	0.11	215	48.85	0.007	3,548
0.07	1,580	0.31	78.36	95.75	0.019	1,293
0.082	2,168	0.49	48.75	131.4	0.030	804.3
0.10	2,349	0.65	50.65	195.4	0.054	443.5
0.15	4,519	1.88	20.53	439.7	0.18	131.4
0.20	6,978	3.87	11.48	781.7	0.43	55.43
0.21	7,494	4.36	10.45	861.8	0.50	47.89
0.25	9,611	6.65	7.56	1,074	0.74	36.68
0.30	12,348	10.26	5.50	1,358	1.13	27.53
0.35	15,145	14.68	4.26	1,656	1.61	21.61
0.40	17,972	19.91	3.46	1,967	2.18	17.51
0.45	20,808	25.93	2.90	2,288	2.85	14.56
0.50	23,640	32.73	2.50	2,620	3.63	12.33
0.60	29,251	48.61	1.96	3,313	5.51	9.26
0.70	34,754	67.37	1.62	4,040	7.83	7.26
0.80	40,120	88.89	1.39	4,797	10.63	5.89
0.90	45,337	113.00	1.22	5,582	13.91	4.89
1.00	50,400	139.58	1.10	6,392	17.70	4.14
1.10	55,308	168.49	1.00	7,226	22.01	3.57

calculate C_D and $U-p$. In this regime, the settling velocity of sand particles was 16.5 times greater than for manure particles of the same diameter.

For particle diameters greater than 0.082 millimeter for sand and 0.21 millimeter for manure, the flow conditions were treated as turbulent and equations 4-3 and 4-10 were solved iteratively to determine C_D and $U-p$. Once conditions were turbulent for sand and manure, $d > 0.21$ millimeter, the settling velocity of sand particles was 8.7 times greater than manure particles.

In many cases, it is desired to remove all sand particles with $d \geq 0.20$ millimeter to protect pumping equipment (Wedel and Bickert 1996). The settling velocity for a 0.20 millimeter diameter sand particle was 6,978 centimeters per hour (228.9 ft/h). Therefore, if a settling basin was designed to trap all particles with a $U-p$ of 6,978 centimeters per hour or greater then only the largest manure particles, $d > 1.0$ millimeters, would be expected to settle out with the sand. Therefore, coarse sand mixtures with very few particles less than 0.20 mm (ASTM C-33 sand) will be required if it is desired to remove sand from liquid manure. However, a small amount of manure may still settle with the sand.

(6) Sizing of settling basins based on particle settling velocity

Settling basins have been widely used to treat feedlot runoff, flushed manure, and milking center wastewater. However, only dilute manure with TS much less than 0.5 percent will approximate discrete particle settling behavior. Consequently, discrete particle settling is rarely fully achieved. Settling basins can be rectangular, circular, and can have flat or sloping bottoms. They can also be operated as continuous flow, intermittent flow (semibatch), or in batch mode (fill, store, withdraw). Continuous flow settling basins, or clarifiers, are commonly used for primary treatment of municipal or industrial waste. However, many settling basins used to treat animal manure operate on an intermittent flow basis or in batch mode.

A simple settling basin consists of four zones: inlet, settling, outlet, and storage zones for settled solids. These areas are shown schematically in figure 4-31.

The inlet, outlet, and storage zones are important to the performance of the basin. The function of the inlet zone is to dissipate influent flow energy and to distribute the flow evenly across the cross section of the

basin. The outlet zone is designed to regulate the flow rate through the basin, often with a weir, and to retain settled solids. The storage area must be sized so as to not impair settling between scheduled solids removal events. If solids build up excessively, the flow velocity (U_F) will increase, the settling depth (D_A) will decrease and reduce the amount of particles captured. The settling zone is the section that can be sized based on the settling characteristics of discrete particles using the ideal basin concepts developed by Hazen (1904) and Camp (1946).

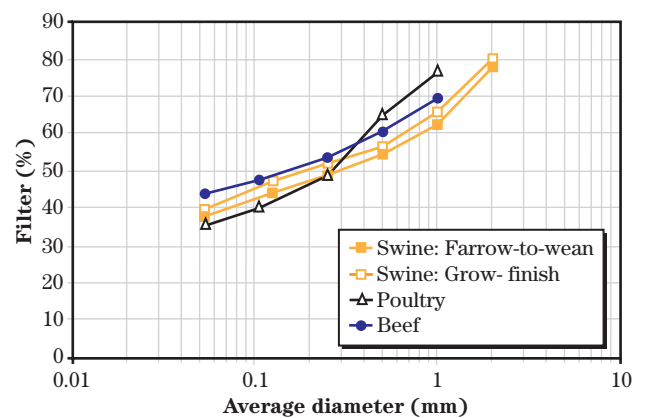
The fundamental concept used to size the settling zone is the overflow rate. In an ideal settling basin, the path of a settling particle will be defined by the vector sum of the vertical settling velocity, $U-p$, and the horizontal flow velocity, U_F . The path of a particle that begins at the top of the settling zone is shown by the straight, diagonal line in figure 4-31. The overflow rate is the velocity for which the particle falls to the bottom of the settling zone, D_A , during the same time it takes to travel the length of the settling zone, L_s . Therefore, the overflow rate is a velocity, U_o , which can be calculated as—

$$U_o = \frac{D_A}{T} \tag{eq. 4-13}$$

where—

T = detention time of the settling basin

Figure 4-30 Particle size distribution for swine, poultry, and beef manure (Gilbertson et al. 1987; Chang and Rible 1975).



All particles with a settling velocity, U_p , that is greater than or equal to U_o will be trapped by the basin and will accumulate in the storage zone. Particles with a settling velocity less than U_o will only be trapped if they are positioned low enough in the inflow so as to fall below the height of the outlet.

The detention time, T , is defined by the volume of the settling zone, V_{SZ} , and the flow rate entering the basin, Q , as—

$$T = \frac{V_{SZ}}{Q} = \frac{L_S}{U_F} \quad (\text{eq. 4-14})$$

The flow velocity is calculated based on the cross-sectional area of the basin in the direction of flow and the flow rate through the basin. The relationship for a rectangular basin is—

$$U_F = \frac{Q}{A_X} = \frac{Q}{WD_A} \quad (\text{eq. 4-15})$$

where—

A_X = Cross-sectional area of the basin

W = Width of the rectangular basin

Substitution of equations 4-13 and 4-15 into 4-14 and simplifying, yields the following relationship that indicates that the surface area of the settling zone, A_s , can be calculated from the flow rate and the overflow rate:

$$A_s = \frac{Q}{U_o} \quad (\text{eq. 4-16})$$

Equation 4-16 is the fundamental relationship used to set dimensions for a basin based on discrete settling. The minimum surface area can be computed once the desired overflow rate is set and the appropriate flow rate is known. The overflow rate is set to the particle settling velocity associated with the smallest particle that is to be captured, $U_{p_{CR}}$. Therefore—

$$U_o = U_{p_{CR}} \quad (\text{eq. 4-17})$$

No real settling basin behaves like an ideal basin. Modifications are needed to reduce problems associated with short circuiting, turbulence, and uneven flow velocities. Furthermore, many waste streams do not exhibit ideal discrete settling behavior, that is, some level of hindrance is common. As a result the actual $U_{p_{CR}}$ may be less than predicted from theory. To deal with these discrepancies, the detention time is increased by a factor of 1.5 to 2.0 (Eckenfelder 1970). The minimum value of L_S is calculated as—

$$L_S = CTU_F \quad (\text{eq. 4-18})$$

where—

C = correction factor that ranges from 1.5 to 2

The other constraint that is recommended is—

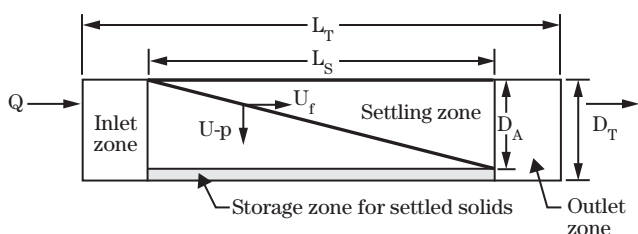
$$L_S - \text{minimum} = 4W \quad (\text{eq. 4-19a})$$

Application of this constraint to a rectangular basin gave this expression to calculate W :

$$W = \left[\frac{V_{SZ}}{4D_A} \right]^{0.5} \quad (\text{eq. 4-19b})$$

It is important to maintain the flow velocity in the appropriate range for the intended purpose of the settling basin. Manure particles will settle at flow veloci-

Figure 4-31 Schematic of particle settling in an ideal basin (Eckenfelder 1970 and Merkel 1981)



ties less than 1 foot per second (Fairbank et al. 1984). Flow velocities less than 0.3 foot per second provide settling conditions that closely approximate that of still (quiescent) wastewater (Kivell and Lund 1940). Velocities greater than 3 feet per second are generally high enough to prevent settling of manure particles. Therefore, maintaining velocities below 0.3 foot per second is recommended if the goal is to trap the maximum number of settleable particles. If the purpose of the settling basin is to allow sand and grit to settle while maintaining organic solids in suspension the flow velocity must be maintained in the range of 0.75 to 1.25 feet per second (Wedel and Bickert 1996).

The settling depth, D_A , and total basin depth, D_T , are to be selected based on the desired storage period for the settled solids and the method used to remove the solids. If the producer intends to remove settled solids with a loader, the settling depth will typically be 1 to 2 feet and the total depth will be in the range of 3 to 6 feet. Such requirement dictates the installation of a ramp to enter the settling area. Use of a ramp often limits the depth of the settling area to 2 to 4 feet. If the settled solids are to be removed using a pump or auger settling depths in the range of 6 to 10 feet can be used. The basin floor should be sloped 1 percent or more towards a pump and sump.

Example 4–1—Continuous flow settling basin for flushed swine manure

Determine settling volume dimensions for a basin to provide primary treatment for an 8,000 head feeder-to-finish swine farm. The average weight of the animals is 145 pounds and manure is removed from beneath slotted floors in 10 buildings 12 times per day at even 2 hour intervals. It was determined that the total flush volume per day was 61,350 cubic feet per day (458,898 gal/day) and the mean TS content was less than 0.5 percent. The purpose of the settling basin is to reduce the volatile solids loading rate on a treatment lagoon, to greatly reduce sludge buildup, and to thicken solids prior to anaerobic digestion. Therefore, the basin will be designed and operated so as to remove as much TS as possible. In addition, the basin will be operated as a wet basin, that is, it will never be allowed to drain completely. The result is that manure solids will be submerged at all times to prevent breeding areas for flies and to reduce odor.

The solids storage area below the settling area will be sloped toward the inlet and settled solids will be removed with a pump. The settled solids will be fed to an anaerobic digester several times each day.

Determine Q: The first step in the process is to define the flow rate, Q . The flush systems in each of the 10 buildings are controlled by a computer to provide a near continuous flow rate. Therefore, $Q = 2,556$ cubic feet per hour (19,121 gal/h).

Select overflow rate: The overflow rate was set equal to the settling velocity of the smallest particle that is to be captured by the basin. From table 4–18, the d_{50} value for grow-finish swine of 0.189 millimeter was selected since capturing particles of this size and larger will greatly reduce the loading on the lagoon. The corresponding $U-p_{CR}$ was determined to be 705.0 centimeters per hour or 23.1 feet per hour by interpolation from the table 4–21.

Calculate basin surface area: The basin surface area can now be calculated using equation 4–16. The surface area for this example is 110.6 square feet.

Select detention time: The detention time, T , was set at 0.5 hour based on settling column observations.

Calculate settling zone volume: The volume of the settling zone was calculated to be 1,278 cubic feet using equation 4–14 ($V_{SZ} = Q T$).

Determine depth of settling zone and surface area: The depth of the settling zone was calculated as $D_A = V_{SZ}/A_S = 11.6$ feet. This depth is greater than is desired. Therefore, D_A was set at 6 feet. The new value of $A_S = 213 \text{ ft}^2$ (V_{SZ}/D_A).

Determine width: The minimum value of L_S is given as $4W$. Since the basin is rectangular, W was calculated to be 7.3 feet using equation 4–19b. The width was rounded up to 8 feet.

Determine length: $L_S = 213 \text{ ft}^2/8 \text{ ft} = 26.6 \text{ ft}$. However, L_S minimum should be 32 feet.

Calculate new surface area: Using W is 8 feet and L_S is 32 feet, the A_S was increased to 256 square feet.

Check flow velocity: The flow velocity was calculated as $U_F = Q/(W D_A) = 53.3$ feet per hour or 0.015 foot per second which is slow enough to achieve near quiescent conditions.

Correct for nonideal conditions: The initial value of T used was 0.5 hour. However, to correct for lack of ideal conditions T was doubled ($C = 2.0$) and L_S was recalculated using equation 4–18 with U_F is 53.3 feet per hour. The new length of the settling zone was calculated to be 53.3 feet and was rounded up to 54 feet.

Summary: The final dimensions and characteristics of the settling zone are—

Dimensions: $W = 8$ ft, $L_S = 54$ ft, and $D_A = 6$ ft

Areas: $A_S = 432$ ft², and $A_X = 48$ ft²

Flow velocity: $U_F = 53.3$ ft/h

Design overflow rate: $U_O = 5.92$ ft/h = 180.4 cm/h

Detention time = 1.0 h

Once corrections were made for nonideal conditions the design overflow rate was calculated to be 5.92 feet per hour or 180.4 centimeters per hour. Therefore, correction for nonideal settling conditions *decreased* the design overflow rate by a factor of 3.9.

Estimate storage zone volume: One of the disadvantages of sizing a settling basin based on discrete particle settling is that it provides no information concerning the sizing of the storage area for settled solids. The storage area must be sized based on other information.

The volume of the settling zone for this example was 2,592 cubic feet ($6 \text{ ft} \times 432 \text{ ft}^2$) and the daily flow was 61,350 cubic feet per day. Settling column data for dilute swine manure indicates that the settled volume was about 10 percent of the total volume. As a result, settled solids will accumulate at a rate of 6,135 cubic feet per day ($0.10 \times 61,350 \text{ ft}^3/\text{day}$) or 256 cubic feet per hour. Allowing 6 hours for settling and thickening to occur results in solids removal from the basin 4 times each day. Therefore, the volume of the solids storage zone should be 1,536 cubic feet ($256 \text{ ft}^3/\text{h} \times 6 \text{ h}$) or 11,489 gallons. A 150 gallon per minute sludge pump could remove the solids in 77 minutes.

Example 4–2—Intermittent flow settling basin for flushed dairy manure

A dairy producer is planning to add a settling basin to provide primary treatment for manure that is flushed from a 300-cow freestall building that uses freestall mattress and minimal amounts of organic bedding (4.5 lb/cow-day). Manure is removed from the building by flushing the two 14-foot-wide feed alleys and two 12-foot-wide stall access alleys three times per day. Flush water is provided by supernatant from a final treatment lagoon. A flush tank is used to store and release the appropriate volume of water at the proper discharge rate. Each alley will be flushed separately while the cows are being milked. Therefore, the four alleys will be flushed over a 2.5-hour period during each of the three milking periods each day. The primary purpose of the settling basin is to prevent a large fraction of the manure solids from entering the lagoon. The settled and thickened solids will be pumped to a mechanical separator for additional dewatering and the liquid fraction from the mechanical separator will be treated in the lagoon.

Determine Q: The flush tanks provide a flush volume of 4,400 gallons per flush for each of the four alleys in the barn. Therefore the total flush volume per day is 4,400 gallons per flush per alley \times 4 alleys \times 3 flushes per alley is 52,800 gallons per day ($7,058 \text{ ft}^3/\text{day}$). It was determined, based on on-farm observations, that the total mass of bedding and manure produced was 151.5 pound per cow-day or 2.40 cubic feet per cow-day (17.95 gal/cow-day). The total volume of liquid manure (VD) removed from the 300 cow freestall barn in this example was estimated as VD is volume of manure plus volume of flush water. Therefore, VD is 17.95 gallons of manure per cow-day \times 300 cows + 52,800 gallons of flush water per day = 58,185 gallons per day ($7,779 \text{ ft}^3/\text{day}$).

The alleys in this barn are flushed over a 2.5-hour period while the cows are being milked. Therefore, the flow into the settling basin is intermittent and occurs over three distinct 2.5-hour periods. The intermittent flow was estimated as—

$$Q_I = \frac{VD}{n\Delta t} \quad (\text{eq. 4-20})$$

where—

n = the number of intermittent flow periods per day

Δt = the length of the intermittent flow period, h

For this example $Q_i = (7,779 \text{ ft}^3/\text{d})/\text{three flow periods per day}/2.5\text{-h per flow period} = 1,037 \text{ ft}^3/\text{h}$.

Select overflow rate: The median particle diameter for dairy manure was determined to be 0.30 millimeters. The settling velocity for a 0.30 millimeters manure particle is 1,358 centimeters per hour or 44.5 feet per hour (table 4–21).

Calculate basin surface area: The basin surface area was $A_s = Q/U_o = 1,037 \text{ ft}^3/\text{h} \div 44.5 \text{ ft/h} = 23.3 \text{ ft}^2$.

Select detention time: The detention time, T , was set at 0.5 hour and was doubled to account for nonideal settling and flow conditions. So use T is 1.0 hour.

Calculate settling zone volume: The volume of the settling zone was calculated to be 1,037 cubic feet ($V_{sz} = Q T$).

Determine depth of setting zone: The depth of the settling zone was calculated as $D_A = V_{sz}/A_s = 44.5 \text{ ft}$. This depth is too large. Set $D_A = 6 \text{ feet}$. The new value of A_s is 172 square feet (V_{sz}/D_A).

Determine width: Basin width was calculated using equation 4–19b and was 6.6 feet. The maximum desired W was set at 6.0 feet.

Determine length: $L_s = 172 \text{ ft}^2/6 \text{ ft} = 28.7 \text{ feet}$. Round L_s up to 30 feet to facilitate construction.

Calculate new surface area: A_s was increased to 180 square feet.

Check flow velocity: The flow velocity was calculated as $U_F = Q/(W D_A) = 28.8 \text{ feet per hour}$ or 0.008 feet per second, which is slow enough to achieve near quiescent conditions.

Summary: The final dimensions and characteristics of the settling zone are—

Dimensions: $W = 6 \text{ ft}$, $L_s = 30 \text{ ft}$, and $D_A = 6 \text{ ft}$

Areas: $A_s = 180 \text{ ft}^2$, and $A_x = 36 \text{ ft}^2$

Flow velocity: $U_F = 28.8 \text{ ft/h}$

Design overflow rate: $U_o = 5.76 \text{ ft/h} = 175.6 \text{ cm/h}$
Detention time = 1.0 h

Doubling the minimum detention time decreased the design overflow rate by a factor of 7.7 for this case. Note that the corrected overflow rates for dairy and swine manure were similar (5.92 and 5.76 ft/h).

Estimate storage zone volume: The volume of the settling zone for this example was 1,080 cubic feet and the intermittent flow was 1,037 cubic feet per hour. Settling column data for dairy manure indicates that the settled volume was about 25 percent of the total volume. As a result, the volume of settled solids that will be removed after flushing the barn once (all four alleys in 2.5 h) was 648 cubic feet ($0.25 \times 1,037 \text{ ft}^3/\text{h} \times 2.5 \text{ h}$). Therefore, the volume of the solids storage zone should be 648 cubic feet (4847 gal). The settled solids would be pumped to the mechanical separator 1 to 2 hours after flushing the barn. This additional time will allow thickening to occur prior to mechanical separation. The mechanical separator can process slurry at a rate of 75 gallons per minute. Therefore, 65 minutes would be required to remove settled solids from the basin.

(c) Hindered settling of animal manure

Most liquid dairy and swine manure has a TS of 0.5 percent or more and hindered settling is the dominate characteristic of the settling process. The defining characteristic of hindered settling is that the particles in the waste do not fall independently, but form a concentrated blanket of particles that settle together in a plug fashion. Whenever hindered settling occurs, a distinct interface can be observed that separates the supernatant from the settling blanket of particles.

Observations from several settling experiments conducted by the author (Chastain and Darby 2000; Chastain et al. 2005) and others (Sobel 1966; Baker 2002) have shown that a consistent pattern describes hindered settling of animal manure. This pattern consists of an initial constant settling velocity period, followed by a period of changing settling velocity that transitions into a final period of slow compression settling that also has a near constant settling velocity. These three zones are classified as linear hindered settling (LHS), transitional hindered settling (THS), and compression settling (CS) (fig. 4–32).

The linear hindered settling zone was not described as flocculant settling since a definable interface between the settling plug of solids and the supernatant was observed quickly. Settling of distinct flocs was only observed during the first few minutes of settling for dilute manure.

(1) Interface velocity for hindered settling

The rate at which the interface falls was termed the interface settling velocity, $U-i$, to distinguish it from the particle settling velocity. The defining relationship for the interface settling velocity over a time interval is—

$$U-i = \frac{(h(0) - h(t))}{(t - t_0)} \tag{eq. 4-21}$$

where—

- $h(0)$ = height of the solid-liquid interface at the at time = 0
- $h(t)$ = height of the solid-liquid interface at time, t
- $(t - t_0)$ = The settling time interval

Interface settling velocities were calculated from settling data taken using a graduated test cylinder. The height of the solid-liquid interface in a graduated cylinder can be calculated from the volume measurements using the equation for the volume of a cylinder:

$$h(t) = \frac{4V_{SM}(t)}{\pi D_{GC}^2} \tag{eq. 4-22}$$

where—

- $V_{SM}(t)$ = volume occupied by the settled material at time, t
- D_{GC} = inside diameter of the graduated cylinder

The normalized settled volume and the normalized height of the interface can be computed using equation 4-23 based on the formula for the volume of a cylinder:

$$\begin{aligned} SVF(t) &= \frac{V_{SM}(t)}{V_I} \\ &= \frac{h(t)}{h(0)} \end{aligned} \tag{eq. 4-23}$$

where—

- $SVF(t)$ = settled volume fraction

V_I = initial volume of the settled material which is the same as the total sample volume

The value of $h(t)$ can also be computed from an empirically determined SVF curve:

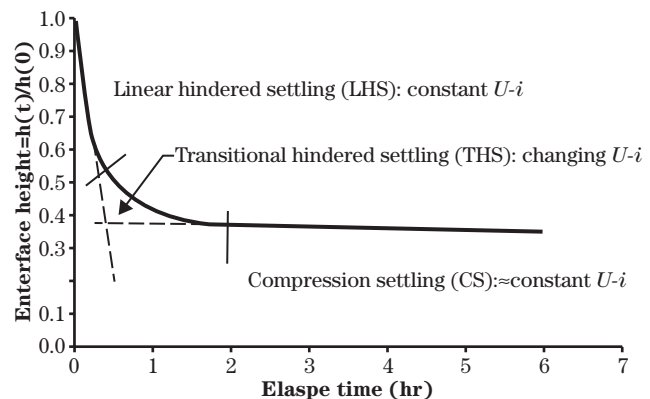
$$h(t) = h(0) SVF(t) \tag{eq. 4-24}$$

Wall effects were considered but a standard equation for hindered settling (RPI 2007) indicated that the expected error for 1.0 millimeters particles using a 1,000 millimeter graduated cylinder ($D_{GC} = 64$ mm) was on the order of 0.1 percent. In addition, a study of the settling of complex particle suspensions provided by Di Felice and Parodi (2004) indicated that wall effects were negligible for hindered settling. Therefore, a correction for wall effect was not included in the analysis.

Interface velocities can be determined by plotting the interface height with respect to settling time and dividing the data into the three hindered settling zones and applying equation 4-21 to each of the available time intervals. Linear regression can be used to determine the interface velocity if several data points are collected for the linear hindered settling and compression settling zones. The interface velocity, $U-i$, is simply the slope of the regression equation.

Interface settling velocities and settled volume fractions (SVF) were determined for liquid dairy manure, milking center wastewater and agitated lagoon sludge-supernatant mixtures using published data sets (Sobel

Figure 4-32 The three hindered settling zones for liquid animal manure (TS ≥ 0.5%)



1966; Chastain and Darby 2000; Baker 2002; Chastain et al. 2005). Interface settling velocities were also determined using settling column data collected by the author for liquid swine manure taken from the Starkey Swine Center at Clemson University. Additional details on settling column procedures are provided by Chastain et al. (2005) and Chastain and Darby (2000).

A sample data set for liquid dairy manure is shown in figure 4-33. Once the data were plotted the three hindered settling zones were apparent. In this case, only one data point and the initial condition was available to determine the interface velocity for the linear hindered settling zone. Using equation 4-21, the magnitude of the settling velocity during the first 15 minutes of settling was determined to be 49.076 centimeters per hour or 1.61 feet per hour. The compression settling zone began after two hours of settling and linear regression was used to determine that the interface velocity had decreased to 0.123 centimeters per hour (0.004 ft/h). The variation of $U-i$ in the THS zone was described by simply applying equation 4-21 over the four available time intervals.

By application of equation 4-23, it was also determined that the settled solids occupied 60 percent (SVF = 0.60) of the total volume at the end of the linear zone, 37 percent (SVF = 0.37) at the end of the transitional settling zone, and 35 percent (SVF = 0.35) at the last point available in the compression zone.

Knowledge of both the variation in $U-i$ and the volume occupied by the settled material will provide information to select the appropriate type of settling basin (continuous, semibatch, or batch), size the settling zone, and size the storage zone.

(2) Summary of interface velocity and settled volume fraction data

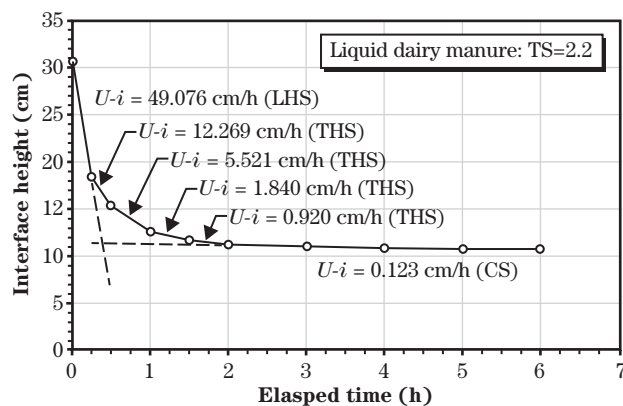
The available settling column data for liquid dairy manure, milking center wastewater, liquid swine manure, and mixtures of lagoon supernatant and sludge were analyzed using the previously described procedure. The data and results are given in figures 4-34, 4-35, 4-36, and tables 4-22, 4-23, and 4-24.

The data and results show that the interface velocities and settled volume fractions associated with the three hindered settling zones varied greatly with the TS content and type of manure. In general, swine manure settled faster than dairy manure and increasing the dilution increased $U-i$ and decreased SVF. Also, the THS zone was decreased in size as the TS of the manure decreased. The compression settling zone could not be observed for the two milking center wastewater samples due to the lack of data. Mixtures of lagoon sludge and supernatant from a dairy lagoon settled better than a swine lagoon sludge mixture. It appears that additional dilution water would be needed to allow swine lagoon sludge to be treated by sedimentation effectively.

The magnitude of the interface velocity during the initial linear zone (LHS) is the most important for settling basin design (mode of operation, sizing of the settling area, and selection of detention time). The initial $U-i$ for lagoon sludge/supernatant mixtures were below 15 centimeters per hour. Therefore, it is most likely that only batch or semibatch settling basins would be practical.

There is a relationship between the initial interface velocity, $U-i_{LHS}$ and the TS content for both dairy and swine manure. Furthermore, the two interface velocities for milking center wastewater appeared to be similar to those observed for liquid dairy manure. The $U-i_{LHS}$ values for dairy and swine manure were plotted with respect to TS to determine if any valuable correlations existed. Significant correlations were found and they are given in figure 4-37.

Figure 4-33 Determination of interface settling velocities, $U-i$, using a 1,000 mL graduated cylinder (data from Sobel 1966)



The results shown in the figure indicated that the $U-i_{LHS}$ values for dairy manure and milking center wastewater could be described by a single regression equation with an R^2 of 0.9634 over the observed range of TS. The correlation of $U-i_{LHS}$ with respect to TS for swine manure was also high ($R^2 = 0.9716$). However, the results should not be extrapolated below the TS range shown, since the division between hindered and discrete settling is not well known.

The other zone of linear interface velocity was the compression settling zone. The interface velocities for compression settling ($U-i_{CS}$) of dairy and swine manure are shown in figure 4-38. The values obtained for the milking center wastewater were not included due to lack of compression settling data (fig. 4-34). While significant correlations between $U-i_{CS}$ and TS were apparent they were not as strong as for the linear hindered settling zone.

The highly variable nature of the THS zone made correlation of interface velocities impossible. However, the values provided in tables 4-22 and 4-23 can be used to make estimates for design purposes.

Figure 4-34 Available settling data for dairy manure (Sobel 1966; Chastain et al. 2005)

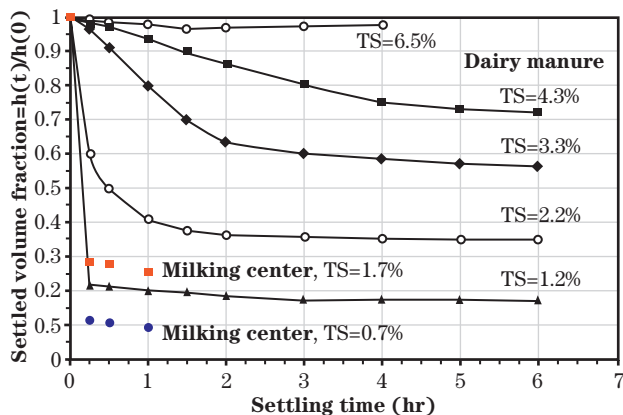


Figure 4-36 Available settling data for lagoon water-sludge mixtures (Chastain and Darby 2000; Baker 2002)

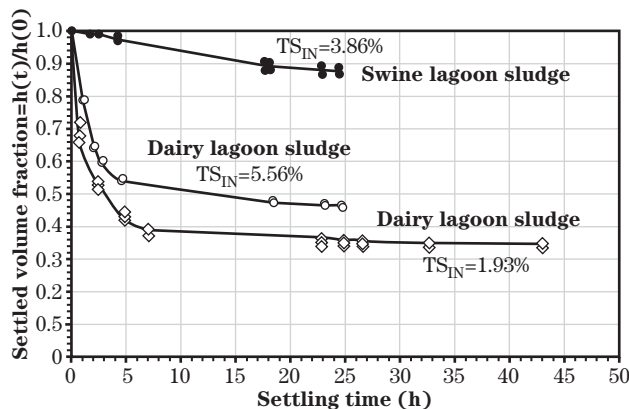


Figure 4-35 Settling data for liquid swine manure

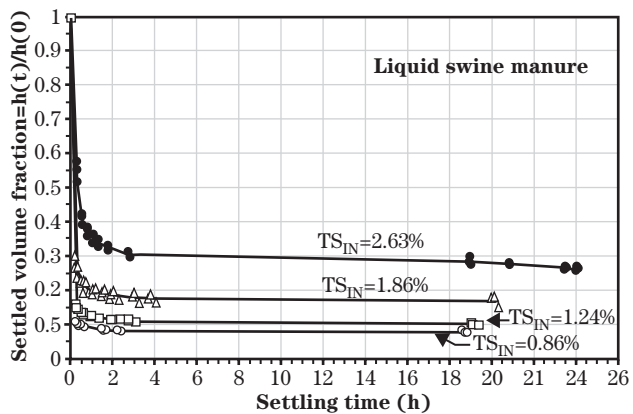
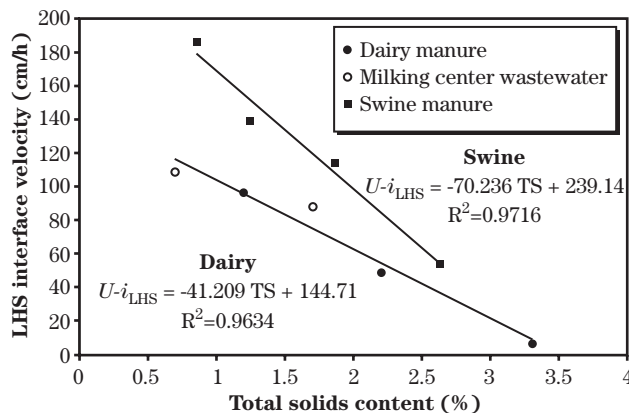


Figure 4-37 Variation of the settling velocity during linear hindered settling (LHS) with respect to TS for dairy and swine manure



The other information that was extracted from settling data was the variation in the volume occupied by the settled solids (SVF). The three most important points that can be used by a designer were the SVF values at the end of the three hindered settling zones.

Interpolation equations for SVF values for liquid dairy and swine manure are given in tables 4-25 and 4-26. The equations shown in the tables were developed by linear regression of the available data.

(3) Settling time—Selection of a detention time is an important part of settling basin design and common values range from 0.33 to 1.0 hours. The settling curve data provided in figures 4-34, 4-35, and 4-36 can be used to select a design value based on manure type and solids content. In addition, the amount of settling time required to reach the end of the linear and transition hindered settling periods are provided in tables 4-22, 4-23, and 4-24.

Dairy manure—The minimum detention time for liquid dairy manure with a TS of 2.2 percent or less was 0.25 hour based on the break point between the linear and transition settling periods (table 4-22). For thicker dairy manure, TS is 3.3 percent, 1.5 hours would be needed to accommodate the linear settling period.

Figure 4-38 Variation of the settling velocity during compression settling (CS) with respect to TS for dairy and swine manure

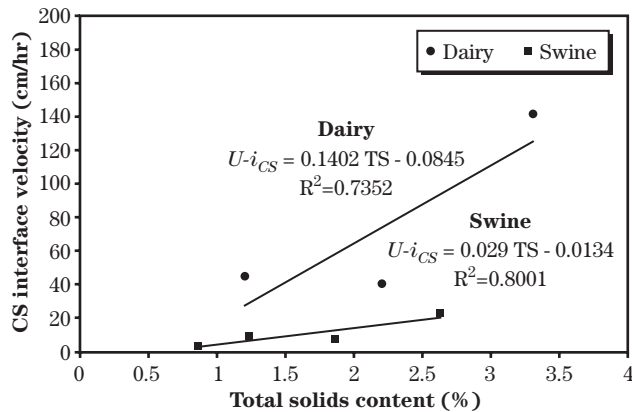


Table 4-22 Empirically determined settled volume fractions and interface velocities for liquid dairy manure and milking center wastewater

TS = 3.3%				
Settling type	SVF range		U-i (cm/h)	Time (h)
Linear (LHS)	1.0	0.70	6.28	1.5
Transition (THS)	0.70	0.64	3.99	
	0.64	0.60	1.07	3.0
Compression (CS)	0.60	0.56	0.43	
TS = 2.2%				
Settling type	SVF range		U-i (cm/h)	Time (h)
Linear (LHS)	1.0	0.60	49.07	0.25
Transition (THS)	0.60	0.50	12.25	
	0.50	0.41	5.52	
	0.41	0.37	1.37	2.0
Compression (CS)	0.37	0.35	0.12	
TS = 1.7%, milking center wastewater				
Settling type	SVF range		U-i (cm/h)	Time (h)
Linear (LHS)	1.0	0.28	87.96	0.25
Transition (THS)	0.28	0.25	1.25	1.0
TS = 1.2%				
Settling type	SVF range		U-i (cm/h)	Time (h)
Linear (LHS)	1.0	0.22	96.32	0.25
Transition (THS)	0.22	0.20	0.49	1.0
Compression (CS)	0.20	0.17	0.14	
TS = 0.7%, Milking center wastewater				
Settling type	SVF range		U-i (cm/h)	Time (h)
Linear (LHS)	1.0	0.11	108.94	0.25
Transition (THS)	0.11	0.09	0.76	1.0

The break point between transition and compression settling of dairy manure ranged from 1.0 to 3.0 hours depending on the TS concentration. In general, a detention time of 0.5 to 1.0 hours will provide sufficient settling and thickening time for sizing the settling zone of a basin being used to treat liquid dairy manure. Settling of dairy lagoon sludge (table 4–24) will require a minimum of 0.75 to 2.0 hours depending on solids content. Detention times of 7 hours or more would be beneficial in most cases for thickening.

Swine manure—The minimum detention time for swine manure ranged from 0.13 to 0.25 hours depending on the solids content (table 4–23). The time required to allow for transition settling ranged from 0.67 to 2.73 hours. A detention time of 0.5 hours would allow a settling basin to function well for the wide range of TS contents that are common on modern swine farms. Longer detention times will allow additional thickening to occur.

(4) Comparison of design overflow rates based on discrete and hindered settling

The most important settling velocity for the design of a settling basin for liquid manure with TS greater than 0.5 percent is the linear hindered settling velocity ($U-i$). Therefore, the recommended design overflow rate for hindered settling of manure is—

$$U_o = U-i_{LHS} \quad (\text{eq. 4-25})$$

The linear hindered settling velocities determined for dairy and swine manure are compared with overflow rates based on the particle settling theory and the range of values used for municipal wastewater in table 4–27.

Table 4–23 Empirically determined settled volume fractions and interface velocities for liquid swine manure

TS = 2.63%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.55	53.98	0.25
Transition (THS)	0.55	0.41	16.76	
	0.41	0.35	3.38	
	0.35	0.31	0.79	2.73
Compression (CS)	0.31	0.26	0.07	
TS = 1.86%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.28	114.18	0.18
Transition (THS)	0.28	0.21	2.86	
	0.21	0.19	0.61	1.47
Compression (CS)	0.19	0.17	0.02	
TS = 1.24%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.16	139.11	0.17
Transition (THS)	0.16	0.12	1.16	0.92
Compression (CS)	0.12	0.099	0.03	
TS = 0.86%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.11	186.42	0.13
Transition (THS)	0.11	0.091	0.82	0.67
Compression (CS)	0.091	0.084	0.01	

Table 4–24 Empirically determined settled volume fractions and interface velocities for dairy lagoon sludge and supernatant mixtures

TS = 5.56%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.64	5.43	2.0
Transition (THS)	0.64	0.54	1.16	4.5
Compression (CS)	0.54	0.46	0.12	
TS = 1.93%				
Settling type	SVF range	$U-i$ (cm/h)	Time (h)	
Linear (LHS)	1.0	0.69	11.03	0.75
Transition (THS)	0.69	0.39	1.22	7.0
Compression (CS)	0.39	0.35	0.03	

The comparisons provided in table 4–27 indicated the following:

- Design overflow rates for hindered settling of swine and dairy manure are more different than suggested by particle settling theory. Corrected U_o values based on particle settling theory were very similar and ranged from 5.76 to 5.92 feet per hour. However the hindered settling velocity for swine manure was 1.6 times faster than for dairy manure (TS=0.75%). This discrepancy is believed to be the result of differences in particle density and shape.
- The corrected overflow rate based on discrete settling theory was in better agreement with the hindered overflow rates for dilute swine manure than dilute dairy manure (TS = 0.75 to 1.0%).
- Overflow rates for hindered settling of swine manure were similar to the values used for municipal wastewater for TS values up to 2 percent.
- Overflow rates for hindered settling of dairy manure were similar to the values used for municipal wastewater for TS values up to 1 percent.
- Liquid manure will require longer values of U_o than municipal wastewater for TS greater than 2 percent for swine manure and TS greater than 1 percent for dairy manure.

Table 4–25 Equations to estimate the settled volume fraction at the end of the three hindered settling zones for dairy manure included in the present study

	TS range	Equation	R ²
Linear hindered settling	0.7% ≤ TS ≤ 3.3%	$SVF_{LHS-f} = 0.2164 TS$	0.8975
Transitional hindered settling	0.7% ≤ TS ≤ 3.3%	$SVF_{THS-f} = 0.194 TS - 0.051$	0.9912
Compression settling	1.2% ≤ TS ≤ 3.3%	$SVF_{CS-f} = 0.186 TS - 0.0551$	0.9997

Table 4–26 Equations to estimate the settled volume fraction at the end of the three hindered settling zones for swine manure included in the present study (0.86% ≤ TS ≤ 2.63%)

	Equation	R ²
Linear hindered settling	$SVF_{LHS-f} = 0.0513 e^{0.9056 TS}$	0.9995
Transitional hindered settling	$SVF_{THS-f} = 0.0507 e^{0.6946 TS}$	0.9985
Compression settling	$SVF_{CS-f} = 0.0464 e^{0.6640 TS}$	0.9883

Table 4–27 Comparison of design overflow rates, U_o , for animal manure and primary treatment of municipal wastewater (ft/hr)

TS =	Based on discrete settling		Based on hindered settling data				
	$U_o = U-p$ for d_{50}	Corrected U_o ($T_{design} = 2 T$)	$U_o = U-i_{LHS}$				
	<< 0.5%	<< 0.5%	0.75%	1%	1.5%	2.0%	2.5%
Swine ^{1/}	23.1	5.92	6.12	5.54	4.39	3.24	2.08
Dairy ^{1/}	44.5	5.76	3.73	3.40	2.72	2.04	1.37
Lagoon Sludge (1.93%) ^{2/}	NA		0.36				
Common municipal wastewater design values =			3.34 to 6.68				

1/ Overflow rates calculated using regression equations in fig. 4–37.

2/ Overflow rate from table 4–24.

- Any settling basin used to treat lagoon sludge will most likely require operation in batch mode with long detention times (7 h or more) due to slow settling rate.

Example 4–3—Sizing of a horizontal flow settling basin for hindered settling of flushed swine manure

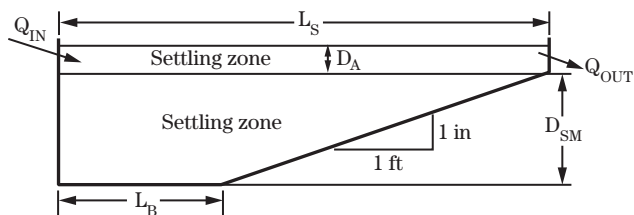
A settling basin is to provide primary treatment for the same 8,000 head feeder-to-finish swine farm as described in example 4–1. The primary difference is that manure is removed from beneath slotted floors by flushing in 10 buildings four times per day. The total flush volume per day is 20,440 cubic feet per day (152,891 gal/day) and the mean TS is about 1.0 percent.

The basin will be operated continuously and the solids storage area below the settling area will be sloped toward the inlet and settled solids will be removed with a pump. The settled solids will be fed to an anaerobic digester several times each day. A schematic of the proposed basin is shown in figure 4–39.

The purpose of the settling basin is to reduce the volatile solids loading rate on a treatment lagoon, greatly reduce sludge buildup, and thicken solids prior to anaerobic digestion.

Use hindered settling data to size the settling and storage areas. The inlet must be designed to disperse the influent and to reduce the kinetic energy of the flow. The outlet must be designed to control the flow out of the basin during peak flow conditions. However, these two design objectives will be met after sizing is complete and are not part of the current design calculations.

Figure 4–39 Schematic of the settling and storage areas for a horizontal flow settling basin used to treat flushed manure on a swine farm



Determine Q: The farm has the same layout as in example 4–1. There will be 80 flush events each day (two per building per flush). As a result, the design flow rate is 852 cubic feet per hour (20,440 ft³/day ÷ 24 h/day).

Set design overflow rate: From table 4–27 the design overflow rate for swine manure with a TS of 1.0 percent is 5.54 feet per hour.

Calculate basin surface area: The basin surface area was calculated using equation 4–16 as—

$$A_s = \frac{852 \text{ ft}^3/\text{h}}{5.54 \text{ ft/h}} = 154 \text{ ft}^2$$

Select detention time: The detention time, T, was set at 1.0 hour.

Calculate settling zone volume: The volume of the settling zone was calculated to be 852 cubic feet using equation 4–14 ($V_{sz} = Q T$).

Determine depth of setting zone: The depth of the settling zone was calculated as—

$$D_A = \frac{V_{sz}}{A_s} = 5.5 \text{ ft}$$

This depth is within the desired range of 4 to 6 feet.

Determine width: The maximum basin width was calculated to be 6.2 feet using equation 4–19b. The width was rounded down to 6.0 feet.

Determine length:

$$L_s = \frac{A_s}{W} = \frac{154 \text{ ft}^2}{6} = 25.7 \text{ ft}$$

Round up to 26 feet.

Calculate new surface area: Using W is 6 feet and L_s is 26 feet the A_s was increased to 156 square feet.

Check flow velocity: The flow velocity was calculated as $U_F = Q/(W D_A) = 25.8$ feet per hour or 0.007 foot per second which is slow enough to achieve near quiescent conditions.

Summary: The final dimensions and characteristics of the settling zone are—

- Dimensions: $W = 6$ ft; $L_S = 26$ ft; and $D_A = 5.5$ ft
- Areas: $A_S = 156$ ft²; and $A_X = 33$ ft²
- Flow velocity: $U_F = 25.8$ ft/h
- Overflow rate: $U_O = 5.46$ ft/h = 166.5 cm/h
- Detention time = 1.0 h

The settling basin volume required for hindered settling of swine manure with a TS of 1 percent was about a third the size of the basin required for discrete settling (TS << 0.5%). The primary cause was the reduction in the total flush volume that corresponded to TS of about 1 percent.

Size storage zone for settled material: The storage zone, shown in figure 4-39, must be able to contain all of the settled material that will accumulate between pumping events while not interfering with settling.

Estimate the fraction of the flush volume that will be retained as settled solids. The settled volume fraction for swine manure at 1.0 percent TS at the end of the three hindered settling zones are calculated using the equations given in table 4-26. The settled volume fraction at the end of the linear hindered settling zone (SVF_{LHS-L}) is 0.13. The value of SVF at the end of the transitional period is 0.10 and after a significant amount of compression settling it is reduced to 0.09. Since most of the settled solids volume reduction occurs during the linear period, the value used to size the storage zone is 0.13. The volume of the solids storage zone is estimated as—

$$V_{SM} = (SVF_{LHS-L} Q) \times t_{SP} \quad (\text{eq. 4-26})$$

where—

V_{SM} = volume of the storage zone

t_{SP} = time period for accumulation of settled solids.

The value of t_{SP} selected was 6 hours since settling data (fig. 4-35) indicated that most of the settled solids volume reduction had occurred after 6 hours

of settling and thickening. As a result, settled material would be pumped from the storage zone and loaded into the digester 4 times per day. For this example, $V_{SM} = (0.13 \times 852 \text{ ft}^3/\text{h}) \times 6 \text{ h} = 664.6 \text{ ft}^3$.

For the geometry shown previously in figure 4-39, the minimum depth for the storage area, D_{SM} , was calculated using—

$$D_{SM} = \frac{V_{SM}}{[L_B W + 0.5(L_S - L_B) W]} \quad (\text{eq. 4-27})$$

Generally, do not allow the flat portion of the basin (L_B) to exceed the width (W) to facilitate solids removal. If L_B is set equal to W (6 ft) for the present example, the minimum depth of the storage zone is 6.92 feet. The total depth (D_T) would be 12.42 feet ($D_A + D_{SM}$). Rounding down D_T 12 feet, to facilitate construction would yield D_{SM} as 6.5 feet. Intrusion of the settled solids into the settling zone by a few inches for a short period of time would not impair basin function. A freeboard of 12 to 18 inches, depending on applicable regulations, must be added to the top of the basin.

The volume of the settled material generated each day will be about 2,658 cubic feet. It will be possible to remove all of the settled material from the storage area by pumping with minimal agitation. If the total volume of settled solids and basin supernatant pumped is maintained at 3,500 cubic feet per day, a simple settling basin can be used to greatly concentrate volatile organic matter so that only 17 percent of the daily flow would be treated in the anaerobic digester. Therefore, the volume of slurry that will be removed from the settling basin and pumped into the digester will be about 26,000 gallon per day ($0.17 \times 152,891 \text{ gal/day}$)

This example also points out that a significant portion of the construction cost of a semibatch, horizontal flow settling basin is the cost of providing storage of settled solids. This volume was reduced by pumping solids four times a day. A pump that is rated to pump slurry at 100 gallons per minute would remove the 6,500 gallons of settled solids in about 65 minutes.

Example 4–4—Sizing of an intermittent flow settling basin for flushed dairy manure using the hindered settling overflow rate

Size the settling and storage zones of a basin to provide primary treatment for the same flush dairy facility as described in example 4–2 using the data collected for hindered settling of dairy manure.

The primary purpose of the settling basin is to prevent large fraction of the manure solids from entering the lagoon. The settled and thickened solids will be pumped to a mechanical separator for additional dewatering and all liquid waste will be treated in a covered lagoon digester.

Determine Q: The intermittent flow rate was estimated in example 4–2 and was determined to be Q_i is 7,779 cubic feet per day divided by 3 flow periods per day divided by 2.5 hours per flow period is 1,037 cubic feet per hour.

Set design overflow rate: It was determined that the average TS content of the flushed manure was 1.3 percent. From figure 4–37, the regression equation used to estimate the overflow rate for dairy manure was $U_o = 144.71 - 41.209 \text{ TS}$.

For a TS of 1.3 percent, $U_o = 91.14 \text{ cm/h} = 2.99 \text{ ft/h}$.

Calculate basin surface area: The basin surface area was $A_s = Q/U_o = 1,037 \text{ ft}^3/\text{h} \div 2.99 \text{ ft/h} = 347 \text{ ft}^2$.

Select detention time: The detention time, T , was set at 1 hour.

Calculate settling zone volume: The volume of the settling zone was calculated to be 1,037 cubic feet ($V_{sz} = Q T$).

Determine depth of setting zone: The depth of the settling zone was calculated as $D_A = V_{sz}/A_s = 2.99 \text{ ft}$. Round up to set D_A , 3.0 feet.

Determine width: The maximum basin width was calculated using equation 4–19b and was determined to be 9.3 feet. The maximum desired W , was 8.0 feet, so W was set at 8.0 feet to facilitate construction.

Determine length: $L_s = 347 \text{ ft}^2 / 8 \text{ ft} = 43.4 \text{ ft}$. Round L_s up to 44 feet to facilitate construction.

Calculate new surface area: A_s was increased to 352 square feet.

Check flow velocity: The flow velocity was calculated as $U_f = Q/(W D_A) = 43.2$ feet per hour or 0.012 feet per second, which is slow enough to achieve near quiescent conditions.

Summary: The final dimensions and characteristics of the settling zone are—

Dimensions: $W = 8 \text{ ft}$; $L_s = 44 \text{ ft}$; and $D_A = 3 \text{ ft}$

Areas: $A_s = 352 \text{ ft}^2$ and $A_x = 24 \text{ ft}^2$

Flow velocity: $U_f = 43.2 \text{ ft/h}$

Design overflow rate: $U_o = 2.95 \text{ ft/h} = 89.8 \text{ cm/h}$

Detention time: 1 h

The settling zone volume required for hindered settling of dairy manure with a TS of 1.3 percent was about the same size as the basin sized based on discrete settling ($\text{TS} \ll 0.5\%$). The main difference was that a much larger flow length, L_s , was required to capture the settling material due to the much lower overflow rate.

Size storage zone for settled material: The settled volume fraction for dairy manure at the end of the linear hindered settling period was determined using the first equation in table 4–25. The value of $\text{SVF}_{\text{LHS-T}}$ for $\text{TS} = 1.3$ percent was 0.28. The solids will be pumped from the basin three times a day to coincide with the three periods of flushing. Therefore, t_{sp} in equation 4–26 was 2.5 hours since the barn will be flushed over a 2.5-hour period three times a day. The volume of the settled material was $V_{\text{SM}} = (0.28 \times 1,037 \text{ ft}^3/\text{h}) \times 2.5 \text{ h} = 725.9$ cubic feet.

The depth of the storage zone was calculated using equation 4–27 by setting $L_b = W = 8$ feet. The value of D_{SM} was calculated to be 3.48 feet. Rounding this up to 3.5 feet gives a D_T of 6.5 feet. Add a minimum free-board of 1 foot above the weir outlet.

Implementation of this settling basin would allow the volume of manure to be processed by the mechanical separator to be reduced by about 30 percent. A separator with a throughput rate of 50 gallons per minute would only be required to operate 5.4 hours per day.

637.0404 Measures of solid-liquid separation performance

Two measures are used to describe how well a solid-liquid separator removes solids and plant nutrients from liquid animal manure. The easiest to implement in field is the concentration reduction (called removal efficiency in some older publications). The other more accurate measure is the mass removal efficiency.

(a) Concentration reduction

The required information to determine the concentration reduction, CR_C , of solids or plant nutrients for a solid-liquid separator is shown in figure 4–40. The only requirement for using this measure of performance is to collect representative samples of the influent manure and the treated effluent. The samples are then analyzed by a qualified laboratory for the constituents of interest (TS, VS, N, P, K, etc.).

The percent reduction in concentration in any constituent is simply—

$$CR_C = 100 \times \left(\frac{[C_{IN}] - [C_{EFF}]}{[C_{IN}]} \right) \quad (\text{eq. 4-28})$$

where—

CR_C = concentration reduction of constituent, C, %

$[C_{IN}]$ = concentration of the constituent in the manure that flows into the solid-liquid separator

$[C_{EFF}]$ = concentration of the constituent in the liquid effluent.

The main advantage of using CR_C as a measure of separator performance is its simplicity, and, in some field situations, it may be the only measure that can be implemented. It does not require flow measurements or measurements of the mass or composition of the separated solids. The CR_C will typically underpredict the removal of solids or plant nutrients as will be demonstrated in the examples that follow (e.g., example 4–5).

(b) Mass removal efficiency

The mass of solids or plant nutrients removed from the waste stream by a separator is the most accurate measure of performance. The mass removal efficiency is expressed as a percentage and the defining relationship is—

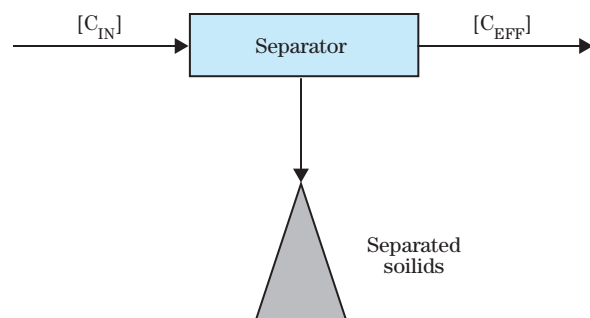
$$MRE_C = 100 \times \left(\frac{\text{Mass of C in separated material}}{\text{Mass of C in influent}} \right) \quad (\text{eq. 4-29})$$

The quantities used for calculating the mass removal efficiency for a particular solid-liquid separation system will vary depending on the complexity of the system and the ability of the evaluator to collect the required information. The beginning point is always a mass balance analysis. Developing an understanding of the separation system, installation, and the applicable mass flows will allow the evaluator to develop a valid protocol prior to taking labor intensive measurements in the field.

Writing the mass balance for a solid-liquid separation system will require the use of one or more of the following three relationships:

$$m_c = [C]Q \quad (\text{eq. 4-30a})$$

Figure 4–40 Concentration reduction for a solid-liquid separator.



$$m_c = [C_M]m \quad (\text{eq. 4-30b})$$

$$m_F = \rho_F Q \quad (\text{eq. 4-30c})$$

where—

m_c = mass flow of C, M/t

Q = volumetric flow rate of the liquid waste stream, V/t

$[C]$ = Concentration of C in the waste stream on a volume basis, M/V

$[C_M]$ = Concentration of C in the waste stream on a mass basis, M of C/M of solids

m = mass flow of solid manure, M/t

ρ_F = density of the fluid, M/V

m_F = Mass flow of liquid manure, M of fluid/t

Equations 4–30a and 4–30b are the relationships that are most often used when writing a mass balance for a separator. When manure is handled as a liquid it is most common to measure the constituent concentrations in terms of mass of C per unit volume of manure (e.g., lb C/gal or mg C/L). Therefore, the mass flows for separator influent or liquid effluent is typically calculated using equation 4–30a. The concentrations of plant nutrients of manure that can be handled as a solid or thick semisolid are typically expressed on a mass basis (lb C/lb or mg C/kg) and the flow rate is generally easiest to measure in terms of mass per unit time (lb/day, lb/h). Consequently, equation 4–30b can be used to observe the mass flow of constituents in separated solids. In some situations the mass flow of the liquid waste stream or effluent is required and equation 4–30c is needed for the analysis.

The use of these fundamental mass balance relationships will be demonstrated in the following examples.

(1) Mass balance on a single separator

The mass flows for a single solid-liquid separator are shown in a simple block diagram in figure 4–41. Application of the continuity of mass ($m_{IN} = m_{OUT}$) to the situation shown gives—

$$[C_{IN}] Q_{IN} = [C_{EFF}] Q_{EFF} + [C_{MSS}] m_{SS} \quad (\text{eq. 4-31})$$

Note that the constituent concentrations of the influent and effluent are expressed on a volume basis (lb/gal or mg/L) while the constituent concentrations

in the separated solids are on a mass basis (lb/lb or mg/kg).

The mass of solid or plant nutrients removed by the separator is simply—

$$[C_{MSS}] m_{SS} = ([C_{IN}] Q_{IN} - [C_{EFF}] Q_{EFF}) \quad (\text{eq. 4-32})$$

The mass removal efficiency (equation 4–29) can be calculated if at least two of the three mass flows can be determined from data. The three relationships for MRE_C are—

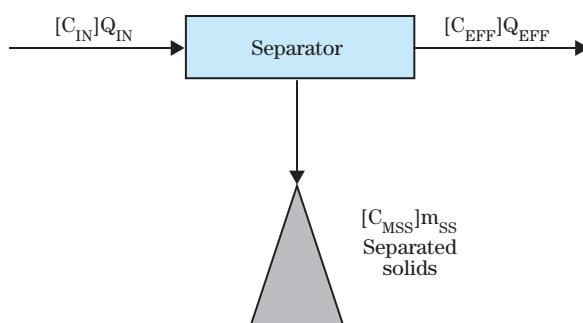
$$MRE_C = 100 \times \frac{([C_{IN}] Q_{IN} - [C_{EFF}] Q_{EFF})}{[C_{IN}] Q_{IN}} \quad (\text{eq. 4-33a})$$

$$MRE_C = \frac{100 \times [C_{MSS}] m_{SS}}{[C_{IN}] Q_{IN}} \quad (\text{eq. 4-33b})$$

$$MRE_C = \frac{100 \times [C_{MSS}] m_{SS}}{([C_{EFF}] Q_{EFF} + [C_{MSS}] m_{SS})} \quad (\text{eq. 4-33c})$$

The expression used to calculate the mass removal efficiency will depend of the measurements that can

Figure 4–41 Mass flows for a solid-liquid separator



be obtained with the greatest accuracy and with a reasonable investment of time and resources. The accuracy of the mass removal efficiencies will depend on the accuracy of the measurements. In many cases, flow meters, or other means, can be used to accurately measure Q_{IN} and Q_{EFF} and representative samples can be obtained over the required time period to determine the influent and effluent concentrations of the desired constituents. If such is the case, the most accurate MRE calculations can be made using equation 4–33a. However, many separators are installed in the field in such a way that it is prohibitively difficult to measure one of the volumetric flow rates (Q_{IN} or Q_{OUT}). In such situations, the next best option is to measure the mass of separated solids over a defined time period to determine m_{SS} . During this time period, samples of the separated solids are to be collected that, when mixed, will provide a representative sample of the entire mass of separated solids. Well-mixed samples of the separated solids will be analyzed to determine the desired values of $[C_{MSS}]$. Either equations 4–33b or 4–33c can be used to calculate the mass removal efficiencies depending on the volumetric flow rate measured.

Example 4–5—Performance of a roller press treating scraped dairy manure

A roller press was used to dewater scraped freestall dairy manure from an 800-cow herd (data from Gooch et al. 2005). The mean opening size of the screen rollers used to press the manure was unknown. Separated solids were used for freestall bedding, therefore the major components of the solids were from manure, separated manure solids, and wasted feed.

Samples were collected on-farm to determine $[C_{IN}]$, Q_{IN} , $[C_{EFF}]$, Q_{EFF} and $[C_{MSS}]$. The constituents that were measured were the total solids (TS), volatile solids (VS), total nitrogen (TKN), total ammonical nitrogen (TAN = $NH_4^+ - N + NH_3 - N$), total phosphorus (TP), and the soluble phosphorus (Ortho-P). The organic-N content was calculated as $Org-N = TKN - TAN$.

The data and performance results are given in table 4–28. The mass removal efficiencies were calculated using equation 4–33a. Comparison of the mass removal efficiencies with the concentration reductions indicates that in this case the CR greatly underpredicted separator performance. Forty-two percent of the TS were removed; however, removal of plant nutrients was significantly less. The low CR values for N and P

as compared to the mass removal efficiencies indicates that the majority of the plant nutrient removal was associated with the moisture in the separated solids.

The screening process did not greatly alter the soluble fraction of N or P in the effluent (TAN/TKN and Ortho-P/TP), but it did slightly reduce the volatile fraction of the solids (VS/TS). The separated material had a stackable consistency and was composed primarily of organic N and P. Also, 91.6 percent of the dry matter was volatile. The carbon content of animal manure can be estimated as $C_T \% \text{ d.b.} = 100 \text{ VS/TS} / 1.8$ (Rynk et al. 1992). As a result, about 50.9 percent of the dry matter in the separated solids was carbon or 243 pounds C_T /ton. The $C_T:N$ of the separated solids was about 28. Therefore, these solids would be a good ingredient for making compost.

Removal of 42.4 percent of the dry matter and the associated liquid resulted in a significant reduction in effluent volume. The effluent volume fraction, (Q_{EFF}/Q_{IN}), was 0.783. Therefore, the volume of liquid that will require additional treatment, storage and handling following separation was reduced by 21.7 percent.

Example 4–6—Performance of a screw press treating anaerobically digested dairy manure and food waste

Field data and results for a screw press treating effluent from a mixed anaerobic digester on a dairy farm in New York are given in table 4–29 (data from Gooch et al. 2005). This situation is unique because manure from 778 dairy animals (lactating cows, dry cows, and heifers) was mixed with food waste prior to digestion. The food waste was from ice cream, fish stick, and grape juice processing plants. After digestion, the manure was processed using a screw press separator with a 2.25 millimeter screen.

The data and results shown in table 4–29 indicate that only a small fraction of the dry matter was removed from the digested mixture because the screen open-

ings were too large. Anaerobic digestion will reduce mean particle diameter in any waste stream. Use of a much smaller screen (≈ 0.5 mm or less) would be expected to greatly enhance solids removal.

The low solids removal of 6.8 percent resulted in only a 1.2 percent reduction in liquid volume. Therefore, no reduction in post digestion storage or application requirements was provided by this separator and screen opening size combination.

The separated solids had a moisture content of 71 percent and a $C_T:N$ of 31. Therefore, the solids that were produced by this separator would be a valuable ingredient for production of compost.

Example 4–7—Performance of a screw press treating effluent from a plug-flow digester on a dairy farm

A screw press with a 0.5 millimeter screen was installed on a dairy farm to remove solids from the outflow of a plug-flow anaerobic digester (Gooch et

al. 2005). Samples of the separator influent and effluent and of the separated solids were collected over time to quantify mean concentrations of solids and selected plant nutrients. Measurements were made to determine flow rate of the liquid effluent (Q_{EFF}) and the mass flow of the separated solids (m_{SS}). However, the physical constraints associated with the installation of the screw press prevented measurement of the influent flow rate (Q_{IN}). Therefore, equation 4–32c was required to calculate the mass removal efficiency for each of the measured constituents. The data and results are shown in table 4–30.

The results shown in the table indicate that a screw press with a 0.5 millimeter screen was capable of removing about half of the solids, 22 percent of the total-P, and 18 percent of the TKN from digested dairy slurry.

Table 4–28 Performance of a roller press treating scraped dairy manure, screen size unknown (data from Gooch et al. 2005)

$Q_{IN} = 5,386$ gal/hr		15,600 gal/day		$(Q_{EFF}/Q_{IN}) = 0.783$			Separated solids
$Q_{EFF} = 4,219$ gal/hr		12,200 gal/day					
Constituent	[C_{IN}] lb/1,000 gal	[C_{EFF}] lb/1,000 gal	CR_C %	[C_{IN}] Q_{IN} lb/hr	[C_{EFF}] Q_{EFF} lb/hr	MRE_C %	[C_{MSS}] lb/ton
TS	859 (10.3%)	632 (7.58%)	26	4,626.6	2666.4	42.4	478 (23.9%)
VS	703	488	31	3,786.4	2058.9	45.6	438
TKN	34.4	33.3	3	185.3	140.5	24.2	8.56
TAN	16.0	15.2	5	86.2	64.1	25.6	2.75
Org-N	18.4	18.1	2	99.1	76.4	22.9	5.81
Total-P	5.59	4.85	13	30.1	20.5	32.0	1.05
Ortho-P	2.64	2.39	9	14.2	10.1	29.1	0.42
TAN/TKN	0.46	0.46					0.32
Ortho-P/TP	0.47	0.49					0.40
VS/TS	0.818	0.772					0.916
						C_T ^{1/}	243 lb/ton
						$C_T:N$ ^{2/}	28

1/ $C_T = 0.5556 \times (VS/TS) \times \text{lb TS/ton}$

2/ $C_T:N = \text{lb } C_T/\text{ton} \div \text{lb TKN/ton}$

The separated solids had a TS of 24.6 percent and could be easily stacked. The $C_T:N$ was 22, which is on the lower limit of the recommended range for composting without addition of a dry carbon rich material.

The volume of the influent could not be measured directly. However the effluent volume fraction (EVF) was estimated from the data as—

$$EVF = \left(\frac{Q_{EFF}}{Q_{IN}} \right) = \frac{Q_{EFF}}{\left[\frac{[TS_{EFF}][Q_{EFF}] + [TS_{MSS}] m_{SS}}{[TS_{IN}]} \right]} \quad (\text{eq. 4-34})$$

Substitution of the data from table 4-30 (using ton/day for m_{SS} and gal/day for Q_{EFF}) indicated that the effluent volume fraction was 0.86 and the screw press reduced the required capacity of the storage structure for the effluent by only 14 percent.

(c) Mass balance on a two-stage solid-liquid separation system

A two-stage separation system involves the use of two mechanical separators operated in series. Varieties of separator types have been and can be used together in series. Some of the possible combinations are an inclined screen followed by a screw press, a screw press followed by a centrifuge, or two inclined screens with different opening sizes. If two inclined screens are used in series, it is most common for a finer screen to be used in the second machine. The mass flows for a two-stage mechanical separation system are given in figure 4-42.

If all of the influent and effluent flows and concentrations associated with the two separators that are

Table 4-29 Performance of a screw press treating anaerobically digested dairy manure and food waste; screen size = 2.25 mm (data from Gooch et al. 2005)

Constituent	$Q_{IN} = 3,312$ gal/hr	25,500 gal/day	CR_C	$(Q_{EFF}/Q_{IN}) = 0.988$		MRE_C	Separated solids
	$Q_{EFF} = 3,273$ gal/hr	25,200 gal/day		$[C_{IN}] Q_{IN}$	$[C_{EFF}] Q_{EFF}$		$[C_{MSS}]$
	$[C_{IN}]$	$[C_{EFF}]$	%	lb/hr	lb/hr	%	lb/ton
	lb/1,000 gal	lb/1,000 gal					
TS	459 (5.50%)	433 (5.19%)	5.7	1520	1417	6.8	586 (29.3%)
VS	354	341	3.7	1172	1116	4.8	548
TKN	26	24.6	5.4	86	81	6.5	9.8
TAN	10.5	9.85	6.2	35	32	7.3	2.35
Org-N	15.5	14.8	4.8	51	48	6.0	7.49
Total-P	4.67	4.53	3.0	15	15	4.1	1.86
Ortho-P	2.51	2.47	1.6	8	8	2.8	0.99
TAN/TKN	0.40	0.40					0.24
Ortho-P/TP	0.54	0.55					0.53
VS/TS	0.771	0.788					0.935
						$C_T^{1/}$	304 lb /ton
						$C_T:N^{2/}$	31

1/ $C_T = 0.5556 \times (VS/TS) \times \text{lb TS/ton}$

2/ $C_T:N = \text{lb } C_T/\text{ton} \div \text{lb TKN/ton}$

shown in the diagram are measurable, then the performance of each of the machines can be described by applying equation 4–33a. The total removal of a constituent is simply the sum of the removal of both machines. However, in many situations the flow between the two separators ($[C_{EFF1}] Q_{EFF1}$) is inaccessible. Application of a mass balance on the complete system provides the needed working equations to allow field evaluation of a two-stage separation system.

The general mass balance relationship for a two-stage system is (fig. 4–42 for nomenclature)—

$$[C_{IN}] Q_{IN} = [C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2} + [C_{EFF}] Q_{EFF} \quad (\text{eq. 4-35})$$

Equation 4–35 points out that it is not necessary to measure the flow and concentrations of effluent from the first separator if accurate measurements can be made for the separated solids that flow from each of the separators. The mass removal efficiencies of both

separators combined can be computed from the following expressions depending on the measurements that can be made in for a particular installation:

$$MRE_{CT} = 100 \times \left(\frac{[C_{IN}] Q_{IN} - [C_{EFF2}] Q_{EFF2}}{[C_{IN}] Q_{IN}} \right) \quad (\text{eq. 4-36a})$$

$$MRE_{CT} = 100 \times \left(\frac{[C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2}}{[C_{IN}] Q_{IN}} \right) \quad (\text{eq. 4-36b})$$

$$MRE_{CT} = 100 \times \left(\frac{[C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2}}{[C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2} + [C_{EFF2}] Q_{EFF2}} \right) \quad (\text{eq. 4-36c})$$

Table 4–30 Performance of a screw press treating effluent from a plug-flow anaerobic digester on a dairy farm; screen size = 0.5 mm (data from Gooch et al. 2005)

$m_{SS} = 1,908 \text{ lb/h} = 7.25 \text{ ton/day}$							
$Q_{EFF} = 1,212 \text{ gal/h} = 9,200 \text{ gal/day}$							
	$[C_{IN}]$	$[C_{EFF}]$	CR_C	$[C_{MSS}]$	$[C_{EFF}] Q_{EFF}$	$[C_{MSS}] m_{SS}$	MRE_C
Constituent	lb/1000 gal	lb/1000 gal	%	lb/ton	lb/hr	lb/hr	%
TS	694	422		492	511	469	48
	(8.32%)	(5.06%)	39	(24.6%)			
VS	548	298	46	438	361	418	54
TKN	43.2	38.5	11	11.1	46.7	10.6	18
TAN	23.4	22.4	4	5.15	27.1	4.9	15
Org-N	19.8	16.1	19	6.0	19.5	5.7	23
Total-P	7.45	6.49	13	2.28	7.9	2.2	22
Ortho-P	4.71	4.31	8	1.26	5.2	1.2	19
TAN/TKN	0.54	0.58		0.46			
Ortho-P/TP	0.63	0.66		0.55			
VS/TS	0.790	0.706		0.890			
			$C_T^{1/}$	243			
			$C_T:N^{2/}$	22			

1/ $C_T = 0.5556 \times (VS/TS) \times \text{lb TS/ton}$

2/ $C_T:N = \text{lb } C_T/\text{ton} \div \text{lb TKN/ton}$

The relationships used to quantify the removal of each individual separator will depend on which flow can be reliably sampled and measured. If only the influent flow can be sampled and measured the following equations apply:

$$MRE_{CS1} = 100 \times \left(\frac{[C_{MSS1}] m_{SS1}}{[C_{IN}] Q_{IN}} \right) \quad (\text{eq. 4-37a})$$

$$MRE_{CS2} = 100 \times \left(\frac{[C_{MSS2}] m_{SS2}}{[C_{IN}] Q_{IN} - [C_{MSS1}] m_{SS1}} \right) \quad (\text{eq. 4-37b})$$

The mass removal efficiencies for each separator can be calculated using the following expressions if the only data for the effluent from the second separator can be obtained:

$$MRE_{CS1} = 100 \times \left(\frac{[C_{MSS1}] m_{SS1}}{[C_{MSS1}] m_{SS2} + [C_{MSS2}] m_{SS2} + [C_{EFF2}] Q_{EFF2}} \right) \quad (\text{eq. 4-38a})$$

$$MRE_{CS2} = 100 \times \left(\frac{[C_{MSS2}] m_{SS2}}{[C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2} + [C_{EFF2}] Q_{EFF2}} \right) \quad (\text{eq. 4-38b})$$

The use of these equations are demonstrated by the example 4-8.

Example 4-8—Performance of a two-stage mechanical separation system on a flush dairy farm

A two-stage mechanical separation system was installed on a 3,600-cow dairy farm in California (adapted from Chastain 2009). The system included two inclined separators operated in series. Manure from the dairy facilities was flushed 8 times a day and collected in a reception pit. Whenever the liquid level exceeded a preset level, the pit contents were agitated and pumped to the first separator. The first incline screen separator had a bar screen with a mean opening size of 0.020 inch (0.508 mm). The separated solids slid down the screen and were collected in a trough where a low-pressure screw press provided additional dewatering and conveyed the solids to an inclined screen stacking conveyor. The effluent from the first separator was

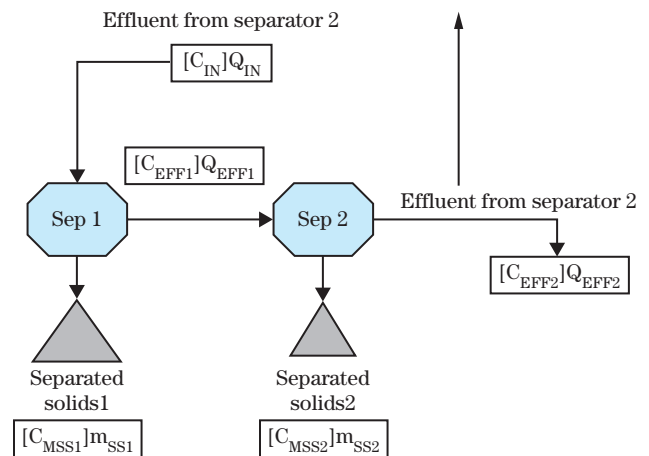
pumped to a second inclined screen separator with a screen size of 0.010 inch (0.254 mm). The two separators had the same design, except the wet solids collected on another inclined screen stacking conveyor without being dewatered by a screw press. The screen conveyor provided the additional drying to facilitate stacking of solids.

Both of the inclined screen separators utilized periodic fresh water sprays to keep fine particles from drying and plugging the screens. In addition, the screens were cleaned several times each week with a high-pressure washer.

The separated solids from each mechanical separator were temporarily stored on separate concrete pads. The separated solids from the first machine were periodically removed and dried to be used as freestall bedding. The separated solids from the second separator were periodically removed and applied to cropland. The effluent from the second separator received additional treatment in a series of settling ponds and a treatment lagoon.

The physical constraints of the installation prevented reliable sampling of the influent to and the effluent from the first mechanical separator. Therefore, the evaluation was limited to samples and material flow measurements of the separated solids from the two machines and the liquid effluent from the second

Figure 4-42 Mass flows for a two-stage solid-liquid separation system



machine. The means of the samples and the flow measurements are given in table 4–31.

The separated solids from both of the separators were dry enough to store and handle as a solid. The $C_T:N$ of the residue from the first separator was 26 with a moisture content of 77.25 percent. With a small amount of drying, this material would be an excellent substrate for composting. The $C_T:N$ of the second residue was 20.5 with a moisture content of 80.6 percent. This material would also be an excellent material for composting, but additional dry carbon is needed to increase the $C_T:N$ and reduce the moisture content. The high $C_T:N$ of the residue from the second separator may cause it to be a net immobilizer of nitrogen if land applied without composting.

The mass removal efficiencies for each separator and the total system were calculated from the means in table 4–31 using the previously given equations and the results are given in table 4–32. The two-stage separation system was able to remove 59.7 percent of the TS and 65.7 percent of the VS from flushed dairy manure. However, two-thirds to three-quarters of the nitrogen, phosphorus, calcium, magnesium, and sulfur remained in the separator effluent. The data also show that most of the solids and plant nutrients were removed by the first machine.

(d) Mass balance on gravity settling

The mass flows for a gravity settling basin are shown in figure 4–42. The volumes shown in the diagram correspond to the time period of interest. For example, the volume loaded into the basin would be the average influent flow rate (Q_{IN}) multiplied by the total time. In most cases, information is gathered to determine the total volume loaded per day. The volume of manure to be removed is the sum of total volume of settled material that will accumulate over the defined time period and the volume of supernatant that will not be removed in the outfall (Q_{OUT}). The volume to be removed at planned time intervals is termed the storage volume, V_{SM} .

Application of the law of conservation of mass to the basin shown in figure 4–43 gives—

$$[C_{IN}] V_{IN} = [C_{OUT}] V_{OUT} + [C_{ST}] V_{SM} \quad (\text{eq. 4-39})$$

where—

$[C_{IN}]$ = concentration of a constituent in the influent liquid manure

$V_{IN} = Q_{IN} \Delta t$ = volume of wastewater treated over time period Δt

$[C_{OUT}]$ = concentration of a constituent in the outfall (supernatant)

$V_{OUT} = Q_{OUT} \Delta t$ = volume of treated liquid that flows out of the basin

$[C_{ST}]$ = concentration of a constituent in the storage volume

V_{SM} = storage volume = volume of settled material that accumulates over Δt + the supernatant that will not flow out of the basin

The relationship for the mass removal efficiency for a settling basin can be written in the following two ways from the mass balance depending on the available information:

$$MRE_C = 100 \times \left(\frac{[C_{IN}] V_{IN} - [C_{OUT}] V_{OUT}}{[C_{IN}] V_{IN}} \right) \quad (\text{eq. 4-40a})$$

$$MRE_C = 100 \times \frac{[C_{ST}] V_{SM}}{[C_{IN}] V_{IN}} \quad (\text{eq. 4-40b})$$

In many design scenarios, the quantities that can be established during the design process and from settling experiments are V_{IN} , V_{SM} , $[C_{IN}]$, and $[C_{OUT}]$. The volume of the outfall can be calculated based on a mass balance as—

$$V_{OUT} = V_{IN} \left(\frac{\rho_{IN}}{\rho_{OUT}} \right) - V_{SM} \left(\frac{\rho_{SA}}{\rho_{OUT}} \right) \quad (\text{eq. 4-41})$$

Where the densities correspond to the mean densities of the manure that flows into the settling basin (ρ_{IN}), the supernatant (ρ_{OUT}) that flows out of the basin, and the settled material that will be removed (ρ_{SA}). In most cases, the density ratios in equation 41 are close to 1.0 (within 0.998 to 1.02) and $V_{OUT} = V_{IN} - V_{SM}$.

The concentration of the solids and plant nutrients in the storage volume that must be removed and treated can be calculated using this equation:

Table 4–31 Mean concentration and flow data for a two-stage separation system used to treat flushed dairy manure

	Solids from Sep 1 Screen Size = 0.020 in $[C_{MSS1}]$ (% wet basis)	Solids from Sep 2 Screen Size = 0.010 in $[C_{MSS2}]$ (% wet basis)	Liquid from Sep 2 $[C_{EFF2}]$ (lb/1,000 gal)
TS	22.75	19.39	93.08 (98.99% TS)
VS	20.44	16.168	64.03
Total-N	0.441	0.460	7.27
Ammonium-N	0.028	0.034	1.98
P ₂ O ₅	0.104	0.128	2.05
K ₂ O	0.130	0.120	8.92
Calcium	0.296	0.351	3.57
Magnesium	0.089	0.101	1.76
Sulfur	0.064	0.074	0.78
Carbon	11.56	9.316	
C _r :N	26.2	20.3	
Daily flow	217,969 lb SS/day	47,741 lb SS/day	425,930 gal/day

Table 4–32 Mass of solids and plant nutrients fed to and removed by a two-stage separation system used to treat flushed dairy manure

	Sep 1 $[C_{MSS1}] m_{SS1}$ lb/day	Sep 2 $[C_{MSS2}] m_{SS2}$ lb/day	Effluent $[C_{EFF2}] Q_{EFF2}$ lb/day	INPUT ^{1/} lb/day	Sep 1 ^{2/} MRE _{CS1} (%)	Sep 2 ^{3/} MRE _{CS2} (%)	MRE _{CT} ^{4/} (%)
TS	49,581	9,259	39,644	98,483	50.3	9.4	59.7
VS	44,557	7,719	27,272	79,547	56.0	9.7	65.7
Total-N	960	219	3,096	4,276	22.5	5.1	27.6
Ammonium - N	62	16	845.0	923	6.7	1.7	8.4
P ₂ O ₅	226	61	872.2	1,160	19.5	5.3	24.8
K ₂ O ₅	283	57	3,798.3	4,138	6.8	1.4	8.2
Calcium	645	168	1,521	2,333	27.6	7.2	34.8
Magnesium	193	48	750	991.1	19.5	4.9	24.4
Sulfur	139	35	332	506.2	27.4	6.9	34.4

1/ INPUT = $[C_{MSS1}] m_{SS1} + [C_{MSS2}] m_{SS2} + [C_{EFF2}] Q_{EFF2}$

2/ Calculated using equation 4–38a

3/ Calculated using equation 4–38b

4/ Calculated using equation 4–36c

$$[C_{ST}] = \frac{[C_{IN}]V_{IN} - [C_{OUT}]V_{OUT}}{V_{SM}} \quad (\text{eq. 4-42})$$

Example 4-9—Calculation of the mass removal efficiencies for a settling basin treating flushed swine manure

A settling basin was sized based on hindered settling principles to provided primary treatment for an 8,000-head swine finishing farm (ex. 4-3). The next step is to determine the mass removal efficiency for each constituent of interest and to calculate the concentrations in the settled portion that is to be loaded into an anaerobic digester.

The amount of flushed manure that will be treated is 152,891 gallons per day. The basin selected is 26 feet long by 6 feet wide with a total depth (D_T) of 12 feet. The volume of settled solids and supernatant that will be pumped to the anaerobic digester was estimated to be 26,000 gallons per day.

The influent and outfall concentration data that will be used to quantify the mass flows for the basin are given in table 4-33.

The concentration reductions were calculated from the data and are also shown in table 4-33. Even this simple measure of separator performance indicates that settling has a potential to remove significant amounts of solids, organic load (VS), nitrogen, and phosphorus.

The concentration data of table 4-33 was used with the defined volumes to calculate the daily mass flows, the mass removal efficiencies, and the concentrations of solids and plant nutrients in the manure that will be loaded into the anaerobic digester. The results are given in table 4-34.

The results of the analysis indicate that the mass removal efficiencies were significantly greater than the concentration reductions. The basin was able to remove 58 percent of the VS and 51 percent of the COD. Furthermore, sedimentation increased the concentrations of TS, VS, COD, Org-N, and P_2O_5 in the manure that will be pumped into the digester by a factor of 3 or more. The nonsettleable organic matter (VS, COD) remaining in the outfall will allow a significant reduc-

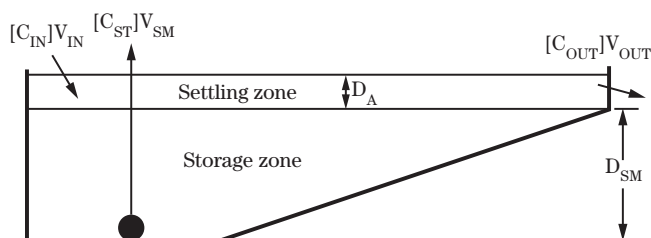
tion in the size of any aerobic or anaerobic treatment process used to treat the liquid fraction.

Summaries of performance data from a variety of solid-liquid separation methods are provided appendix 4B. Appendix 4C provides short summaries and Web addresses for reports of field demonstration studies funded by the Farm Pilot Project Coordination, Inc.

637.0405 High-rate solid-liquid separation

High-rate solid-liquid separation methods are typically physical or chemical enhancements of common screening, pressing, or settling processes. An example of a physical enhancement is the application of greater pressure on the influent manure to force the liquid fraction through a fine screen or filter. An example of a chemical enhancement is the addition of alum to react with soluble phosphorus to form large particles of organic aluminum phosphate that can be removed by settling or screening. Many chemical treatment additives improve separation efficiency by coagulation, flocculation and precipitation to improve separation efficiency. Therefore, many high-rate solid-liquid separation systems use both chemical and physical means of treatment.

Figure 4-43 Mass flows for a settling basin at the end of the defined solids accumulation period



(a) Coagulants and flocculants

Coagulation and flocculation is a two-step, physico-chemical process that involves the addition of a floc-forming chemical to liquid manure that combines colloidal ($d = 1 \text{ m}\mu$ to 100μ) and slow-settling suspended solids to form a rapid-settling floc. The large flocs are subsequently removed by settling or screening. As a result, addition of a flocculant to a solid-liquid separation system will often greatly enhance removal of solids and plant nutrients.

Coagulation is a chemical process that destabilizes colloidal particles so that they are able to come together to form a round mass of small particles called microfloc (agglomerate). Colloidal particles have electrostatic charges that are responsible for the forces that keep the particles dispersed in the manure. As long as these electrostatic charges are maintained in a stable condition these tiny particles will not agglomerate. A coagulant is an electrolyte or charged organic polymer that is rapidly mixed in liquid manure and acts to chemically disrupt or destabilize these charges to allow the forces of attraction between the particles (called van der Waals' forces) to overcome repulsive forces to enable micro floc formation. The chemical theory of coagulation is very complex and is beyond the scope of this publication. However, the best models of the chemical process provide only approximate

estimates and empirical results are typically needed for process design.

Flocculation is a physical process by which micro floc clump together to form large, dense flocs that settle rapidly or screen easily. Flocculation occurs typically during gentle agitation where micro floc form large flocs by colliding and sticking together (patch flocculation) or by being caught in a web of filamentous material (polymer) that joins many floc together (polymer bridging) to form a large, dense stringy mass of flocs. Tiny suspended particles can also be trapped in the forming flocs or by a falling organic precipitate and removed from the liquid by a process called sweep coagulation or entrapment.

(1) Types of coagulants

The most widely used coagulants for wastewater and liquid manure treatment are the metal salts of aluminum (Al), iron (Fe), and calcium (Ca). In particular, the metal salts that have been considered for manure treatment include aluminum sulfate (alum), aluminum chloride, ferric sulfate, ferrous sulfate, ferric chloride, and calcium hydroxide (lime). Ferrous sulfate has been shown to be inferior to ferric sulfate for removal of solids, phosphorus, and other plant nutrients commonly found in liquid manure (Barrow et al. 1997). As a result, only ferric forms of iron are typically considered as possible coagulants for manure treatment.

Table 4–33 Influent and outfall concentrations for a settling basin treating flushed swine manure (Chastain and Vanotti 2003)

Constituent	Influent concentration [C _{IN}]	Supernatant concentration [C _{OUT}]	Concentration reduction
	lb/1,000 gal	lb/1,000 gal	(%)
TS	83.45 (1.0% TS)	46.88 (0.56% TS)	43.8
VS	52.51	26.60	49.3
COD	74.93	44.39	40.8
TKN	9.35	7.57	19.0
TAN	5.42	5.42	0.0
Org-N	3.93	2.15	45.2
P ₂ O ₅	9.86	3.85	61.0
K ₂ O	6.78	6.78	0.0

The main factors that influence the effectiveness of metal salt coagulants are the total solids content of the manure, suspended solids content of the manure, influent temperature, pH and alkalinity of the manure, cationic and anionic composition and concentration, and degree of agitation provided during coagulation and flocculation. Some of the important properties and a general description of possible precipitates formed are summarized in table 4–35.

Aluminum and iron salts—By far the most common metal salts used for treatment of liquid manure are alum due to its lower cost, and ferric chloride because it is effective over a wide range of pH (4.0 to 12). In most cases, manure has a pH in the range of 7.0 to 8.0 and contains plenty of indigenous alkalinity. Therefore, salts of Al or Fe can typically be used without pH adjustment (table 4–35).

When Al or Fe salts are added to liquid manure or wastewater under the right conditions, these metal ions react with hydroxyl ions (OH⁻) to form settable particles of aluminum or ferric hydroxide (table 4–35). In addition, many of the Fe or Al ions will also react

with soluble phosphorus (ortho-P, PO₄³⁻) to form particles of aluminum or ferric phosphate (AlPO₄ or FePO₄) that settle rapidly. These metal salts also neutralize charges of colloidal and tiny suspended solids to facilitate coagulation. These small-diameter flocs will then settle. As these organic precipitates and small flocs settle, they also entrap and remove other suspended particles from the liquid fraction.

The chemical reactions that occur during coagulation with alum or iron salts are much more complicated than has been included in this brief discussion. Under perfect conditions with no competing reactions, one unit mass of iron or aluminum (1 mole) would be sufficient to react with 1 unit mass (1 mole) of phosphate. However, the demand for reactants from competing reactions and the effects of alkalinity, pH, and many other factors require much larger doses of metal salts than predicted by basic stoichiometric equations. The optimal dose of Al or Fe salt needed to enhance the settling of solids and removal of phosphorus (P) varies by manure type and consistency and is typically determined by bench or pilot scale testing that is appropriate to the solid-liquid separation method that is to be used.

Table 4–34 Performance of a settling basin treating flushed swine manure

Constituent	Influent mass ^{1/}	Outfall mass ^{2/}	Mass removed from storage volume ^{3/}	Mass removal efficiency ^{4/}	Storage volume concentration [C _{ST}] ^{5/}
	lb/day	lb/day	lb/day	(%)	lb/1000 gal
TS	12,759	5,949	6,810	53.4	261.9 (3.1%)
VS	8,028	3,375	4,653	58.0	179.0
COD	11,456	5,633	5,823	50.8	224.0
TKN	1,429	960.6	468.4	32.8	18.02
TAN	828.7	687.7	141.0	17.0	5.42
Org-N	600.9	272.8	328.1	54.6	12.62
P ₂ O ₅	1,508	488.5	1,020	67.6	39.23
K ₂ O	1,037	860.3	176.7	17.0	6.80

1/ V_{IN} = 152,891 gal/day
 2/ V_{OUT} = 126,891 gal/day
 3/ V_{SM} = 26,000 gal/day
 4/ Equation 4–40a
 5/ Equation 4–42

One of the main disadvantages of using aluminum or iron salts to precipitate P is that aluminum phosphate and ferric phosphate are organic forms of P that are not available to plants. In fact, reactions of ortho-P with indigenous Al and Fe in low-fertility soils is one of the common chemical pathways by which P in fertilizers are rendered unavailable to crop. Addition of Al in solution to liquid manure will immobilize soluble-P and render it unavailable. Therefore, precipitated aluminum phosphate in separated solids fraction will not have any fertilizer value at normal ranges of soil pH (Moore et al. 1998b). The aluminum added to soil by application of separated solids will not be soluble either and will not be phytotoxic (Moore et al. 1998a). Using alum to enhance separation of liquid manure by sedimentation will increase the concentration of Al in the supernatant that flows from the settling basin as shown in figure 4–44. This increase in soluble Al in the liquid fraction would have the potential to immobilize plant available P in the manure storage or in the soil following land application. The practical impact on soil fertility will depend on the native Al concentrations in the soil, soil pH, and remaining soil Al fixation capacity, and the fertilization history of the field. If the soil is high in available P and tends to be acidic the formation of aluminum phosphate following application could occur.

Lime—The optimal dose of lime (CaO or Ca(OH)₂) needed to cause formations of calcium compounds to form and settle depends on the amount of natural alkalinity that is present in the liquid manure. As lime is mixed into the manure, it reacts first with the natural alkalinity to produce calcium carbonate (CaCO₃). As the available lime consumes the alkalinity, and more lime is added, the pH of the manure must be allowed to increase to a value greater than 10. At high pH the soluble Ca ions will react with phosphate to form hydroxyapatite. Other phosphorus containing precipitates that may form are dicalcium phosphate and tricalcium phosphate. In addition, a large portion of the settled solids from lime treatment will be the calcium carbonate that was formed to remove alkalinity.

Lime is the least used coagulant because large quantities are required to raise manure pH to 10 or more and an excessively large amount of precipitates are generated (table 4–35). Raising the pH of liquid manure has the additional disadvantage of increasing the fraction of the total ammonical-N (TAN) that is in the ammonia form (fig. 4–45). At a pH of 7.5 to 8.0, less than 5 percent of the TAN is in the ammonia form and can be readily lost to the air by volatilization. Raising the pH to greater than 10 will cause the ammonia fraction to increase to 80 percent or more. As a result, using lime as a coagulant will greatly increase ammonia volatilization to the air, causing a loss of valuable fertilizer

Table 4–35 Some properties of metallic salts and precipitates

Coagulant	Formula	Metal content (%)	pH range	Available forms and concentrations ^{1/}	Common precipitates	
Aluminum sulfate (Alum)	Al ₂ (SO ₄) ₃	15.772% Al	4.5 to 8.0	Liquid	4.3% to 4.5% Al	
				Dry	9.0% to 9.2% Al	Aluminum phosphate
Aluminum chloride	AlCl ₃	20.235% Al	4.5 to 8.0	Liquid	5.3% to 5.8% Al	Aluminum hydroxide
Ferric sulfate	Fe ₂ (SO ₄) ₃	27.931% Fe	4.0 to 12	Liquid	10% to 14% Fe	
				Dry	18.5% to 20.5% Fe	Ferric phosphate
Ferric chloride	FeCl ₃	34.429% Fe	4.0 to 12	Liquid	11.3% to 14.5% Fe	Ferric hydroxide Hydroxyapatite
Calcium hydroxide (Lime)	Ca(OH) ₂	54.091% Ca	10 <	Slurry	15% to 20% (CaO)	Dicalcium phosphate
				Dry	63% to 73% (CaO)	Tricalcium phosphate
				Powder	85% to 99% (CaO)	Calcium carbonate

1 Concentration of chemical sold expressed as percent of metal or compound in parenthesis (DeBusk 2007)

quality N as well as increasing the release of an air contaminant.

(2) Removal of solids, phosphorus, and other plant nutrients using metal salts as coagulants

The most common way to use metallic salts in animal manure treatment is to inject and mix the optimum amount of coagulant into liquid manure and then allow separation to occur by sedimentation. Such methods are similar to the use of coagulants for treatment for municipal wastewater. Several studies have been published that provide the results of jar tests and field studies to evaluate the efficacy of most metal salts for the enhancement of solids, phosphorus and plant nutrient removal from liquid swine and dairy manure by sedimentation. The results from several studies are provided in tables 4–36 and 4–37. Each researcher used slightly different techniques, used different doses of coagulant, and reported different levels of detail on nutrient removal. Some provided valuable information on coagulant efficacy, while others provided information on the effect of coagulant dose. Not all of the researchers provided dosage information using the same units. However, a dose conversion factor is provided with each study to allow calculation of the dose in terms of mass of coagulant per liter of manure treated. The type of manure pretreatment prior to sedimentation with a coagulant also varied from study to study. The level of pretreatment ranged from none to treatment by sedimentation and screening prior to secondary settling with addition of a coagulant. The details of the pretreatment used, if any, are provided with the data summary. While results from all of these studies provide useful information for a manure system designer, care should be taken to observe the type of manure used and any pretreatment when evaluating the applicability of these results to a particular situation. The purpose of the discussion that follows is to highlight the most important results that are of a more general nature.

Evaluation of metal salt effectiveness based P removal—Removal of P from manure following coagulation and settling is one of the key results that have been used to evaluate the effectiveness of aluminum-, iron-, and calcium-based salts. While it is common for the removal of organic solids to be enhanced by settling with metal salts, detailed studies have shown that surplus dissolved Al and Fe and other elements contained in the coagulant can be dissolved in the liquid effluent.

These dissolved elements cause a slight increase in the total solids content of the liquid effluent. This can be observed as decreasing or negative TS removal efficiencies as the coagulant dose was increased (tables

Figure 4–44 Effect of alum dose on supernatant aluminum content following sedimentation of liquid dairy manure (adapted from Sherman et al. 2000)

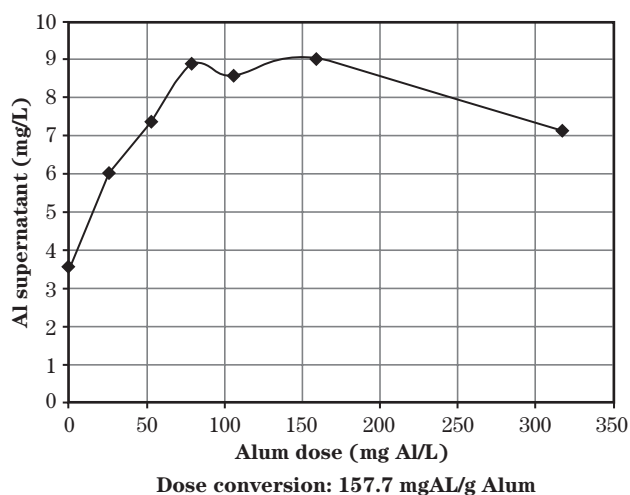
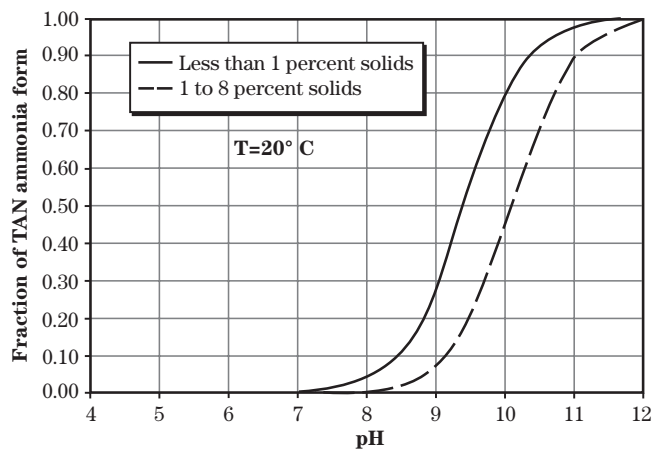


Figure 4–45 Variation in the fraction of total ammoniacal nitrogen (TAN = $\text{NH}_4^+ - \text{N} + \text{NH}_3 - \text{N}$) in ammonia form for liquid and slurry animal manure (adapted from Denmead et al. 1982; Zhang 1992)



4–42 and 4–43). The amount of Al or Fe in the effluent has also been observed to increase with the use of coagulants (fig. 4–44 and table 4–42).

Powers and Flatow (2002) compared the removal of total solids and total phosphorus from liquid swine manure in response to coagulant doses of 40, 250, and 625 milligrams of coagulant per liter of manure (table 4–36). The coagulants studied were alum, ferric chloride, ferrous sulfate, calcium carbonate and calcium oxide. Overall, the two coagulants that provided the highest increase in phosphorus removal from swine manure as compared to natural sedimentation (control) were ferric chloride and aluminum sulfate. Ferrous forms of iron (ferrous sulfate, FeSO_4) were also shown to be inferior to ferric salts for treatment of dairy manure (Barrow et al. 1997). However, ferric sulfate provided similar enhancement of settling of liquid dairy manure at the appropriate dose as shown in table 4–40.

The only calcium-based coagulant that provided effective enhancement of TS and TP removal from swine manure was CaO (table 4–36). Barrow et al. (1997) made similar observations for settling of dairy manure. It was determined that calcium sulfate (CaSO_4) was not an effective coagulant and that CaO applied at a dose of 293 milligrams Ca/L provided only a modest enhancement of settling. Part of the reason for the poor performance was the fact that pH was increased modestly from 8.25 to a maximum of 9.0, which was

less than required to form large quantities of the most common Ca precipitates (table 4–35). Sheffield et al. (2010) demonstrated that a hydrated lime milk solution could be used to reduce the total and soluble phosphorus concentrations in screened and un-screened milking center wastewater following 1-hour of settling. Key results and optimal lime milk dosages are given in table 4–38. A 5 percent lime solution was shown to be effective for improving the settling of P in the effluent from a sand-dairy manure separator (table 4–37). However, alum was more effective at P removal if similar settling times and dosage rates were compared. The dairy manure used in this study had a TS concentration of 2.85 percent, which was much higher than for most other studies. As a result, the amount of lime and alum needed to provide high removals of P were greater than for more dilute manure.

The comparison of coagulants provided by Kirk et al. (2003) in table 4–37 point out that some coagulants may not always be effective at high TS contents. In this case, adding 800 to 2,000 milligrams FeCl_3 /L to dairy manure provided little benefit, and increasing the dose to 4,000 to 8,000 mg FeCl_3 /L caused the flocs to float and not settle due to reactions that caused off-gassing of CO_2 (Kirk et al. 2003). Chastain et al. (2001a) observed a similar coagulant failure when 3,194 mg alum/L was added to flushed dairy manure with a TS content of about 3.8 percent. Instead of settling the solids floated. Using a two-stage treatment process that included screening flushed dairy manure with

Table 4–36 Comparison of the effectiveness of using three dose levels of various coagulants to enhance removal of total solids (TSR) and total phosphorus (TPR) from dilute swine manure (TS = 0.24%) from growing pigs by gravity settling (adapted from Powers and Flatow 2002)

Coagulant	----- Coagulant concentration -----					
	40 mg/L		250 mg/L		625 mg/L	
	TSR (%)	TPR (%)	TSR (%)	TPR (%)	TSR (%)	TPR (%)
Control ^{1/}	52.6	19.0	50.1	17.8	50.2	14.6
$\text{Al}_2(\text{SO}_4)_3$	53.6	21.0	86.5	73.9	92.8	90.9
FeCl_3	62.2	30.0	90.9	82.7	91.9	78.2
$\text{Fe}_2(\text{SO}_4)_3$	52.4	21.8	53.8	41.7	58.2	49.1
CaCO_3	52.4	15.0	57.9	17.6	71.1	21.2
CaO	54.7	26.7	78.1	55.4	92.3	66.7

1/ A separate control was used for each coagulant concentration

Table 4–37 Effect of addition of lime, alum, and ferric chloride on the reduction in phosphorus provided by settling of effluent from sand-manure separator on a dairy farm (adapted from Kirk, et al. 2003); the TS content of the separator effluent was 2.85% and the initial concentration of TP was 2,831 mg/L and the initial concentration of soluble P (Ortho-P) was 196 mg/L

Chemical	Dose	Concentration reduction (%)			
		1 hour settling		24 hour settling	
		Soluble-P	TP	Soluble-P	TP
Control		23	24	72	60
5% lime solution	mg lime/L				
	1,320	39	42	78	70
	2,640	41	39	82	67
	3,970	62	53	83	68
	5,290	78	63	84	74
	6,610	79	68	82	67
40% alum solution	mg alum/L				
	800	41	16	80	76
	2,000	73	38	89	85
	4,000	93	48	104*	90
	6,000	96	70	104*	88
	8,000	102*	82	108*	101*
40% FeCl ₃ solution	mg FeCl ₃ /L				
	800	43	33	79	56
	2,000	53	25	79	57
	4,000–8,000	Floating solids formed - No settling			

* Removal was 100%. Values greater than 100 are due to uncertainties in the measurements.

Table 4–38 Reduction in supernatant phosphorus concentrations following addition of hydrated lime milk solution to screened and unscreened milking center wastewater (adapted from Sheffield et al. 2010)

Type of dairy wastewater	Lime Milk Dose (% by Vol.)	Reduction in supernatant concentration as compared to control	
		TP (%)	Sol-P (%)
Hydrated lime milk solution = 1:9 (Ca(OH) ₂ to water solution (mass basis) was mixed into 1-L of manure for 2 seconds and then allowed to settle for 1 hour.			
Screened milking center wastewater, [TS] = 1% to 2%	4.14	83	99.7
Unscreened milking center water, [TS] = 0.5% to 2.0%	5.0	78	63
Screened milking center wastewater + manure from a flushed feed alley, [TS] = 4.0% to 4.5%	10	66	66

an inclined screen separator followed by mixing the effluent (TS = 1.2%) with 3,194 mg Alum/L and settling for 60 minutes provided a TP removal of 99.6 percent (Chastain et al. 2001a).

These data sets point out that in the majority of cases the best metal salts for treating animal manure are alum, ferric chloride, and ferric sulfate. However, these coagulants may not work in all cases. Dairy manure with high solids content may require removal of large solids to make settling with coagulants effective.

The vast majority of the available studies recommend the use of alum or ferric chloride (FeCl₃) as a coagulant for settling animal manure. Ferric sulfate is also suitable but requires a higher dose than FeCl₃. A dose of about 178 milligrams of Fe per liter as ferric sulfate was required to remove 79 percent of the TP from liquid dairy manure (table 4-40). However, only 139 milligrams of Fe per liter were needed to remove 81 percent of the TP from the same manure when ferric chloride was used. One gram of FeCl₃ contains 344.3 grams of Fe and one gram of Fe₂(SO₄)₃ contains 279.3 milligrams of Fe. As a result, removal of 80 percent of the total P would require 60 percent more ferric sulfate than ferric chloride (0.40 g FeCl₃/L versus 0.64 g Fe₂(SO₄)₃/L).

Effectiveness of sedimentation with metal salts on plant nutrient removal—Many evaluators of the effectiveness of metal salts for enhancing sedimentation of animal manure limited their observations

Table 4-39 Removal of suspended solids and phosphorus from finishing swine manure ([TS] = 1%) using various doses of aluminum sulfate and ferric chloride to enhance gravity settling (settling time = 4 hr, adapted from Ndegwa et al. 2001)

Coagulant dose (mg/L)	Aluminum sulfate		Ferric chloride	
	TSSR (%) ^{1/}	TPR (%) ^{2/}	TSSR (%)	TPR (%)
0	66	42	66	42
1,500	96	78	76	86
2,000	96	65	98	45

1/ TSSR = total suspended solids removal

2/ TPR = total phosphorus removal

to the removal of solids and phosphorus. Given the need to protect water quality by reducing phosphorus transport from farms to surface waters, such a narrow focus was timely and understandable. However, metal salt coagulants can also be an effective way of improv-

Table 4-40 Effect of adding ferric sulfate and ferric chloride on the removal of total solids and major plant nutrients from liquid dairy manure (TS = 1.0%) by Sedimentation (adapted from Barrow et al. 1997); results from laboratory settling for 20 minutes

Initial concentrations (mg/L) =	Dose	pH	TS	TKN	TP	TK	
			10,000	583	104	241	
Chemical		Mass removal efficiency (%)					
		mg Fe/L	TS	TKN	TP	TK	
Control		0	8.28	63.0	22.2	60.3	41.3
10.78% Fe, ferric sulfate ^{1/}							
		53.9	7.91	71.0	25.9	68.9	39.5
		107.8	7.55	77.5	36.9	72.6	47.4
		161.7	7.05	77.3	42.9	79.0	56.3
		215.6	6.71	83.5	46.8	84.0	57.4
12.46% Fe, ferric sulfate							
		62.3	7.90	71.2	29.1	69.9	41.0
		124.6	7.53	78.5	34.7	71.9	45.9
		186.9	7.07	78.8	44.0	79.0	56.4
		249.2	6.68	84.0	49.3	84.8	58.0
12.35% Fe, poly-ferric sulfate							
		61.8	7.90	72.2	29.3	69.8	41.4
		123.5	7.56	77.0	39.2	72.9	47.6
		185.3	7.08	79.5	46.4	79.6	58.2
		247.0	6.72	83.0	48.0	84.2	57.0
13.90% Fe, ferric chloride ^{2/}							
		69.5	7.82	70.8	31.1	78.1	53.8
		139.0	7.40	81.5	48.1	80.8	57.8
		208.5	6.89	85.5	49.5	83.8	58.6
		278.0	6.50	88.8	55.8	87.8	59.7

1/ Dose conversion: 279.3 mg Fe/g ferric sulfate.

2/ Dose conversion: 344.3 mg Fe/g ferric chloride.

ing the settling of other important plant nutrients. The enhancement of plant nutrient removal by adding alum, ferric chloride, and ferric sulfate to swine and dairy was included in several studies and the results are summarized in tables 4–39 through 4–46.

The data in the tables provide a summary of controlled laboratory studies (jar tests) and field studies. The laboratory studies were conducted in such a way that the removal of solids and plant nutrients was observed on a mass basis, allowing the calculation of mass removal efficiency (MRE) for each constituent measured. Under field conditions, the most common performance variable was the concentration reduction (CR). This distinction is important when comparing results between studies and making observations concerning the removal of soluble plant nutrients. The data for settling of swine manure with and without coagulation alum given in table 4–41 is useful for

pointing out these differences. The ammonical-N is soluble and its concentration was the same within measurement error before and after settling. Therefore, the concentration reduction would be zero. However, the MRE of TAN was calculated to be 0.02 percent for the control and 14 percent after coagulation with alum. The reason was that a portion of the TAN was removed in the solution contained in the settled solids. Such is the case with any soluble constituent that is not involved in the reaction with a metal salt coagulant.

The sedimentation results given in table 4–41 also can be used to observe that while Al reacts with the soluble P in the manure, the sweeping action of falling flocs and organic-P compounds will also remove suspended organic phosphorus and organic-N that would normally remain in suspension. A similar entrapment can also be observed in the enhanced removal of total suspended solids (TSS) and chemical

Table 4–41 Enhanced settling of nursery swine manure ([TS] = 0.18%) by using alum as a coagulant (adapted from Vanotti and Hunt 1999)

	Influent (mg/L)	After 60 min of settling		After coagulation with 1,430 mg alum/L followed by 60 min of settling	
		Supernatant (mg/L)	MRE ^{1/} (%)	Supernatant	MRE
TS	1,830	1,860	0.02 ^{2/}	1,630 ^{3/}	24
TSS	340	370	0.02 ^{2/}	140	65
COD	1,370	1,330	2.9	580	64
Total-P	60	46	23	6	91
Organic-P	44	31	30	5	90
Soluble-P	16	15	6.3	1	95
TKN ^{4/}	374	363	3.0	343	21
Organic-N	88	67	24	37	64
TAN ^{5/}	286 ^{2/}	296 ^{2/}	0.02 ^{6/}	306 ^{2/}	14.0 ^{6/}
pH	8.1	8.3	—	7.1	
Settled solids volume	—	0.2 mL/L	—	139.6 mL/L	

1/ $MRE = 100 \times ([C\text{-Influent}] \times 1\text{ L} - [C\text{-Supernatant}] \times \text{Settles Solids Volume}) / [C\text{-Influent}] \times 1\text{ L}$

2/ Concentration of TAN not significantly affected by sedimentation.

3/ [TS] of supernatant was estimated as [TSS] + [Dissolved TS]

4/ $TKN = TAN + \text{Organic-N}$

5/ $TAN = (NH_4\text{-N} + NH_3\text{-N})$

6/ $\text{Mass removal efficiency} = 100 (1L - (1\text{-Settled Solids Volume, L})/1L)$

oxygen demand (COD). Use of an effective coagulant will enhance removal of small suspended particles, organic plant nutrients and can be used to reduce the organic load for subsequent biological treatment process. While the results in table 4–41 are for alum, the observations are also valid for iron- and calcium-based coagulants.

The mass removal efficiency data provided in tables 4–40 through 4–43 also indicated that increasing the dose of a coagulant salt will enhance the removal of not only P, but also significant amounts of N, K and key minor plant nutrients. When alum or ferric salts were added to liquid dairy manure in a sufficient dose to remove 80 percent or more of the mass of TP, then 40 percent or more of the total nitrogen and total potassium was also removed by sedimentation. Furthermore,

entrapment by falling particles and flocs also enhanced the removal of Ca, Mg, Mn, Zn, and Cu (tables 4–42 and 4–43). When alum was used as the coagulant, settling of iron was also enhanced (table 4–43). However, concentrations of the metal ion used in the salt was increased in the supernatant. The increase in soluble Fe was indicated by the negative mass removal efficiency in table 4–42.

Field data have shown that alum can be effectively used to enhance sedimentation of liquid dairy and swine manure in practical applications. The results from field studies of batch and continuous flow settling tanks at the University of Florida Research Dairy Farm are provided in tables 4–44 and 4–45 using low and moderate doses of alum. A flow-through, drain-dry, settling basin was used to treat manure that flowed

Table 4–42 Effect of adding ferric chloride on the removal of total solids, major plant nutrients, and key minor plant nutrients from liquid dairy manure by sedimentation (adapted from Sherman et al. 2000); results from laboratory settling for 20 minutes

(a) Removal of solids and major plant nutrients

				TS	TKN	TP	TK
Initial concentrations (mg/L) =				10760	584	143	270
FeCl ₃ dose				-----Mass removal efficiency (%) -----			
mL FeCl ₃ /L	mg Fe/L ^{1/}	SVF ^{2/}	pH	TS	TKN	TP	TK
0	0	0.165	8.18	28.2	16.6	62.9	23.7
1.05	188	0.400	7.58	8.5	42.8	81.9	43.7
2.10	376	0.471	7.06	2.9	53.1	88.8	52.6

1/ Dose conversion: 344.3 mg Fe/g FeCl₃

2/ SVF = Settled solids volume fraction = Volume of settled solids/influent volume.

(b) Removal of key minor plant nutrients

		Ca	Mg	Zn	Cu	Mn	Fe
Initial concentrations (mg/L) =		286	92	2.6	0.47	1.98	7.61
FeCl ₃ dose		-----Mass removal efficiency (%) -----					
mL FeCl ₃ /L	mg Fe/L ^{1/}	Ca	Mg	Zn	Cu	Mn	Fe
0	0	44.1	63.0	22.7	19.1	48.5	59.1
1.05	188	68.5	66.3	66.2	61.7	72.7	-3.8
2.10	376	74.1	57.6	80.4	72.3	72.2	-24.0

1/ Dose conversion: 344.3 mg Fe/g FeCl₃

from a swine finishing barn at the University of Georgia research farm. Concentration reductions with and without injection and mixing of 2,900 mg alum/L are given in table 4–46. Both of these field studies were limited to the use of the concentration reduction as the measure of basin performance and as a result the concentration reductions of most of the soluble constituents were either small or not significantly different from zero.

Effect of sedimentation with alum and ferric chloride on volume of settled solids—Gravity settling of liquid dairy and swine manure with a TS concentration of 2 percent or less yields a settled volume fraction in the range of 10 percent to 25 percent of the influent volume (figs. 4–33 and 4–34). One of the consequences of using a metal salt to enhance solid and nutrient removal is the substantial increase in the volume of settled material that must be handled and managed separately from the liquid fraction. Adding 546 mil-

Table 4–43 Effect of adding aluminum sulfate on the removal of total solids, major plant nutrients, and key minor plant nutrients from liquid dairy manure by sedimentation (adapted from Sherman et al. 2000); results from laboratory settling for 20 minutes

(a) Removal of solids and major plant nutrients from liquid dairy manure

				TS	TKN	TP	TK
Initial concentrations (mg/L) =				10,760	584	143	270
Alum dose		-----Mass removal efficiency (%) -----					
mL Alum/L	mg Al/L ^{1/}	SVF ^{2/}	pH	TS	TKN	TP	TK
0	0	0.165	8.18	28.2	16.6	62.9	23.7
0.45	26	0.182	7.97	24.0	19.2	68.5	25.6
0.90	53	0.232	7.78	19.7	26.9	72.4	29.6
1.35	79	0.266	7.61	17.2	32.7	73.1	33.0
1.80	106	0.318	7.42	10.8	36.5	76.8	36.3
2.70	159	0.387	7.11	4.6	45.9	82.5	43.0
5.40	317	0.540	6.41	-13.4	63.2	96.9	56.7

1/ Dose conversion: 157.7 mg Al/g Alum

2/ SVF = Settled solids volume fraction = Volume of settled solids / influent volume

(b) Removal of key minor plant nutrients from liquid dairy manure

		Ca	Mg	Zn	Cu	Mn	Fe
Initial concentrations (mg/L) =		286	92	2.6	0.47	1.98	7.61
Alum dose		----- Mass removal efficiency (%) -----					
mL Alum/L	mg Al/L ^{1/}	Ca	Mg	Zn	Cu	Mn	Fe
0	0	44.1	63.0	22.7	19.1	48.5	59.1
0.45	26	46.9	67.4	26.9	19.1	53.5	68.3
0.90	53	54.2	65.2	45.0	36.2	59.6	74.8
1.35	79	59.4	60.9	53.5	31.9	66.2	76.5
1.80	106	63.3	58.7	64.2	59.6	71.2	86.9
2.70	159	70.3	55.4	81.9	72.3	76.3	90.9
5.40	317	76.6	60.9	98.8	80.9	72.2	93.0

1/ Dose conversion: 157.7 mg Al/g Alum

ligrams FeCl₃/L of dairy manure (TS = 1.0%, table 4–42a) was observed to improve the phosphorus removal from 62.9 to 81.9 percent while increasing the settled volume fraction from 16.5 to 40 percent of the influent volume. Therefore, use of FeCl₃ increased the phosphorus removal by 30 percent while increasing the volume of settled solids by 142 percent. Using alum instead of ferric chloride as the coagulant provided about the same results (table 4–43). To provide a TP removal of 82.5 percent required a dose of 1008 mg alum/L. A 31 percent increase in TP removal resulted in a 135 percent increase in the settled solids that must be managed separately from the liquids. Such large increases in settled solids that must be handled as a slurry or semisolid tend to increase infrastructure and labor costs on dairy and swine farms while eliminating or diminishing the fertilizer value of liquid manure. The practical problems and costs created by the large volume of settled solids is one of the deterrents to the use of metal salt coagulants for phosphorus treatment on many commercial dairy and swine farms.

Selection of dose—Selection of the dose of metal salt (alum, ferric chloride or other salt) to implement for a particular case depends on many factors. Some of the most important practical considerations are the

amount of phosphorus that needs to be removed to meet farm nutrient management goals, the lost value of the precipitated phosphate compounds (AlPO₄ or FePO₄), chemical costs, and costs to manage the increased volume of settled solids. To complicate matters further, the response to increasing the dose of a coagulant is not linear. Instead, there exists a diminishing TP removal benefit as the dose is increased. This nonlinear response can be seen in the laboratory test data provided previously in the tables. However, the clearest presentation of this concept was provided by Zhu et al. (2004) using a two-stage settling experiment. Zhu allowed flushed swine manure (TS = 16,820 mg/L) to settle for 24 hours. This yielded a supernatant that contained only suspended and dissolved phosphorus. The second settling step involved the addition of alum at doses that ranged from 0 to 2,900 milligrams of alum per liter. Since all of the settleable P was removed prior to addition of alum the TP removal for Zhu’s second stage ranged from 0 percent with no alum addition to about 93 percent after adding 2,900 milligram alum per liter. Using an alum dose of 400 milligrams per liter provided a TP removal of 20 percent and 0.206 milligrams P was removed per milligram of alum. Increasing the alum dose 1,600 milligrams per liter removed

Table 4–44 On-farm batch settling of flushed dairy manure following primary sedimentation and screening with and without injection of alum (adapted from Sherman et al., 2000); settling time = 24 hours

Treatment		pH	TKN	TP	TK	Ca	Mg	Zn	Cu	Mn	Na
		----- (mg/L) -----									
Control											
	Influent	7.06	187	47.5	187	214	63.4	0.88	0.16	0.4	68
	Effluent	7.01	190	46.6	186	197	64.0	0.94	0.34	0.33	67
	Concentration reduction, %		-1.6	1.9	0.5	7.9	-0.9	-6.8	-112.5	17.5	1.5
0.9 mL/L Alum (53 mg Al/L)^{1/}											
	Influent	7.07	218	49	209	212	61.8	1.07	0.28	0.41	88
	Effluent	6.77	182	16.9	205	187	62.7	0.61	0.30	0.57	81
	Concentration reduction, %		16.5	65.5	1.9	11.8	-1.5	43.0	-7.1	-39.0	8.0
1.8 mL/L Alum (106 mg Al/L)											
	Influent	7.15	193	47	187	211	64.0	1.31	0.24	0.44	70
	Effluent	6.66	148	9.7	176	185	56.6	0.34	0.16	0.26	81
	Concentration reduction, %		23.3	79.4	5.9	12.3	11.6	74.0	33.3	40.9	-15.7

1/ Dose conversion: 157.7 mg Al/g Alum

70 percent of the total P and only 0.15 milligrams of P was settled per milligram of alum added. That is, increasing TP removal by a factor of 3.5 required 300 percent more alum that was 27 percent less efficient based on the mass of P removed relative to the mass of coagulant added. While these data are for alum a similar decrease in chemical use efficiency has been observed for most metal salt coagulants.

Zhang and Lei (1998) determined optimal doses of ferric chloride using a different approach. Instead of evaluating the dose based on TP removal they determined the dose of FeCl₃ that provided the best hindered settling velocities for swine and dairy manure at different TS concentrations. Their recommended doses and hindered settling velocities are provided in table 4–47. Their results indicated that dairy manure required a higher dose of FeCl₃ than swine manure and settled more slowly than swine manure.

Enhanced settling of liquid dairy manure with metal salts is best applied following mechanical solid-liquid separation and/or sedimentation to reduce the amount of coagulant needed and to reduce the chance of causing solids to float instead of settle (Chastain et al. 2001; Sherman et al. 2000). Using a TP removal of about 70 percent as a target, the recommended beginning points for selecting a coagulant dose for dilute dairy manure (TS of about 1%) are 340 milligrams of alum per liter, 200 milligrams FeCl₃ per liter, and 425 milligram Fe₂(SO₄)₃ per liter. Optimal values will need to be determined for each farm based on testing with the chemical and manure to be used (jar test or on-farm evaluation). If high P removals are desired, or the P levels in the manure are high, larger dose of coagulants may be needed (e.g., 800 to 1,000 mg alum/L).

The amount of published information on dose response of coagulants is much lower for swine manure as compared to dairy manure. On-farm data provided by Worley and Das (2000) indicated that 2,900 milligrams of alum per liter were needed to provide 70 percent reduction in the effluent concentration for

Table 4–45 On-farm continuous flow settling of flushed dairy manure following primary sedimentation and screening with and without injection of alum (adapted from Sherman et al. 2000); flow through tank, Q= 23 L/min (6 gpm) and detention time, DT = 91.3 minutes

Treatment		pH	TKN	TP	TK	Ca	Mg	Zn	Cu	Mn	Na
		----- (mg/L) -----									
Control	Influent	7.25	148	30	170	185	50.8	1.40	0.71	0.30	65
	Effluent	7.28	142	28.1	167	181	48.5	0.72	0.28	0.29	64
	Concentration reduction, %		4.1	6.3	1.8	2.2	4.5	48.6	60.6	3.3	1.5
0.9 mL/L Alum (53 mg Al/L)^{1/}	Influent	7.28	127	34.8	157	201	53.2	0.82	0.80	0.40	62
	Effluent	6.70	101	4.9	154	169	50.4	0.38	0.19	0.24	63
	Concentration reduction, %		20.5	85.9	1.9	15.9	5.3	53.7	76.3	40.0	-1.6
1.8 mL/L Alum (106 mg Al/L)	Influent	7.04	152	38.3	163	212	57.3	0.95	0.20	0.45	66
	Effluent	6.43	107	2.9	162	176	54.8	0.03	0.15	0.34	66
	Concentration reduction, %		29.6	92.4	0.6	17.0	4.4	96.8	25.0	24.4	0.0

1/ Dose conversion: 344.3 mg Al/g Alum

settling raw manure from a swine finishing barn (TS = 1.52%). Ferric chloride doses for treating swine manure based on optimum settling would be expected to give high rates of TP removal and 500 milligrams FeCl₃/L is a recommended beginning dose for on-farm applications. Optimal values would need to be determined for any coagulant based on field evaluation or a jar test (appendix D).

Use of metal salt coagulants with mechanical solid-liquid separators—Since coagulants greatly increase the volume of settled solids it would be desirable to use mechanical separators to dewater the solids and reduce their volume. The precipitates and flocs formed by the addition of alum and FeCl₃ are not easily removed by screening. Zhang and Lei (1998) coagu-

lated and flocculated liquid swine and dairy manure with various doses of ferric chloride and attempted to remove the solids using a screen with 0.8 millimeter openings (20 mesh). The flocs and organic particulates were too small to be captured by the screen. Oh et al. (2005) attempted to enhance solids and phosphorus removal from dairy manure using a screw press by injecting and mixing alum before the separator. The 0.38 millimeter openings in the wedge wire screen could not remove the solids because the flocculate formed was too fragile to withstand the pressures within the screw press. They broke apart and passed through the screen. Mixing metal salt coagulants with polymer flocculants to form large flocs is required if metal salts are to be used with most types of mechanical solid-liquid separators.

Table 4–46 Primary treatment of finishing swine manure (TS = 1.52%) using a gravity settling pond with and without alum (adapted from an on-farm study by Worley and Das 2000)

	Control CR (%)	2900 mg Alum/L CR (%)
TS	60	70
TP	38	75
TKN ^{1/}	20	20
TK ^{1/}	8	8

1/ No improvement provided by the addition of alum

Table 4–47 Variation in optimal dose of ferric chloride with respect to influent TS concentration to enhance settling of swine and dairy manure (adapted from Zhang and Lei 1998)

----- Swine manure -----			----- Dairy manure -----		
Influent TS (%)	Optimal dose mg FeCl ₃ /L	Linear hindered settling velocity cm/hr	Influent TS (%)	Optimal dose mg FeCl ₃ /L	Linear hindered settling velocity cm/hr
0.5	100	222	0.4	250	300
1.0	250	90	0.8	750	162
1.5	500	48	1.2	1,000	102
2.0	750	24	1.6	1,000	54

The type of mechanical separator that may be used with coagulants is a centrifuge, since it increases the force on the particles by providing acceleration that is many times that of gravity. Researchers at North Carolina State University concluded that a centrifuge could be used to treat flushed swine manure and swine lagoon sludge (Westerman and Ogejo 2005). However, addition of lime as a coagulant did not substantially improve the performance (table 4–48). It is speculated that the lime dose was insufficient to raise the pH high enough to form the desired organic particles.

(3) Polymer flocculants

A polymer is a large molecule composed of one or more repeating groups of atoms called structural units. The most common type of polymer used in the food industry and for wastewater treatment are the polyacrylamides (PAM). PAM are water-soluble organic polymers that vary in molecular weight, charge type

(positive, negative, or neutral), charge density (0 to 100%), chain structure (branched or linear), and comonomer (Vanotti et al. 2002). This large variety of properties yields a wide range of performance characteristics and applications for this class of polymers. PAM have been used to enhance separation and thickening processes in the food industry, remove solids from municipal wastewater, remove particles from drinking water, enhance screening and settling of manure, and as a soil conditioner to reduce erosion (Barvenik 1994; Vanotti and Hunt 1999; Chastain et al. 2001a). Studies have shown that the types of PAM that have performed best for primary treatment of animal manure are those with a moderate cationic (+) charge density (20 to 35 mole percent), linear long-chain structure, with a high molecular weight (Vanotti and Hunt 1999; Rodriguez et al. 2005; Hjorth et al. 2010).

Table 4–48 Centrifuge treatment (5,000 rpm, 40 to 60 L/min feed rate) of flushed swine manure and lagoon sludge mixture with and without addition of lime (adapted from Westerman and Ogejo 2005)

Constituent	----- Flushed manure -----			----- Lagoon sludge mixture -----		
	Influent mg/L	Control MRE (%)	2.94 g lime/L MRE (%)	Influent mg/L	Control MRE (%)	6.18 g lime/L MRE (%)
TS	14,900	38	51	15,600	32	47
VS	9,900	44	52	8,000	25	44
TSS	12,700	47	63	14,300	41	55
TKN	1,289	21	17	1,384	26	21
TAN	728	17	4	598	33	23
Total P	394	61	69	620	63	63
Ortho-P	207	55	46	424	71	74
K	1,001	14	6	824	11	15
Na	264	14	8	217	10	15
Ca	532	34	74	755	11	30
Mg	155	69	78	200	68	61
Cu	1.6	23	24	6.2	17	23
Zn	11.7	23	32	26.8	14	24
COD	14,929	31	35	13,773	21	41

Cationic PAM polymers form large flocs by destabilizing suspended negatively charged particles in liquid manure. They form flocs by adsorbing colloids and other tiny particles and by building web-like bridges between many particles. The large floc behaves as a single particle that settles rapidly and can be removed by a screen. When used to enhance sedimentation the large flocs remove other suspended solids by entrapment. If PAM is used with a screen-type mechanical separator suspended particles that are not part of the flocs are also entrained by the screened solids and flocs.

The extreme impact of the charge of a flocculant is demonstrated for dilute swine manure in table 4–49. All three of the PAMs used in the study were applied at a rate of 10 mg/L and they all had similar structure and molecular weight. Use of a neutral or negatively charged PAM caused a slight increase in the suspended solids (TSS) observed in the supernatant following 1 hour of settling and no improvements in

Table 4–49 Enhancement of nursery swine manure (TS = 0.18%) settling by using cationic, neutral, and anionic charged polyacrylamide (PAM) polymers (adapted from Vanotti and Hunt 1999); polymer dose was 10 mg PAM /L for all three chemicals

	Influent (mg/L)	20% charge density			
		Control MRE ^{1/} (%)	Cationic PAM MRE (%)	Neutral PAM MRE (%)	Anionic PAM MRE (%)
TS	1,830	0.02 ^{2/}	7.0	-2.2	-1.6
TSS	340	0.02 ^{3/}	33.0	-11.7	-8.8
COD	1,370	2.9	38.6	8.1	8.8
Total-P	60	23	58.8	20.0	23.3
Organic-P	44	30	77.5	22.8	27.3
Soluble-P	16	6.3	1.02	0.03	0.02
TKN ^{3/}	374	3.0	16.4	-0.5	5.6
Organic-N	88	24	82.0	15.9	31.8
TAN ^{4/}	286 ^{2/}	0.02 ^{6/}	1.02	0.03	0.02
pH	8.1	8.3	8.2	8.4	8.3
Settled solids volume	--	0.2 mL/L	10.2 mL/L	0.3 mL/L	0.2 mL/L

1/ Mass removal efficiency = $100 \times ((C-\text{Influent}) \times 1 \text{ L} - [C-\text{Supernatant}] \cdot \text{settles solids volume}) / [C-\text{Influent}] \times 1 \text{ L}$

2/ TS of supernatant was estimated as [TSS] + [Dissolved TS]

3/ Concentration of TAN not significantly affected by sedimentation.

4/ TKN = TAN + Organic-N

5/ TAN = (NH₄-N + NH₃-N)

6/ Mass removal efficiency = $100 (1L - (1-\text{Settled Solids Volume, L})/1L)$

settling of plant nutrients as compared to the control. However, using a cationic PAM with a positive 20-percent charge density resulted in a significant removal of solids and organic plant nutrients.

The experimental results provided in table 4–49 can also be used to observe some advantages and disadvantages of using PAM to enhance solid-liquid separation as compared to alum or ferric chloride. Using PAM did not result in a large drop in pH as observed for alum or ferric chloride (tables 4–43 and 4–42a). Large drops in pH can hinder downstream biological treatment processes and may require pH adjustment. The majority of the phosphorus that was removed following flocculation with PAM was in the organic form and no organic phosphate precipitates were formed. Therefore, the fertilizer value of the phosphorus in the settled solids was preserved. Use of PAM instead of alum or ferric chloride had the advantage of not yielding an increase in soluble Al or Fe (fig. 4–44 and table

42a) in the supernatant that could hinder downstream biological treatment or promote unwanted reactions with P in the manure storage structure or in soil. Since no phosphate precipitates were formed the volume of settled solids per liter of influent was much lower for PAM treated swine manure as compared to alum treated manure (table 4–41). A practical advantage of using PAM over a metal salt is that generally smaller doses of PAM are needed when compared to alum or FeCl₃. Effective doses for Al and Fe salts have been shown to be in the range of 100 to 4,000 milligrams per liter whereas PAM doses in the range of 10 to 350 milligrams per liter have been shown to be optimal depending on animal species and solids content (table 4–50). The practical benefit of using a lower mass of chemical is that material handling and mixing costs are lower for PAM as compared to metal salts. An often-noted disadvantage of using PAM instead of alum or FeCl₃ is the higher cost per unit mass of chemical (Zhang and Lei 1998; Oh et al. 2005; and Hjorth, et

Table 4–50 Removal of solids, COD, and plant nutrients from flushed dairy manure by settling for 60 minutes with and without addition of PAM (Chastain et al. 2001a); optimum dose was about 300 milligrams PAM per liter

Constituent	Flushed manure mg/L	Amount of PAM added ^{1/} mg/L				
		0	250	300	350	400
		Concentration reduction (%) ^{2/}				
TS	41,763	60.8	72.9	76.1	78.0	80.1
TSS	32,955	71.5	89.9	92.6	96.2	98.0
VS	34,957	63.8	78.1	80.3	83.1	84.7
VSS	30,113	74.1	90.7	93.2	96.5	98.3
COD	66,416	63.6	79.3	80.8	84.5	86.5
TKN	1,464	24.0	43.8	45.7	50.9	53.6
Organic-N	923	43.3	70.3	72.3	81.1	84.4
P ₂ O ₅	1,061	37.7	58.6	61.8	64.9	66.8
K ₂ O	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

1/ Food grade cationic polyacrylamide polymer with 20 percent charge density.

2/ Concentration reduction based on concentration of manure removed from the freestall barn.

al. 2010). Another disadvantage is that PAM has been shown to be more efficient at solids and plant nutrient removal at TS concentrations in the range of 1.5 to 2.6 percent as compared to 0.5 percent TS (Vanotti et al. 2002). Another small disadvantage of using PAM over alum or FeCl_3 is that the pH of the manure is not lowered during the process. Reduction of manure pH to below 8.0 reduces the potential for ammonia loss to the air by volatilization as shown previously in figure 4–44. If a chemical treatment lowers the pH from 8.0 to 7.0 ammonia loss is small, and at a pH of 6.5 or less ammonia loss falls to zero.

Flocculation and settling of liquid manure can be an effective way to improve the overall performance of a flushed manure treatment system on a dairy farm. A case study was carried out on a dairy farm that used an incline screen separator followed by a settling basin (Chastain et al. 2001a). Flushed manure samples were collected from the farm and settling experiments were conducted to determine the impact of PAM dose on settling of raw flushed manure. Polymer doses in the range of 250 to 400 milligrams of PAM per liter were mixed into 1 liter samples and were allowed to settle for 1 hour. The concentration reductions observed for settling of unscreened dairy manure were calculated and are shown in table 4–50.

The solids content of the manure flushed from this freestall barn had a TS content of about 4.1 percent, which was higher than expected for a flushed dairy facility. The high solids content was due to the large amounts of pine shavings used to bed the freestalls. Even at this high solids content, gravity settling was able to reduce the supernatant concentrations of solids and plant nutrients significantly as indicated by a 60.8 percent reduction in TS and a 37.7 percent reduction in P_2O_5 . The lowest effective PAM dose was 250 milligrams per liter and provided an 89.9 percent concentration reduction for the total suspended solids (TSS) and a 58.6 percent reduction in total-P. At the highest PAM dose (400 mg/L) 98 percent of the TSS and 66.7 percent of the total-P was removed by settling. Improvement in P removal with an increase in PAM dose tended to decrease significantly once about 60 percent reduction in P_2O_5 was attained. As a result, the optimum PAM dose for untreated flushed dairy manure was about 300 milligrams of PAM per liter if 60 percent total-P removal was used as the criterion. This dose also provided a TSS reduction of 92.6 percent.

Samples were also collected on-farm from the effluent of the 1.5-millimeter incline screen separator. The same settling experiment was performed as for the unscreened manure and the same doses of PAM were used. Therefore, this experiment was designed to provide information concerning the benefits of using a two-stage separation process. The first stage was mechanical separation using an inclined screen, and the second stage consisted of gravity settling with and without flocculation with PAM. Key results for this experiment are provided in table 4–51.

It was determined that if the treatment goal was to remove 60 percent of the total-P, then gravity settling of the separator effluent without addition of PAM was sufficient and provided a reduction in P_2O_5 concentration of 69.9 percent. Furthermore, the combination of screening followed by flocculation and settling was more effective than flocculation with PAM and settling prior to screening (table 4–50). It was determined that using a PAM dose of 250 mg/L prior to settling would remove more total-P (82%) and about the same removal of suspended solids (92.8%) as flocculating unscreened manure with a dose of 300 milligrams of PAM per liter. The amount of VS removed (VSR) by the two-stage system was also higher than settling with 300 milligrams of PAM per liter (85% VSR vs. 80% VSR). Therefore, the combination of mechanical separation followed by flocculation and settling with PAM can provide high levels of primary treatment for high-solids animal manure. Such high removals of solids would greatly reduce the amount of organic load on a downstream biological treatment process and would reduce sludge buildup in a treatment lagoon.

Enhancing the settling of manure by flocculation with PAM will concentrate the majority of degradable organic matter (VS or COD) in a volume that is smaller than the daily flow from animal facilities. Recent research has shown that flocculation with PAM does not decrease the biodegradability of the manure and provides a substantial increase in methane production per unit volume fed to a digester (Gonzalez-Fernandez et al. 2008).

One of the most widely investigated uses of PAM is to enhance primary treatment of swine manure using screen type separators to remove a larger portion of the plant nutrient rich fine particles. Zhang and Westerman (1997) observed that particles smaller than 0.25 millimeter must be removed to substantially

reduce the plant nutrients and odor-generating compounds from manure. However, using fine screens with swine manure typically yielded a solid fraction that had the consistency of thick slurry. Furthermore, separator throughput rates (gal/h) are greatly reduced and screens tend to clog when using small screen sizes. Flocculation of swine manure with PAM prior to screening has been shown to greatly enhance the removal of solids and plant nutrients from liquid swine manure while generated a solids fraction that dewater to the consistency of a semisolid to stackable solid.

Polyacrylamides have been used to enhance the performance a large variety of mechanical separators, including incline screens, rotary screens, screw presses, and filter presses (Hjorth et al. 2010). Screen sizes tested have ranged from 0.25 to 3.0 millimeters. The best results were obtained with screen sizes in the range of 0.25 to 1.0 millimeters. Many brands of PAM have been used successfully and the optimal dose for a particular situation must be determined by laboratory or field testing. However, detailed results for cationic

PAMs with three charge densities (20, 30, and 35%) and two screen sizes (0.25 and 1.0 mm), and TS concentrations common on flush and pit-recharge swine farms (TS = 0.5 to 2.6%) are provided in tables 4–52 through 4–56. The data summaries provided demonstrate that high removal of TSS and TP can be obtained for liquid swine manure using screens in the range of 0.25 to 1.0 millimeter. A screen with 1 millimeter openings is often preferred to allow for drier solids and a higher throughput rates. Unfortunately, detailed throughput rate data for mechanical separators treating flocculated manure is lacking.

All of the data provided in these tables can assist in the establishment of a PAM dose and the magnitude of the expected reduction in concentration in the liquid fraction. The information provided by Vanotti et al. (2002) and summarized in tables 4–55 and 4–56 provide the

Table 4–51 Removal of solids, COD, and plant nutrients from flushed dairy manure by an inclined stationary screen separator (1.5 mm) followed by settling for 60 minutes with and without application of PAM (Chastain et al. 2001a); optimum dose was about 250 mg PAM/L

Constituent	Flushed manure mg/L	After separator mg/L	Amount of PAM added ^{1/} mg/L				
			0	250	300	350	400
			----- Concentration reduction (%) ^{2/} -----				
TS	41,763	11,962	76.5	89.7	92.4	92.8	93.7
TSS	32,955	7,468	77.8	92.8	97.1	97.7	98.8
VS	34,957	9,626	75.5	84.8	88.1	88.4	89.2
VSS	30,113	6,255	82.7	93.5	97.3	97.7	98.7
COD	66,416	12,789	86.8	91.7	93.5	95.2	96.1
TKN	1,464	643	54.9	67.1	71.1	73.1	74.5
Organic-N	923	390	58.2	74.6	84.1	84.1	89.0
P ₂ O ₅	1061	370	69.9	82.1	86.0	87.9	88.9
K ₂ O	958	526	49.9	52.3	50.5	52.6	52.5
Zn	15	7	53.3	86.0	92.0	95.1	98.2
Cu	6	8	0.0	45.6	74.4	83.3	95.6

1/ Food grade cationic polyacrylamide polymer with 20% charge density

2/ Concentration reduction based on concentration of manure removed from the freestall barn

most detailed practical information on selection of a PAM dose available in the literature. They showed that PAM can be more effectively and efficiently used for swine manure with a TS content in the range of 1.0 percent to 2.6 percent. Information was also provided by these researchers on the amount of PAM used per ton of separated dry matter. Several useful correlations from the work of Vanott et al. (2002) are suitable for use in system design spreadsheets and are provided in table 4–56. A similar level of detail for using PAM to enhance screening of dairy manure is not currently available.

Polyacrylamides do not react with soluble phosphorus, and, as a result, the only soluble-P that is removed with the water is contained in the separated solids. Using a two-step chemical treatment that involves coagulation with alum or FeCl₃ followed by flocculation with PAM prior to mechanical separation has been used to remove soluble-P and to reduce the PAM application rate. In general, alum or ferric chloride cannot be used with a screen or press unless combined with PAM so that the precipitates and tiny flocs formed during coagulation can be trapped by the large flocs formed during flocculation. Summaries from two studies that combine a metal salt and PAM prior to mechanical separation are provided in tables 4–57 and 4–58.

Oh et al. (2005) demonstrated that alum and PAM could be used to increase the performance of a screw press used to treat dairy slurry (table 4–57). The dry matter capture efficiency (mass of TS removed) was increased from 66 to 82 percent by these two chemicals. The chemically enhanced separation system also reduced the concentration of TP by 82 percent and soluble-P by 96 percent. The system would also greatly reduce the amount of organic matter in the waste stream as indicated by a removal of 71 percent of the COD.

The enhanced treatment benefits of using ferric chloride and PAM on the treatment of flushed dairy manure prior to screening is provided in table 4–58. Zhang and Lei (1998) demonstrated that a relatively small dose of FeCl₃ followed by a small dose of PAM could greatly improve solids and plant nutrient remov-

Table 4–52 Removal of solids, N, P and COD, from flushed swine manure by flocculation with a cationic polymer with a 20% charge density followed by screening (1 mm openings, adapted from Vanotti and Hunt 1999); optimal PAM dose was about 100 mg PAM/L based on TSS reduction

Constituent	Initial concentration mg/L	Amount of PAM added ^{1/} , mg/L					
		0	10	25	50	100	200
----- Concentration reduction (%) -----							
TS	6,500	8.5	13	22	42	58	61
TSS	4,120	13	21	36	66	92	96
VSS	3,360	13	21	38	66	92	96
COD	10,950	7	10	29	52	69	74
TKN	505	5.0	11	18	27	37	38
Organic-N	234	11	24	39	58	80	83
TP	189	11	15	26	39	54	57
Org-P	122	17	24	40	60	83	89

1/ Food grade cationic polyacrylamide polymer with 20 percent charge density

al by a 0.8 millimeter screen. The optimal dose of FeCl₃ was 400 milligrams per liter followed by addition of 0.2 milliliters of alum solution per liter. This combination removed 95 percent of the TP, 67 percent of the TS, and 74 percent of the VS. Zhang and Lei (1998) used dairy manure diluted with tap water, and many of the suspended solids and plant nutrients common in dairy manure flushed from freestalls with recycled lagoon water were not present in their samples. It is likely that larger doses of both chemicals may be needed in many practical cases.

Westerman and Ogejo (2005) evaluated the performance of a centrifuge for treatment of flushed swine manure and mixed lagoon sludge and supernatant. They evaluated the performance of the machine fol-

lowing addition of a synthetic coagulant polymer (C) combined with a polymer flocculant (F) and the combination of the coagulant, flocculant, and lime (C+F+L). The description of chemicals that are used and the performance of the centrifuge following these two chemical treatments are compared with the control in table 4–59. While use of the polymers alone (C+F) improved the removal of TSS and TP, the combination of the polymers with a lime solution that was 71.5 percent CaO provided the highest removal of solids and phosphorus.

Recent work has shown that a natural polymer called chitosan is effective at improving the treatment of flushed dairy manure. Chitosan is a natural and biodegradable polycationic polymer that is a form of chitin

Table 4–53 Removal of solids, COD, and nitrogen liquid swine manure by a 0.25 mm screen following flocculation with a cationic PAM with 30% charge density (adapted from Gonzalez-Fernandez et al. 2008); optimal PAM dose was about 80 mg/L

	Influent concentration	Polymer dose, mg PAM/L				
		0 CR (%)	80 CR (%)	120 CR (%)	160 CR (%)	200 CR (%)
Feeder-to-finish						
TS (g/L)	25.9	51.4	61.4	69.9	62.5	69.5
VS (g/L)	18.7	58.3	69.5	71.7	71.1	79.1
TSS (g/L)	18	59.4	74.4	79.4	80.0	85.6
VSS (g/L)	15.3	56.9	72.5	77.8	78.4	84.3
TCOD (g/L)	50.4	43.5	55.4	58.1	61.9	65.7
SCOD (g/L)	23.3	33.0	36.9	36.9	32.6	39.5
TKN (mg/L)	3165	10.0	21.0	21.0	24.2	27.3
Sol-P (mg/L)	614	8.5	28.2	27.4	33.4	38.3
pH	7.3	7.4				
Feeder-to-finish + nursery pigs						
TS (g/L)	9.3	48.4	66.7	69.9	71.0	73.1
VS (g/L)	6.8	57.4	77.9	82.4	83.8	88.2
TSS (g/L)	7.7	62.3	85.7	89.6	92.2	98.7
VSS (g/L)	6.6	60.6	84.8	90.9	95.5	98.5
TCOD (g/L)	16.8	42.9	63.1	69.0	70.8	71.4
SCOD (g/L)	5.7	3.5	8.8	14.0	14.0	14.0
TKN (mg/L)	1,005	15.1	30.3	30.3	40.3	40.3
Sol-P (mg/L)	183	1.1	20.8	24.0	30.1	33.9
pH	6.9	7.0				

Table 4–54 Removal of solids, N, P, COD, and BOD from pit-recharge swine manure by flocculation with a cationic polymer with a 35% charge density followed by screening (1 mm openings, adapted from Vanotti et al. 2002); optimal PAM dose was about 110 mg PAM/L

Constituent	Initial concentration mg/L	Amount of PAM added, ^{1/} mg/L							
		0	20	40	60	80	100	120	140
		----- Concentration reduction (%) -----							
TS	10,890	9	17	28	39	46	51	54	55
TSS	6,290	15	29	48	68	79	89	93	95
VSS	5,070	17	31	54	69	79	88	93	95
COD	12,560	5	19	29	47	59	65	68	69
BOD	3,910	7	26	39	48	52	54	56	59
TKN	1,293	7.0	13	18	23	26	32	33	35
Organic-N	569	13	23	41	49	61	79	83	85
TP	270	10	21	38	53	63	71	74	74
Org-P	223	10	21	44	61	77	87	91	92

^{1/} Food grade cationic polyacrylamide polymer with 35% charge density

Table 4–55 Variation of optimal PAM dose and PAM use efficiency for primary treatment of swine manure removed from a recharge pit; manure was flocculated with a cationic PAM with a 35% charge density and then passed through a screen with 1 mm openings (adapted from Vanotti et al. 2002)

Influent TS (g/L)	TSS (g/L)	Optimum	Removed by screen		PAM Use	PAM Usage Rate
		PAM Dose (mg/L)	TSSR CR (%)	TSR CR (%)	Efficiency (g TSSR/g PAM)	(lb PAM/ton dry solids removed)
4.30	1.47	68	87	30	18.7	107
5.70	2.19	68	89	34	28.6	70
7.65	4.39	71	96	55	59.1	34
9.73	5.33	82	94	51	61	32
11.40	7.21	87	93	59	77.2	26
12.57	7.63	81	96	58	90.3	22
24.80	15.84	111	93	60	133.6	15

that is found in certain fungi and the exoskeletons of arthropods (Garcia et al. 2009). One of the greatest sources of chitin are shrimp and crab shell wastes. Therefore, a waste from the fishing industry may have a use for manure treatment. Garcia et al. (2009) used various doses of chitosan to flocculate mixtures of dairy manure and the lagoon supernatant that was used to flush freestall alleys. The flocculated manure was separated into a liquid and solids fraction using screens with 0.25 millimeter and 1.0 millimeter openings. The results are shown in tables 4–60 and 4–61.

Flocculation and screening with chitosan provided high removals of solids, total N, and total P as compared to the control and the increase in removal with respect to an increase in dose was similar to that observed for synthetic cationic polymers. Optimum doses of this natural polymer were determined based on the concentration reduction in TS (table 4–61). The optimal dose of chitosan increased with influent manure TS content in a similar manner for the 0.25 and 1.0 millimeter screen. Both screens provided TS removals of 90 percent or more at the optimal dose. The

primary difference was that the TP removal tended to be larger for the larger screen (1.0 mm, table 4–60). These data show that chitosan was very effective at enhancing the treatment of dairy manure by screening. Similar benefits would be expected to enhance screening of swine manure using the optimal dose.

(4) Methods used for mixing coagulants and flocculants

The effective use of coagulants and flocculants requires sufficient mixing to disperse the chemicals in the manure, provide sufficient particle contact time, and provide sufficient conditions for formation of precipitates and flocs. The two factors that describe the mixing process are the mixing intensity (rpm, power input) and mixing duration. Insufficient mixing results in a significant reduction in solids and plant nutrient removal, while too much mixing (either intensity or duration) may cause destruction of previously formed flocs.

Table 4–56 Correlations for primary treatment of liquid swine manure using a cationic PAM with a 35% charge density as a flocculant followed by separation with a 1 mm screen (adapted from Vanotti et al. 2002)

Regression equation	R ²	x- variable and range	
Optimal PAM Dose ^{1/} (mg/L) = 57 + 2.17 [TS]	0.95	[TS], g/L	(4.30 ≤ [TS] ≤ 24.8)
[COD] = 1.2794 [TS] – 0.843	0.994	[TS], g/L	(4.30 ≤ [TS] ≤ 24.8)
[TSS] = 0.7026 [TS] – 1.3492	0.994	[TS], g/L	(4.30 ≤ [TS] ≤ 24.8)
[VSS] = 0.786 [TSS]	0.996	[TSS], g/L	(1.47 ≤ [TSS] ≤ 15.84)
PAM use efficiency (g TSS removed/g PAM) = PUE			
PUE = - 29.2 + 12.05 [TS] – 0.2214 [TS] ^{2/}	0.984	[TS], g/L	(4.30 ≤ [TS] ≤ 24.8)
[BOD ₅] (g/L) = 0.341 [COD] – 0.09	0.934	[COD], g/L	(0.8 ≤ [COD] ≤ 31)
CODR (g/L) = 1.32 TSSR (g/L) ^{2/}	0.923	TSSR (g/L)	(0 ≤ TSSR ≤ 15)
Org-NR (mg/L) ^{3/} = 72.6 TSSR	0.929	TSSR (g/L)	(0 ≤ TSSR ≤ 15)
Org-PR (mg/L) ^{4/} = 33.2 TSSR	0.942	TSSR (g/L)	(0 ≤ TSSR ≤ 15)

1/ Food grade cationic polyacrylamide polymer with 35% charge density

2/ CODR = COD removed by the screen and TSSR = total suspended solids removed by the screen

3/ Org-NR = organic-N removed by the screen.

4/ Org-PR = organic-P removed by the screen

The general parameter that is used to quantify the mixing intensity is the velocity gradient (G , 1/sec). The velocity gradient for a paddle type mixer varies with many factors. The most important are the paddle design, fluid viscosity, rotational speed (rpm), and liquid volume. Knowledge of the velocity gradient in field applications is difficult and little information is available in the literature. Sievers (1989) provided a useful comparison of the variation in G with respect to propeller rpm for water and dilute manure. The dynamic viscosities of liquid manure and water as determined by Sievers are compared in table 4–62. The data provided clearly demonstrate that liquid animal manure has a much greater viscosity than water. As a result, greater rotational speed is required to provide a given velocity gradient for manure than for water. The experimental results indicated that manure with a TS content of one percent would require five times more input power

than mixing pure water. While these numerical results are limited to the characteristics of the mixing equipment used, they do point out the significant increase in power required to mix manure as compared to water.

Sievers (1989) determined the optimal velocity gradient and mixing time, t , for dilute manure following addition of optimum doses of FeCl_3 and a natural polymer flocculant (chitosan). The change in supernatant turbidity following 5 minutes of sedimentation was used as the criterion to determine optimum mixing and the results are given in table 4–63.

The overall index used for describing mixing for coagulation and flocculation is the product of the velocity gradient and mixing time, Gt . The results in table 4–63 show that the polymer required longer mixing

Table 4–57 Performance of a screw press treating thin dairy slurry (TS = 4%) with and without the use of a coagulant and flocculant (adapted from Oh et al. 2005); screw press had a wedge wire screen that was 100 mm in diameter, 343 mm long, and had 0.38 mm openings; the press was operated with 3 kg weights on the discharge pressure plate and rotated at 24 rpm

		[TS] (%)	[TP] (mg PO_4^{3-} /L)	[Sol-P] (mg PO_4^{3-} /L)	[COD] (mg/L)
Control	Influent =	4.0	625	280	22,717
	Effluent =	2.5	533	250	19,185
	CR (%) =	38%	15%	11%	16%
Dry matter capture efficiency = 66%					
Screw press throughput = 3.91 L/min (62 gal/hr)					
Coagulant: 4 ml alum solution/L, Al:P = 7.5:1					
Flocculant: 55.5 mg cationic PAM/L					
		[TS] (%)	[TP] (mg PO_4^{3-} /L)	[Sol-P] (mg PO_4^{3-} /L)	[COD] (mg/L)
	Influent =	4.0	568	271	22,717
	Effluent =	0.9	103	11	6,650
	CR (%) =	78%	82%	96%	71%
Dry matter capture efficiency = 82%					
Screw press throughput = 0.74 L/min (12 gal/hr)					

Table 4–58 Effect of combinations of FeCl₃ and PAM on removal of solids and major plant nutrients by screening (0.8 mm openings) from flushed dairy manure (TS = 0.5%, adapted from Zhang and Lei 1998)

PAM ^{1/} Dose mL/L	FeCl ₃ Dose mg/L	SVF (%)	Supernatant pH	Concentration deduction (%)				
				TS	VS	TN	TP	TK
0.40	0	5	6.65	67	74	67	53	7
0.20	400	6	6.18	67	74	67	95	10
0.10	500	5	6	67	74	67	98	9
0.05	700	10	5.34	65	73	69	99	19
0.03	800	10	5.1	63	71	69	96	11

1/ 40% cationic PAM with a high charge density, mixed to a 2% aged solution

Table 4–59 Centrifuge treatment (5,000 rpm, 40 to 60 L/min feed rate) of flushed swine manure and lagoon sludge mixture following addition of a coagulant, flocculant, and lime (adapted from Westerman and Ogejo 2005)

Description of chemicals

C = Strong cationic, medium molecular weight liquid coagulant

F = Anionic, medium charge density, high molecular weight polymer flocculant

L = Lime, 71.5% CaO, 1% MgO, and 128% CaCO₃ equivalent

Constituent	Flushed swine manure				Swine lagoon sludge mixture			
	Influent mg/L	Control MRE (%)	C+F MRE (%)	C+F+L MRE (%)	Influent mg/L	Control MRE (%)	C+F MRE (%)	C+F+L MRE (%)
TS	14,900	38	53	69	15,600	32	51	76
VS	9,900	44	65	73	8,000	25	55	79
TSS	12,700	47	78	81	14,300	41	73	88
TKN	1,289	21	30	41	1,384	26	40	48
TAN	728	17	19	14	598	33	30	25
Total P	394	61	70	88	620	63	54	82
Ortho-P	207	55	62	79	424	71	76	91
K	1,001	14	14	18	824	11	1	13
Na	264	14	15	20	217	10	0	18
Ca	532	34	42	91	755	11	56	88
Mg	155	69	68	88	200	68	73	92
Cu	1.6	23	45	76	6.2	17	63	80
Zn	11.7	23	71	75	26.8	14	61	79
COD	14,929	31	66	65	13,773	21	71	77
Chemical doses used								
	C dose =	0	1.9 mL/L	0.9 mL/L		0	0.9 mL/L	0.9 mL/L
	F dose =	0	13 mg/L	13 mg/L		0	40 mg/L	40 mg/L
	L dose =	0	0	3.9 g/L		0	0	7.5 g/L

times than the metal salt coagulant for all three manure types. The longer mixing time was needed for the formation of large flocs and agrees with trends seen in treatment of municipal wastewater. The longer mixing times for the polymer resulted in G t values that were greater than for FeCl₃. Values for rapid mixing of wastewaters have been reported in the range of 8,000 to 10,000 for alum, 30,000 to 50,000 for FeCl₃ and as high as 100,000 in extreme cases. Therefore, the optimum G t values observed for manure were in the low range of what has been observed for municipal wastewater.

Most wastewater treatment plants use two stages of mixing when using coagulants and flocculants. Rapid mixing is provided during the first stage to disperse the added chemicals to promote coagulation and is of relatively short duration. The second stage consists of lower-speed mixing for a longer duration to promote flocculation prior to separation by settling or screening. In some cases, the coagulants are added during the first stage of mixing, and the flocculants are added during the second stage. Zhu et al. (2004) performed a detailed study to determine the effects of alum dose, the G t provided for the first stage of mixing, and the G t provided for the second stage of mixing on the

Table 4–60 Removal of Solids, N, and P from liquid dairy manure by screening following mixing with chitosan (a natural flocculant) (adapted from Garcia et. al. 2009)

Initial Concentrations (mg/L) =		TS	TSS	VSS	TKN	TP
		32,200	28,300	13,800	794	236
Screen Opening	Dose mg chitosan/L	Concentration reduction (%)				
		TS	TSS	VSS	TKN	TP
0.25 mm	0	56.3	64.1	67.8	8.3	12.1
	60	57.9	65.9	63.9	14.8	16.9
	120	58.4	66.4	69.2	14.0	16.3
	180	60.5	68.8	68.5	19.6	22.9
	240	64.8	73.7	72.7	27.6	28.0
	300	65.7	74.7	75.4	31.3	29.6
	360	70.9	80.7	76.4	40.7	36.0
	420	73.8	84.0	81.7	43.8	37.3
	480	84.8	96.5	96.0	67.9	49.4
	540	86.7	98.7	98.4	72.5	53.9
1.0 mm	0	49.1	55.9	34.7	35.7	39.0
	60	47.9	54.5	33.3	41.7	42.2
	120	47.5	54.1	31.9	43.1	43.6
	180	49.2	56.0	34.2	34.7	33.5
	240	50.8	57.8	35.7	43.7	38.0
	300	54.8	62.3	44.3	51.0	45.1
	360	63.0	71.7	57.2	70.8	61.0
	420	67.1	76.4	65.4	67.1	56.0
	480	80.4	91.5	85.8	79.9	56.4
	540	83.8	95.3	92.3	86.0	61.9

removal of TSS from swine manure by sedimentation. The alum dose used were 130 and 800 milligrams per liter, the first rapid mixing stage (coagulation) G t values were 2,000 and 10,000, and the second slow mixing stage (flocculation) G t values were 8,400 and 25,200. Zhu et al. (2004) used a two-level, three factorial experimental design to test all possible combinations. Their findings indicated that the TSS removal was not significantly different for any of the combinations. Therefore, alum treatment was successful at low values of G t for both the rapid and the slow mixing stages. A rapid mix G t of 2,000 followed by a slow mix G t of 8,400 was sufficient for coagulation and flocculation with alum. These results qualitatively agree with the observation by Sievers that dilute liquid manure requires mixing G t in the lower range used in municipal wastewater treatment.

The mechanics of mixing are far more complicated than indicated by the current description. In addition, it is often difficult to know the mixing parameters in the laboratory or the field. As a result, mixing methods for most laboratory and field evaluations were determined by trial and error, and there is minimal consistency between published results. A summary

of the bench top mixing parameters reported by a variety of studies is provided in table 4–64. Generally, researchers tend to provide more mixing revolutions per minute or duration than needed to ensure that the best chemical performance is obtained. For cases where no second-stage mixing was explicitly provided, a stilling period was provided as part of the sedimentation phase or prior to screening. Flocculation generally occurred as the rotational speed of the manure slowed to quiescent conditions. Additional information on the use of jar tests to evaluate the performance of a coagulant or flocculant is provided in appendix D.

Four field studies provided information concerning the mixing methods used with coagulants and flocculants and the mixing methods used are summarized in table 4–65. Three of the investigators were able to use the turbulence in the flow of manure in a pipe (Worley and Das 2000) or from a pump (Sherman et al. 2000; Westerman and Ogejo 2005) to provide the initial mixing needs for chemical dispersal and coagulation. The two studies that evaluated sedimentation of swine and dairy manure used the stilling period following the initial mixing stage for flocculation. The flocculation step was not separate from the chemical dispersion and coagulation phase for the field test of a centrifuge (Westerman and Ogejo 2005). Vanotti et al. (2005)

Table 4–61 Variation in optimum chitosan (a natural flocculant) dose to be used with screening of liquid dairy manure (adapted from Garcia et al. 2009)

Influent TS (g/L)	TSS (g/L)	Optimum chitosan Dose (mg /L)	Removed by screen		Polymer use efficiency (g TSSR/g chitosan)	Polymer usage rate (lb chitosan/ton dry solids removed)
			TSSR CR (%)	TSR CR (%)		
0.25 mm screen						
4.6	2.65	176.8	91	53	13.71	145.8
8.3	5.34	222.3	96	62	22.98	87.02
16.3	11.32	317.8	97	68	34.68	57.68
32.2	28.30	518.8	99	87	53.78	37.19
1.0 mm screen						
4.6	2.65	173.0	89	51	13.64	146.6
8.3	5.34	240.1	91	59	20.24	98.80
16.3	11.32	294.0	92	64	35.41	56.48
32.2	28.30	518.9	96	84	52.09	38.40

Table 4–62 Comparison of dynamic viscosities (μ) for liquid manure and water (adapted from Sievers 1989)

Total solids content (%) = Manure type	Viscosity (N sec/m ²)	
	0.2%	1.0%
Dairy	0.00217	0.00409
Poultry	--	0.00099
Swine	0.00339	0.00502
Water	0.00089	

1/ Totals solids content of all manure types was in the range of 0.2 to 0.3%.

Table 4–63 Empirically determined optimal mixing parameters for coagulation and flocculation of dilute manure using bench-top mixing equipment (adapted from Sievers 1989)

Manure type ^{1/}	Optimum dose		Velocity gradient, G		Mixing time, t		G×t	
	FeCl ₃ (mg/L)	Chitosan (mg/L)	FeCl ₃ (1/sec)	Chitosan (1/sec)	FeCl ₃ (sec)	Chitosan (sec)	FeCl ₃	Chitosan
	Cattle	300	100	22.3	22.3	240	480	5,352
Swine	300	150	17.5	12.9	360	720	6,300	9,288
Poultry	300	150	14.5	32.7	240	480	3,480	15,696

1/ TS content of all manure types was in the range of 0.2 to 0.3%

Table 4–64 Summary of mixing procedures used for laboratory studies (jar test) of the effectiveness of coagulants and flocculants for enhancing solid-liquid separation of animal manure; all of the studies used bench-top mixers with six-blade paddles or impellers

Reference	Manure type	Chemical(s)	First stage mixing		Second stage mixing	
			Speed (rpm)	Duration (sec)	Speed (rpm)	Duration (sec)
Sherman et al. (2000)	Dairy	alum, FeCl ₃ , PAM	50	300	none	none
Karthikeyan et al. (2002)	Dairy	alum, FeCl ₃ , lime	100	120	35	900
Timby et al. (2004)	Dairy	AlCl ₃	326	300	none	none
		PAM	326	7	none	none
		AlCl ₃ + PAM	326	300	326	7
Rico et al. (2006)	Dairy	FeCl ₃ + PAM	175	120	50	780
Hjorth et al. (2008)	Swine	FeCl ₃ + PAM	220	120	75	120
Rodriguez et al. (2005)	Swine	FeCl ₃ , Fe ₂ (SO ₄) ₃ +PAM	500	10	400	10
Vanotti et al. (2002)	Swine	PAM	100	60	40	120
Zhang and Lei (1998)	Swine & Dairy	PAM	100	60	50	240
		Metal Salt + PAM	100	60	50	240

used a commercially available inline flocculation unit that provided rapid mixing by pumping liquid manure following PAM injection into a specially designed section of pipe that allowed for flow splitting and flow recirculation (tortuous path). The tortuous flow path provided the turbulence needed for mixing PAM (fig. 4–45). The flow rate and turbulence decreased in the plumbing that distributed the flocculated manure to the sand bed that was used for solid-liquid separation (Vanotti et al., 2005). Distinct coagulation flocculation zones were not apparent but good PAM performance was achieved as was indicated by an average TS removal of 76 percent.

(b) Advanced final treatment technologies for high-rate systems

(1) Struvite formation

Struvite, or magnesium ammonium phosphate hexahydrate, is a salt crystal that commonly forms in liquid

and slurry manure under the right conditions. Struvite has the chemical formula $Mg NH_4 PO_4 \cdot 6(H_2O)$ and can be caused to precipitate if the correct amounts of soluble Mg, phosphate, and ammonium phosphate are present in the manure at the optimal pH. At a pH of 7.0 or less, little struvite will form; however, as the pH of manure increases, struvite formation will increase. The optimum pH for struvite formation has been determined to be about 9.0 (Hjorth et al. 2010). However, increased struvite formation is common at a pH above 8.0. Struvite buildup has been observed to plug pipes used to transport recycled lagoon supernatant to flush tanks on swine farms when the pH and reactant concentrations reach the right conditions.

Bowers and Westerman (2005) developed a cone-shaped fluidized bed that promoted the formation and settling of struvite as a means to reduce the phosphorus content of swine lagoon supernatant. A summary of that field study is provided in table 4–66. They were

Table 4–65 Description of mixing methods used for field trials of enhancing solid-liquid separation of manure using coagulants and flocculants

Reference	Manure type	Chemicals	Description of chemical mixing method
Worley and Das (2000)	Swine	Alum	Alum was injected at a rate of 26.4 lb alum/min into manure flowing into a settling basin at about 1061 gal/min. Quiescent settling period lasted 15 min followed by a 1.5 hr decant period.
Westerman and Ogejo (2005)	Swine & Lagoon Sludge	Lime, and Polymer	Used a 450-gal mixing tank in series with a 60-gal feed tank. Chemical solutions were added to the mixing tank and mixing was accomplished by continuously pumping manure from the bottom to the top of the tank. Mixing tank contents were pumped to a centrifuge feed tank at a rate that exceeded the throughput rate of the centrifuge (10 to 15 gpm) and excess influent was recycled to the mixing tank.
Sherman et al. (2000)	Dairy	Alum	Alum was metered into a batch settling tank as the tank was filled with a pump. Flow turbulence was used for mixing. Alum was metered into the influent stream for flow-through settling tests. Flow rate was about 6 gpm.
Vanotti et al. (2005)	Swine	PAM	Well-mixed manure was pumped into an inline, tortuous path flocculation unit at the rate of 130 gpm. Polymer solution was injected into manure stream as it entered the flocculation unit.
Mukhtar et al. (2007)	Dairy	Alum + PAM	Alum and two polymers were injected prior to pumping the chemically treated slurry through a section of pipe with a series of 8, 90° bends.

able to reliably increase struvite formation by raising the pH from 7.71 to 8.21 and 8.71 by adding ammonia to the lagoon water prior to pumping it into the cone-shaped crystallizer. They were also able to make additional increases in struvite formation by adding soluble Mg. In the field study, they ran the crystallizer at two flow rates, and the lower flow rate provided greater P removal since the retention time was longer. The averages provided in table 4–66 demonstrate that they were able to provide a total phosphorus removal of 80 percent and soluble-P removal of 78 percent if Mg was

supplemented at the rate of 30 mg/L and the pH was raised to 8.7 with a swine lagoon supernatant flow rate of 341 L/h (88 gal/h).

Sheffield et al. (2005) implemented the same type equipment on flush dairy farms in the Pacific Northwest. His TP removals were inconsistent (table 4–67) and average TP removals of 8 to 19 percent were much lower than observed by Bowers and Westerman (2005). The authors determined that the lower degree of P removal was due to higher amounts of Mg and

Table 4–66 Phosphorus removal from swine lagoon supernatant using a cone-shaped fluidized bed struvite crystallizer with different levels of Mg supplementation and pH adjustment (field study, adapted from Bowers and Westerman 2005); the influent lagoon water had an average pH of 7.71 and contained 82 to 93 mg TP/L, 38 to 46 mg ortho-P/L, 53 to 67 mg Mg/L, and 176 to 197 mg TAN/L

pH rise	----- Liquid flow rate = 341 L/hr -----			----- Liquid flow rate = 568 L/hr -----		
	+ 0 ppm Mg	+ 30 ppm Mg	+ 60 ppm Mg	+ 0 ppm Mg	+ 30 ppm Mg	+ 60 ppm Mg
Soluble-P removal						
None	13%	23%	24%	13%	22%	27%
0.5 point	61%	73%	82%	56%	70%	78%
1.0 point	68%	78%	76%	64%	81%	80%
Total P removal						
None	0%	14%	23%	7%	12%	14%
0.5 point	59%	70%	69%	41%	63%	67%
1.0 point	64%	80%	72%	63%	75%	73%

Table 4–67 Removal of phosphorus from liquid swine and dairy manure by Struvite precipitation and sedimentation

Chemical addition	Species	Removal of TP (%)	Reference
Mg, OH ⁻	Swine	85	Nelson et al.(2003)
Mg, Ammonia, pH	Swine	60–80	Bowers and Westerman (2005)
Mg, increase pH	Swine	18–49	Suzuki et al. (2007)
Mg, increase pH	Swine	96–98	Burns et al. (2003)
Fe, OH	Swine	98–99	Laridi et al. (2005)
Mg, Ammonia, pH	Dairy	8–19	Sheffield et al. (2005)

TAN in the dairy manure indicating that much of the struvite may have already precipitated and could not be captured by the cone-shaped fluidized bed.

Several other researchers have also evaluated struvite formation and sedimentation as a means to reduce the phosphorus content in swine manure. Their results are compared in table 4–67. This method of manure treatment is best applied as a final treatment for previously treated wastewater. Besides removing a significant amount of P under the right conditions the struvite precipitate can be used as a solid N, P, and Mg fertilizer. The primary disadvantage is the cost of chemicals to adjust pH (ammonia) and the possible need for Mg supplementation.

(2) Electrocoagulation

Electrocoagulation (EC) is a technology that has been in existence since the early 1900s. The first patent was obtained by A.E. Dietrich in 1906 and it was used to treat bilge water from ships (KASELCO 2012). It is an advanced final treatment technology that has been used to remove metals, oil and grease, fine suspended solids, phosphorus and other contaminants from industrial, food processing, municipal, and agricultural wastewaters (Butler et al. 2011).

An EC reactor is designed to provide an electrolytic contact area that allows the wastewater to pass between an anode plate and a cathode plate that act as electrodes. A regulated direct current (DC) power source is used to apply a DC voltage across the plates. The power source is regulated to control the voltage drop and the current density (mA/cm^2). The plates are most often made of aluminum or iron and are degraded during the treatment process and thus are called sacrificial electrodes and must be periodically replaced. Molecules of Al or Fe ions are released into the wastewater and the released ions neutralize the charges of the particles and thereby initiate coagulation and precipitation. Depending on the size and density of the precipitates and flocs, they are removed downstream from the EC unit by sedimentation, filtering, or dissolved air floatation. The effectiveness of the EC system depends on the composition of the plates, the residence time in the electrolytic contact area (i.e., detention time), the magnitude of the DC voltage, the current density, and the concentrations of the target contaminants in the wastewater. While the basic principle behind electrocoagulation is simple few cost-effective applications has been developed.

Removal of suspended solids, COD, and phosphorus from treated wastewater is the primary potential application for EC technology in agriculture. Yetilmmezsoy et al. (2009) developed an EC system that could provide final treatment for anaerobically treated poultry manure wastewater. Poultry manure was treated in an up-flow anaerobic sludge blanket reactor and an EC system was tested to treat the supernatant. They determined that aluminum was the best electrode material for removal of COD and turbidity (TSS). The optimal operating conditions were to adjust the influent pH to 5.0, apply a current density of $15 \text{ mA}/\text{cm}^2$, and provide an electrolysis time of 20 min. Under these conditions they reported 90 percent reduction in COD and 92 percent reduction in turbidity. Researchers at Texas A&M University (Mukhtar et al. 2006) tested the use of an electrocoagulation system for the treatment of dairy lagoon effluent with a TS content of 0.6 milligrams per liter (0.006% TS). It was determined that large amounts of solids had to be removed from this low-strength wastewater before the EC system would function properly. Therefore, the concentrations of total and soluble phosphorus were so low it was difficult to accurately access the effectiveness of the EC unit. The total system reduced TP by 96 percent and soluble-P by 99.6 percent and the greatest contributor to post-lagoon treatment was the centrifuge. Hansen (2008) demonstrated that EC treatment of liquid effluent from a novel anaerobic digester used to treat dairy manure was capable of removing 85 percent of the remaining total solids, 94 percent of the remaining VS, 74 percent of the remaining nitrogen, and 93 percent of the remaining phosphorus. However, also concluded was that EC was expensive to operate at a cost of about \$16 per thousand gallons of digester effluent. Much additional work is needed with regards to application of EC technology on-farm before it will become a recommended treatment option for animal producers.

(3) Membrane filtration

A membrane filtration is the process by which dilute, treated wastewater is forced through a membrane that has openings on the order of 1 micron or less. The types of filtration are classified by the pore size of the membrane and the size and molecular weight of the molecules that can be captured. The pore size of the membrane closely reflects the size of the molecule or particles that can be removed from the liquid. The four types of membrane filtration are called microfiltration, ultrafiltration, nanofiltration, and reverse osmosis and the approximate particle sizes and operating pressures

used for each are summarized in table 4–68. The size of the particles that can be removed from a liquid by filtration range from less than 0.001 micron (reverse osmosis) to 10 microns (microfiltration).

Applications of membrane filtration for treatment of liquid animal manure are extremely limited and are generally only considered when it is desired to remove almost all of the suspended solids, nitrogen, phosphorus, potassium, metals and sodium from highly treated liquid manure wastewater. For example, microfiltration (0.1 to 10 microns particle removal) would generally be considered for treatment of the liquid effluent from an advanced treatment system that included high-rate liquid solid separation followed by biological treatment of the liquids. In addition, application of reverse osmosis would be used after treating the liquid with a series of microfiltration, ultrafiltration, and possibly nanofiltration steps.

An extensive review of the available research on using membrane filtration for post-treatment separation of liquid animal manure is provided by Masse et al. (2007). Their review discussed in detail the problems and emerging solutions related to membrane clogging, liquid flow rates through the membranes, removal of separated matter from fouled membranes, and method selection. They also provided a review of membrane filtration performance and indicated that removals of suspended solids, N, P, K, and metals from dilute manure wastewaters on the order of 50 to 100 percent can be attained.

One of the most successful membrane filtration systems identified by Masse et al. (2007) was the vibratory shear enhanced process (VSEP) Reverse Osmosis Membrane Filtration System that was developed by New Logic Research, Inc. (Johnson et al. 2004). This system combines a series of vibrating membrane and filtration steps that culminates in a novel application of reverse osmosis (RO) that requires 500 to 600 pounds per square inch across the final RO membrane. Johnson et al. (2004) provided a detailed summary of the application of this high-level treatment technology for final treatment of swine and dairy manure wastewaters in South Korea. This system can provide removals of 100 percent of the TSS, 96 percent of the total-N, 94 percent of the ammonium-N, 98 percent of the TP and TK, and 100 percent of the sodium and key metals (Cu, Zn, Fe, Mg, and Mn).

Table 4–68 General classifications of membrane filtration (Johnson, et al. 2004; Masse, et al. 2007; Hjorth, et al. 2010)

Filtration type	Particle size retained	Molecular weight range	Transmembrane pressure
Reverse osmosis	≤ 0.001 micron	≥ 100 Daltons ^{1/}	500 to 1,000 psi
Nanofiltration	0.001 to 0.01 micron	100 to 1,000 Daltons	50 to 435 psi
Ultrafiltration	0.01 to 0.1 micron	1000 to 500,000 Daltons	25 to 116 psi
Microfiltration	0.1 to 10 micron	≥ 500,000 Daltons	15 to 25 psi

^{1/} Dalton = unified atomic mass unit = 1.66053873 × 10⁻²⁷ kg

637.0406 Unique applications of solid-liquid separation technology

(a) Sand-laden dairy manure

Sand is often the bedding of choice for dairy animal health and comfort; however sand-laden dairy manure (SLDM) presents special challenges. Sand removal from flushed dairy manure is critical to minimize wear on pumping and manure handling equipment and to reduce sand buildup in liquid manure storages, treatment lagoons, and anaerobic digesters. In many cases, the dairy producer also desires to reuse sand for freestall bedding to reduce annual bedding costs. Settling basins, sand lanes, traps, and beaches are all methods that use gravity settling to remove sand from dilute, flushed dairy manure while allowing manure solids and liquids to be conveyed to the next step in the manure treatment system. Each of these methods requires addition of significant amounts of dilution water and many rely on separation of sand and manure by settling; therefore, dilution and settling requirements will be described first.

Separation of sand from liquid manure requires adequate dilution of the manure. The dilution must be sufficient to allow the sand particles to move past the manure particles and descend unimpeded to the bottom of the water column. The dilution ratio was defined by Wedel and Bickert (1996) as the pounds of water added to 1 pound of SLDM to be treated. The research, conducted in Michigan, indicated that for sand and manure to separate by settling, at least two parts of water must be added to one part of sand-laden dairy manure by weight. That would be a dilution ratio of 2:1. A dilution ratio of 5:1 was not high enough to result in true discrete settling of manure particles. In practice, dilution ratios of 2:1 to 5:1 can be used to achieve separation of sand from dairy manure. As a result, the higher the dilution rate, the faster and better the sand separation. High dilution requirements can be provided by frequent flushing of freestall alleys with large volumes of water.

The amount of SLDM produced by an operation will vary with breed of cattle, level of milk production, sand type, and sand use rate. It has been observed that the amount of sand used in freestall barns in Michigan has varied from 52 to 82 pounds of sand per stall per day with a mean of 68 pounds of sand per stall per day (Wedel and Bickert 1994). The design value used in a New York Extension publication was 55 pounds of sand per cow per day (Gooch and Wedel 2008). Recent values for manure production from dairy cows (excluding bedding) are on the order of 82 to 84 pounds of manure per 1,000 pounds of animal weight. Therefore, the amount of manure produced by a 1,400-pound dairy cow ranges from 115 to 118 pounds per day. Addition of 50 to 60 pounds of sand bedding per day results in about 165 to 178 pounds of SLDM per 1,400-pound cow per day.

The dilution ratios were calculated for 300 cows housed in a four-row freestall barn with four flush alleys with drive-through feeding based on the number of alley flushes per day, and are given in table 4–69. These results show that two full barn flushes per day achieved a dilution ratio greater than 4:1, and, therefore, provided adequate dilution for separation of sand

Table 4–69 Variation of dilution ratio with respect to number of full-barn flushes for SLDM; four-row freestall barn with drive-through feeding; the two alleys were 12 ft wide and the two stall alleys were 10 ft wide

Number of full-barn flushes per day ^{1/}	165 lb SLDM/cow-day	178 lb SLDM/cow-day
	Dilution ratio ^{2/}	Dilution ratio
1	2.4:1	2.2:1
2	4.7:1	4.4:1
3	7.1:1	6.6:1
4	9.4:1	8.7:1
6	14.2:1	13.1:1

^{1/} Four-row drive-through freestall barn, lanes flushed with 3,500 gal/lane. Total volume of water per full-barn flush was 14,000 gal and mass of water was 116,760 lb. Flush velocity used was the minimum recommended of 5 ft/sec (Fulhage and Martin, 1994; Fulhage, 2003; Harner et al., 2003).

^{2/} Calculated based on a barn population of 300, 1,400-lb Holstein cows.

and manure (Fulhage 2003). Flushing all four alleys three times per day would provide a dilution ratio greater than 5:1, and excellent sand settling would be expected. Field trials have documented that high dilution ratios facilitate improved floor cleaning and the production of cleaner sand for reuse as bedding (Harner et al. 2009).

Two critically important variables associated with the separation of sand from manure through gravity settling are the maximum settling flow velocity and the minimum scour velocity of both the sand and manure particles (Wedel 2012; Wedel 2000; Camp 1946; Merritt 1968). Particles of a given size and density will settle by gravity from standing water and from water flowing at low velocities. As the flow velocity increases to the maximum settling flow velocity, some of the particles remain in suspension. As the velocity of flow continues to increase to the minimum, scour velocity all of the particles remain in suspension. The maximum settling flow velocity for manure particles is in the range of 0.01 to 0.02 foot per second, and the minimum scour velocity is in the range of 0.75 to 1.0 foot per second. The maximum settling velocity for sand is in the range of 1.0 to 1.3 feet per second, and the minimum scour velocity is in the range of 5.0 to 8.0 feet per second. Notice that the maximum settling velocity for sand (1.0 to 1.3 ft/sec) is greater than the minimum scour flow for manure particles (0.75 to 1.0 ft/sec). Therefore, the flow velocity in a basin, or lane used to separate sand from dilute manure must be above 1.0 foot per second and below 1.3 feet per second to capture sand particles while minimizing the capture of manure particles. A design value of 1.25 feet per second is a good general recommendation (Harner et al. 2009).

A short detention time of about 2 to 4 minutes is sufficient to remove sand from diluted sand-laden manure. If the detention time is too long then large manure particles will settle with fine sand particles. Comparison of ideal discrete particle settling velocities of sand and manure (table 4–20) indicated that settling velocities of large manure particles (1.0 mm and larger) are about the same as for sand particles with a diameter of about 0.20 mm. Therefore, attempts to capture clean fine sand particles by gravity settling techniques have a low probability of success. As a result, coarse sand mixtures (table 4–19) with a median diameter of 0.70 millimeters and only 12 percent finer than 0.20 millimeter are recommended for bedding freestalls if alleys are to be cleaned by flushing or if any type of sand-manure

separation technique is to be used. These theoretical considerations also suggest that the maximum amount of sand that could be recovered and reused is on the order of 88 percent.

Only sand that is sufficiently clean and dry can be reused as freestall bedding. Harner et al. (2009) provided a summary of the literature on recycled sand bedding quality requirements. The general recommendations are that the sand must have an organic matter content ($VS/TS \times 100$) that is less than 3 percent and that the sand must be allowed to drain dry for 30 to 48 days prior to reuse. One of the common problems associated with sand lanes is the deposition of large organic particles along with the sand. Many of the largest particles are wasted feed grains (fig. 4–46). Studies cited indicated that recycled sand organic matter contents of 2 percent or less was possible with sand lanes or sand beaches, while sand traps could be managed to provide sand with less than 3 percent organic matter. Sand recovery rates were in the range of 75 to 90 percent, with the highest recovery rates being for sand lanes. A good planning number for sand recovery appears to be in the range of 80 to 85 percent.

Figure 4–46 Large organic and grain particles captured with sand in a sand lane (University of Wisconsin, Cooperative Extension Service, Holmes 2010)



(1) Guidelines for design of sand lanes

A sand lane is a long, shallow channel designed to slow flushed manure from a velocity of over 3 feet per second to a velocity of 1.25 feet per second to allow sand to settle while maintaining organic solids in suspension until they exit the lane (Harner et al. 2009). Sand is removed from the lane each 1 or 2 days and is piled on a concrete slab for drying and conditioning. The concrete pad is typically sloped toward the sand lane so that leachate, and runoff from the sand storage area is collected and stored with the manure. Sand that is too dirty to be reused for bedding can be redistributed near the entrance of the lane in a thin layer to allow manure solids and other organics to be washed from the sand during subsequent flushes. The solids content of the recycled flush water is critical to producing clean sand. Therefore, provision of good physical and biological treatment is typically necessary downstream from a sand lane. It is recommended that sand lanes be constructed in pairs to allow one to function while the other is being cleaned, as shown in figure 4–47.

Most sand lanes are narrow, 10 to 14 feet wide, and flush manure is transferred to the lane by way of a pipe or open channel that is designed to maintain flow velocities in excess of 3 feet per second. As the flush

wave enters the lane, the velocity must be reduced, and flow must be spread across the width of the lane to promote sheet flow at about 1.25 feet per second (Harner et al. 2009). The energy of the flush water can be dissipated and spread near the lane inlet using a concrete block wall, stem wall, or a baffle. The narrow sand lane, shown in figure 4–48, included an energy dissipation baffle to slow and spread the flush wave. Such an inlet will provide the desired sheet flow in a defined channel several feet downstream from the baffle. If the velocity in the lane falls to 1 foot per second or less, large manure particles will settle and contaminate the sand (fig. 4–46).

The flow velocity is controlled by Manning's equation and as a result the lane width and slope are critical parts of sand lane design. The amount of time allowed for sand settling is controlled by the lane length (Harner et al. 2009). Little practical design information is available in the literature, however, the recommendations provided based on experience on several dairies in Kansas are summarized in table 4–70.

Sand lanes have been used in conjunction with gravity settling of solids and lagoon treatment. A simple weir outlet has been used to convey the effluent from a sand lane into a settling basin to complete primary treatment on a dairy farm in Wisconsin as shown in figure 4–49 (Holm 2010).

Figure 4–47 Dual sand lanes used to remove sand from dilute, flushed dairy manure (Holmes 2010). One lane is allowed to drain and is cleaned while the other is used to treat manure. Note the location of equipment access ramps and sloped pads for sand conditioning and storage



Table 4–70 Guidelines for sizing of sand lanes and sand traps (adapted from Harner et al. 2009; Holmes 2010)

Flow velocity in lane or trap to prevent manure settling = 1.0 < Velocity < 1.5 ft/sec (1.25 ft/sec)

Sand lanes

Flow into lane must be spread using a short wall energy dissipater.

Lane width and slope

Flows of 2,500 gpm or less

Lane width = 12 ft

Lane slope = 0.15 to 0.25%

Flows of 5,000 gpm or more

Lane width = 14 to 20 ft

Lane slope = 0.20 to 0.25%

Lane length = Minimum of 150 ft.

Minimum curb height = 12 inches

Sand traps

Flush water is allowed to spread out to the width of the trap on a concrete apron that is at the end of the flush alleys to provide sheet flow. The flushed manure drops into the trap like a water fall.

Width = 40 to 48 ft typical. Maximum is set by design flow velocity

Depth = 2 to 4 ft.

Flat bottom length = 24 ft (minimum)

Minimum volume = 2 times the total volume of flush from the entire building

Detention time = 2 to 4 minutes including drain down

High volume outlet

Typically provide one 18-in-diameter pipe or two 12-in-diameter pipes to quickly convey manure to the next phase of treatment.

The sand-lane design concept provided a well-defined channel cross section and flow length with the outlet at the end of the lane. Therefore, estimation and observation of the mean wave velocity was the simplest of all of the designs reviewed. In contrast, the flow path and mean flow velocities for the sand trap and sand beach concepts were largely unknown and difficult to define.

Example 4-10—Calculation of dimensions for a sand lane

Determine the dimensions of a sand lane used to settle sand from flushed sand-laden dairy manure. The volume per flush is 3,500 gallons (467.88 ft³) and the flow rate from the barn is about 3,500 gallons per minute.

Step 1: Select the detention time, T, and calculate the flow rate in the sand lane, Q_{SL}. Select a detention time of 2.5 minutes. The flow rate is

$$Q_{SL} = 467.88 \text{ ft}^3 / 2.5 \text{ min} \\ = 187.2 \text{ ft}^3 / \text{min}$$

Step 2: Calculate basin cross-sectional area assuming a mean velocity of 1.25 foot per second equals 75 feet per minute.

$$A_x = \frac{Q_{SL}}{U_F} \\ = 187.2 \text{ ft}^3 / \text{min} / 75 \text{ ft/min} \\ = 2.50 \text{ ft}^2$$

Step 3: Select trap width and calculate mean depth at the wave front. The flush flow rate is 3,500 gallons per minute, so a 14-foot-wide sand lane was selected based on the guidelines provided in table 4-70. Flow depth:

$$D_A = \frac{A_x}{W} \\ = 2.50 \text{ ft}^2 / 14 \text{ ft} \\ = 0.179 \text{ ft} \\ = 2.14 \text{ in}$$

Figure 4-48 Short baffle used to dissipate energy and spread influent to a sand lane (University of Wisconsin, Cooperative Extension Service, Holmes, 2010). Other materials that can be used include poured concrete curb or concrete block attached to slab by filling cores with concrete around steel bars set in the slab



Figure 4-49 Effluent from a sand lane falling directly into a settling basin (Holmes 2010)



Step 4: Calculate the length of the sand lane, L_s , based on the detention time selected and flow velocity (eq. 4-14).

$$\begin{aligned} L_s &= T \times U_F \\ &= 2.5 \text{ min} \times 75 \text{ ft/min} \\ &= 187.5 \text{ ft (round to 188 ft)} \end{aligned}$$

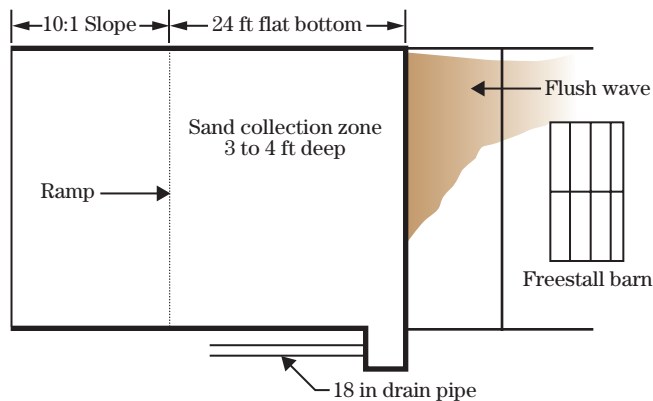
Note that the use of a baffle to dissipate flow energy and to spread the flow across the width of the sand lane will require a portion of this length to establish the desired sheet flow conditions. The minimum distance to develop sheet flow will be on the order of two times the channel width.

Therefore, the total length of the sand lane should be increased by 28 feet to give a total length of 216 feet.

(2) Guidelines for design of sand traps

A sand trap is a shallow, drain-dry settling basin that is designed to maintain the flow velocity high enough to prevent the settling of organic solids while allowing sand to settle. Detention times in sand traps are short, 2 to 4 minutes, to minimize the capture of organic solids. A sand trap built onto the end of a two-row freestall barn in Kansas (fig. 4-50).

Figure 4-50 Sand trap positioned on the end of a flushed, two-row freestall barn (Wisconsin University, Cooperative Extension & Kansas State University, Cooperative Extension, Harner 2009).



The sand trap design shown used a concrete apron that was the same width as the building (40 ft) and it extended out from the building about 30 feet to permit equipment access to the stalls. The slope of the apron matched the slope of the flush alleys (2%), and the added width allowed the flush wave to expand and dissipate a portion of the flow energy without allowing sand to settle prior to entrance into the sand trap. The flush manure cascaded off of the concrete apron into a 2-foot-deep settling trap. This reintroduced a high level of turbulence into the flow and consequently the actual length of the settling area could not be easily determined. However, the turbulence of the water as it flowed over the vertical wall kept the lighter manure solids in suspension while allowing sand to settle in the trap. The water and manure solids drained quickly away through a single 18 inch pipe located at the bottom of a sump that was divided from the basin by a screen. The bottom of the basin was 40 feet wide and extended 24 feet away from the building. A ramp (40 ft wide) was located on the opposite side of the building and it was sloped up at a 10:1 slope. The ramp served as a place to unload the recovered sand and as a place to spread out sand to drain. Notice also that the flush wave traveled up the ramp and deposited sand on the ramp. A summary of Harner’s recommendations for sand trap design were provided in table 4–70.

The desired sand storage volume (SSV) can be estimated based on an estimate of the sand recovered in as similar way as suggested by Fulhage (2003):

$$SSV = N_{FS} \times SP \left(\frac{R_{SAND}}{100} \right) \left(\frac{SU}{\rho_{SAND}} \right) \quad (\text{eq. 4-43})$$

where—

- SSV = Sand storage volume, ft³
- N_{FS} = Number of freestalls in the building
- SP = Design storage period, days
- R_{SAND} = Sand recovery rate, %
- SU = Sand use rate, lb of sand/freestall-day
- ρ_{SAND} = Density of sand, 115 lb/ft³ (range = 110 to 120)

Sand recovery rates can be in the range of 70 to 90 percent of the sand used to bed the stalls. Assumption of a sand recovery rate of 85 percent, and a sand use rate of 60 pound per stall per day the volume needed to store sand for a 100-stall barn would be 44.3 cubic

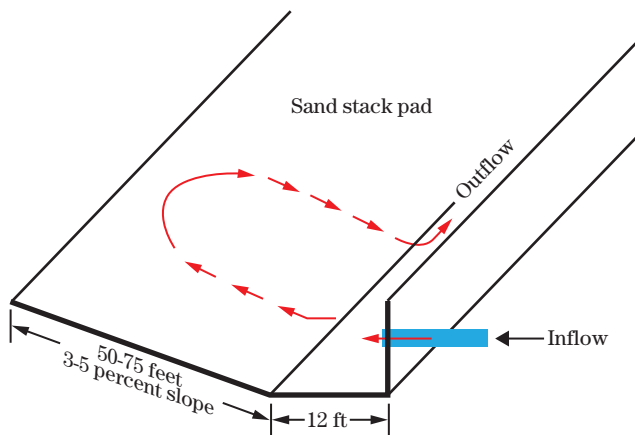
feet per 100 stalls per day. The storage volume for one week would be 310 cubic feet per 100 cows.

If it is desired to use a sand trap design similar to that presented by Harner et al. (2009) for a 100 foot-wide four-row, drive-through freestall barn, then two sand straps could be used with the drive-through lane passing between them. Sheet flow would be established in a manner similar to Harner’s design.

(3) Guidelines for design of a sand beach

A sand beach incorporates elements of a sand trap and a sand lane. Such a system cannot be designed using typical calculation methods. As of 2009, there were only a few known to be operating on dairy farms in the United States. A sketch of the sand beach concept is shown in figure 4–51. Flushed sand-laden dairy manure was discharged onto a long, 12-foot-wide lane that was sloped (≈0.25%) toward the outlet in the same way as a sand lane. The primary differences were that no energy dissipation baffles were provided and the concrete curb opposite the influent pipes was replaced by a long concrete slab that was 50 to 75 feet long and sloped upward. The sloped concrete slab functions like a beach at the ocean. The flush water is discharged from a pipe at a high flow rate perpendicular to the ramped slab. The flush water forms a wave that flows as a sheet up the incline till the velocity falls to zero and then recedes. Sand is deposited on the concrete “beach” and many of the organic particles that settle on the sand are washed back to the lane.

Figure 4–51 Sketch of the sand beach concept (Kansas State University, Cooperative Extension)



One of the sand beaches that were evaluated by Harner had a concrete slab that was 50 feet long, with a slope of 3 percent. It was soon determined that this combination of slab length and slope was insufficient because the high velocity of the flush water leaving the inlet pipe (18-in-diameter pipe and 8,000 gpm) pushed the wave beyond 50 feet. The problem was solved for this early attempt by forming a dike-like sand windrow along the top of the slab to limit the length of the flush wave. Harner recommended that the slope of the concrete slab beach be increased to 5 to 6 percent if the length is to be maintained at 50 feet. An increase in the length of the slab to about 75 feet is recommended if a 3 percent slope is desired.

One of the advantages of the sand beach concept is that one long structure can be used to treat manure from several barns. The flush pipes can be spaced 50 to 100 feet apart and the slab area not used to dissipate the flush waves can be used to store sand. A concrete ramp can be provided if needed to provide equipment access (fig. 4–52). On-farm observations indicate that it may be possible to recover 90 percent of the sand from flushed SLDM with an organic content that is low enough (<3%) to allow reuse as bedding after a drying and conditioning.

(4) Mechanical sand-manure separation

All of the previously described methods of sand-manure separation depend on sedimentation combined with high amounts of dilution to be effective. However, a few mechanical sand-manure separation systems

Figure 4–52 Recovered sand storage and concrete access ramp used with a sand beach (Kansas State University Cooperative Extension, Harner 2009)



have been developed for use with slurry SLDM that combine sedimentation with mechanical conveyances, and cyclones. Some of these mechanical systems are commercially available, but a few were found to not meet the desired objective of yielding clean sand that can be reused for freestall bedding and may no longer be available. In most cases, the machine or system is manufactured and marketed by only one company. The purpose of this section is to provide an overview of techniques that have been investigated. However, neither the author nor NRCS is formally endorsing any particular product. It is expected that additional mechanical sand-manure separation systems will be developed in the future.

Sand-manure separator

Researchers at Michigan State University (Wedel and Bickert 1994 and 1998) developed the concept for a mechanical sand-manure separator (SMS) that can be used to remove a large portion of the sand from heavy slurry manure on dairy farms where sand is used as stall bedding and slurry is removed from alleys by tractor scraping. The machine that was developed and patented is marketed by McLanahan Corporation. While the machine was initially designed to address issues associated with slurry sand-laden dairy manure the applications have been expanded to include systems designed for flush dairy buildings and extra-high sand removal for use prior to an anaerobic digester (Wedel 2012). The sand-manure separator has been described as a mining-duty, screw sand washer that has been modified to allow manure to be separated and washed from sand. A schematic that shows the operation principles of the sand-manure separator is provided in figure 4–53 .

A mechanical SMS operates using four general steps as described by Wedel and Bickert (1996)—namely, metering, dispersion, settling, and removal. Metering is the addition of SLDM at into a hopper where it is diluted to approximately one part water to one part SLDM (1:1 by weight). An auger or piston pump is used to add the manure to the hopper at a rate that provides the desired flow rate. The dilution water is typically recycled parlor wash-down water, or recycled supernatant from a treatment system. The total solids content of the recycled dilution should be less than two percent. However, provision of dilution water with low total solids content (less than 1%) can enhance

SMS performance. Dispersion is needed to break the cohesion between manure and sand particles and is achieved by injecting a high pressure air stream near the paddles of the receiving hopper. The air flow is provided by an industrial-quality blower and is introduced with the dilution water near the bottom of the hopper which serves as a dispersion tank.

The mixing provided by the air and the impact on the paddles provide the needed mixing to break apart the bonds between the manure and sand. The air also causes some of the solids to float. Following dispersion, separated manure, that contains a little sand, flows over a weir where it is collected and transferred to a storage facility, or for additional treatment. The sand is allowed to settle on a slow moving inclined auger where it is removed from the tank. As the sand is lifted, dilution water drains back to the hopper, and the separated sand is washed with fresh water spray to remove manure particles. This water also flows back to the hopper and provides additional dilution water. The sand is lifted a few feet higher to allow the sand to drain, and then it is discharged onto a stacking pad. Drainage from the pad is collected and flows out with the manure or is reused for dilution water.

The amount of dilution water needed will correspond to the mass of SLDM to be treated. The flow rate of the fresh wash water spray is about 5 gallons per minute (≈ 2 gal/cow/day) and the sand recovery rate

will range from 80 to 90 percent (Wedel 2012). The SMS operates best with coarse concrete sand and has been shown to produce clean sand with organic matter content of 1.6 percent or less (Wedel and Bickert 1998). A conditioning period of at least 1 month (30 days) is recommended before the sand is reused for free-stall bedding (fig. 4–54). The effluent manure from a SMS will be in a slurry form (TS = 5 to 7%), and can be transferred to additional stages of treatment or storage. The remaining fine sand will settle in lagoons, storages, and digesters, but the excessive handling difficulties associated with unloading SLDM storages will be eliminated.

Sand-manure separators are manufactured in several capacities. Systems have been installed that provide sand-manure separation for dairy farms ranging from 60 to 1,500 cows.

Cyclone

The other type of equipment that has been used to remove sand from liquid SLDM is a heavy-duty cyclone separator. Such cyclones are commonly used to remove grit and sand from municipal and industrial wastewater. These types of machines can effectively remove sand from liquid manure, but many are not designed to yield washed sand that can be reused for freestall bedding. Little information is available con-

Figure 4–53 Operational diagram of the McClanahan sand-manure separator (Holmes 2010)

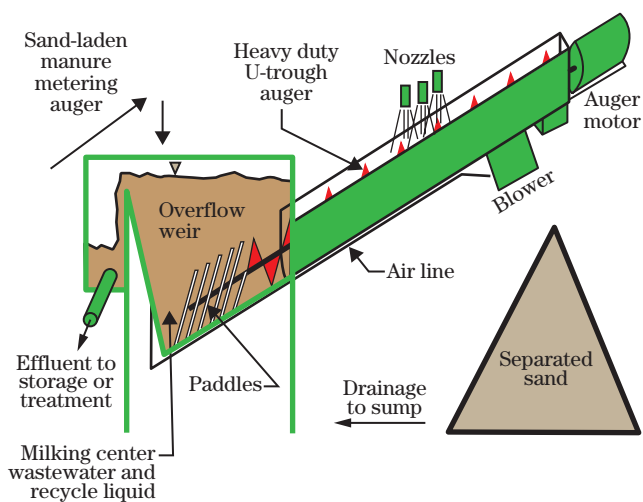


Figure 4–54 Sand recovered from a McClanahan sand-manure separator stacked on a conditioning pad (University of Wisconsin, Cooperative Extension Service, Holmes 2010)



cerning the efficacy and efficiency of using cyclones to treat SLDM.

Parkson Corporation developed a cyclone sand manure separator that removed 80 to 90 percent of the sand from dairy manure (fig. 4–55). Manure entered the top of the cyclone and recycled dilution water entered the bottom in a counter flow arrangement. The water lifted the organic matter up and out the top of the unit, while the auger removed the separated sand from the bottom. The sand drained as it was lifted and was stored on a concrete pad. Field experience in Wisconsin showed that the cyclone was able to remove an impressive amount of sand from SLDM but close inspection of the separated sand showed evidence of a large amount of organic matter (fig. 4–56), and would prevent the reuse of the sand for bedding freestalls.

At the present it appears that one of the best uses of a cyclone is to remove fine sand from the effluent of a sand-manure separator (fig. 4–57) when fine sand could compromise the performance of the next step in manure treatment. For example, fine sand can build up in biological treatment systems (e.g., anaerobic digester or aerobic treatment system), and cause the system to be shut down while sand is removed. Cyclones

have been shown to improve sand removal by 5 to 10 percent following a SMS, and increased the recycled sand recovery rate from 85 to 90 percent to about 95 percent (Wedel 2012).

Figure 4–55 The Tru-Grit® Manure Sand Saver manufactured by Parkson Corporation (Holmes 2010)



Figure 4–56 Closeup of the sand from a cyclone sand-manure separator, note the large amount of feed grains and other organic matter mixed with sand (Holmes 2010)



Figure 4–57 A cyclone separator used to remove fine sand from the effluent of a SMS (University of Wisconsin, Cooperative Extension Service, Holmes 2010)



Wedel introduced a three-step sand-manure separation system that was able to yield sand-free dairy manure that was to be further treated in a heated anaerobic digester. Without sand removal, the anaerobic digester would eventually need to be shut down and cleaned out periodically. The fine sand would also reduce the useful life of pumping, and mixing equipment. The three-step system used included a sand-manure separator, cyclone, and sand settling lanes. The sand removed from the sand lanes was too dirty for reuse and was land applied.

(b) Guidelines for design of a weeping wall settling basins

Weeping wall settling basins are a relatively new concept that is an expansion of the settling basin concept that had been previously used for treatment of runoff from outside lots and for smaller dairy farms (Chastain et al. 2001a; Mukhtar et al. 2011). One of the first publications that explained the weeping wall concept was the evaluation of a porous-wall settling basin for treatment of sand-laden flushed manure by Fulhage (2003). The terms porous wall and weeping wall are both used to describe the same concept. The techniques described are not limited to treatment of SLDM, but can also be used to achieve solid-liquid separation by settling for flushed manure.

Fulhage carried out a 2-year study of a porous wall-settling basin and its associated flushing system to evaluate the flushing requirements for sand-laden dairy manure, the settling basin performance, and quantity and quality of the sand recovered for reuse as freestall bedding. The porous-wall settling basin observed provided sand reuse rates of about 73 percent. If adequate dilution was provided, the reclaimed sand met the requirements for reuse. However, other field experiences with this system (Holmes 2010) suggest that sand reuse rates may be much lower.

The porous wall settling basin was designed and built to remove manure and sand from flushed manure on a 450-cow dairy farm in Missouri. The porous wall settling basin had two large equal-sized solids storage areas with a drainage channel located in the middle as shown in figure 4–58. The effluent from the drainage channel was conveyed to a lagoon. The two walls used to form the drainage alley were constructed with alternating 8-foot-wide sections of concrete and porous panels. The porous wall sections were constructed by fastening steel flooring panels to vertical posts and they were keyed into the concrete wall section using vertical slots (fig. 4–59). These flooring panels are often called “tri-bar” panels and the normal use is to

Figure 4–58 Cross section of a two-chambered, porous wall settling basin evaluated by Fulhage (2003). Basin length was 350 ft. and volume of each chamber was 43,000 ft³

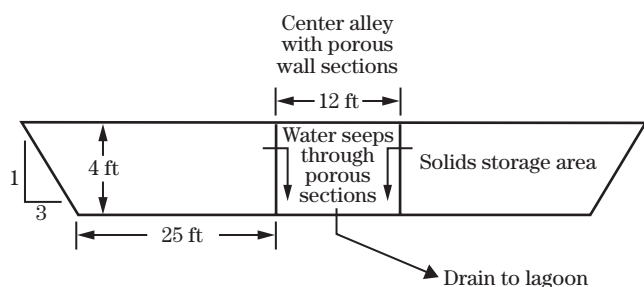


Figure 4–59 Swine nursery flooring panels used to provide the 8 ft. wide porous sections bar spacing is about 3/8 of an inch (Fulhage 2003)



provide perforated flooring in swine nursery buildings. The bar spacing for the panels used was about three-eighths of an inch. The total length of the basin was 350 feet and the volume of each chamber was 43,400 cubic feet.

Design and operation of the flush system was critically important. The alley floors were sloped 2 percent toward the settling basin and the alleys were flushed three times per day with an alley flow velocity of 5.2 feet per second. The flush velocity was measured by timing the movement of the leading edge of the flush wave over the last 200 feet of the alley length. At flow velocities less than 5.2 feet per second, an unacceptable amount of sand remained in the alleys. Even with a flush velocity of about 5 feet per second, a small amount of sand remained near the curbs of the freestalls and had to be removed occasionally by scraping with a loader bucket or tractor scraper. Flushing more than three times per day improved sand removal but did not provide an improvement that warranted a change in the management plan for the barn. Flushing manure at least three times also provided enough dilution to facilitate settling of sand and manure in the two-chambered settling basin.

The design of this two-chambered, porous wall settling basin allowed one side to be used to treat liquid sand-laden manure from the freestall barn while the settled sand and manure solids were removed from the opposite chamber. The sand-laden manure received enough dilution to allow the majority of the sand to settle in a segregated mass near the front of the basin and the manure solids accumulated near the back of the basin (fig. 4–60). Manure solids and sand was removed from the settling basin with a front-end or skid-steer loader

Figure 4–60 Full settling chamber with sand near the fill end (beneath the dairy producer and accumulated dairy solids at the back) (Fulhage 2003)



using a two-step process. Manure solids were removed from the back of the basin and sand was recovered from the front, or fill, end. With careful operation of the sand removal equipment, and avoiding obviously manure contaminated sand, provided a sand recovery rate of 73 percent. After removal from the basin, the settled sand was stockpiled in an area near the lagoon for a 30-day conditioning period. Any runoff or drainage from the sand pile drained into the lagoon.

Fulhage (2003) conducted total colony bacteria tests of the conditioned, recovered sand and newly purchased sand. The results of this limited evaluation indicated that bacterial colony counts were similar for conditioned recovered and unused sand. After the 30-day conditioning period the recovered sand was mixed with newly purchased sand and was used to replenish freestalls.

The type of sand used for bedding the freestalls had a significant impact on the performance of the flush system and the settling basin. The two types of bedding sand evaluated were less expensive fine sand that contained a significant percentage of small sand and clay particles and coarse, graded “concrete” sand that contained few fine particles. The coarse sand was more expensive (\$5.25/ton vs. \$4.25/ton) and more difficult to flush, but it resulted in cleaner cows and settled better than the fine sand. The coarse sand was also determined to harbor fewer bacteria colonies. The dairy producer preferred the coarse sand over the fine sand since three flushes per day cleaned the floors adequately and coarse sand could be more easily recovered, conditioned, and reused.

The results of the 2 year study of this porous walled settling basin are summarized in table 4–71. Each of the two chambers provided an average of 44 days of storage for manure and sand from 450 cows housed in a 400 stall freestall barn. The stocking rate averaged 1.125 cows per stall and 66 pounds of coarse sand were used per freestall per day. The average chamber storage volume was 2.22 cubic feet per cow-day, of which 75 percent was sand. The average sand recovery rate was 73 percent.

The data from this study allowed Fulhage (2003) to recommend an equation to calculate the storage volume per chamber for the settling basin. His equation assumed a stocking rate of 1.10. A more generalized form of Fulhage’s equation is—

$$CV = N_{FS} \times SP \left(\frac{SU}{120} + SR \times 1.67 \right) \quad (\text{eq. 4-44})$$

where—

- CV = Chamber storage volume, ft³
- N_{FS} = Number of freestalls in the building
- SP = Design storage period, days
- SU = Sand use rate, lb of sand/freestall-day
- 120 = Density of sand, lb/ft³
- SR = Stocking rate = no. of cows/no. of freestalls
- 1.67 = Settled manure solids accumulation rate, ft³/cow-day.

Equation 4-44 provides a useful way to calculate the needed settling storage volume based on a specified sand use rate, number of cows, and number of freestalls.

The mechanics of sand-manure separation by sedimentation are difficult to quantify without empirical observations. Many of the designs described do not conform to common recommendations for settling basin design. For example, provision of outlets at a continuous interval along the length of a porous-wall basin (fig. 4-60) does not allow for the definition of a minimum basin length (LS, in eq. 4-14) and corresponding detention time since the outlets begin about 8 feet from the inlet of the settling chamber. The consequence is that the flow velocity and flow length varies as the flush wave moves down the channel. Maintenance of a solid

wall will permit the designer to define the mean flow velocity and detention time. The porous wall sections would begin at a distance from the inlet that is greater than the desired minimum LS. Such a design modification would be expected to provide more control over the location of the sand deposition and manure deposition zones.

Meyer et al. (2004) described a weeping wall basin as a settling basin with a large surface area that allows solids to dewater (drain dry) and provides 3 months of storage for the solids. The basin evaluated was similar to that described by Fulhage. Figure 4-61 is a schematic of the two-chambered weeping wall settling basin. Each chamber was 440 feet long by 54 feet wide and 7 feet deep. Weeping wall sections were formed using tri-bar swine flooring with a bar spacing of 0.25 inches. Mukhtar et al. (2011) provided a detailed evaluation of a large multicell, two-stage series of weeping wall basins. Each primary settling chamber was 300 feet long by 40 feet wide and 8 feet deep. A secondary double-chambered weeping wall basin was used to provide additional treatment. Each secondary chamber was 80 feet long by 40 feet wide and 8 feet deep. Manure was conveyed by channel to the primary basin that had four parallel chambers (fig. 4-62). The secondary basin had two parallel chambers using the same design. The primary settling basin chambers provided 60 to 90 days of storage for dewatered solids and the secondary chambers provided about 21 days of storage. The main differences between the basins evaluated by Fulhage, Meyer, and Mukhtar are related to size of the settling chambers, number of settling chambers, the types of prefabricated panels used to form the weep-

Table 4-71 Summary of two-chambered, porous wall settling basin performance measurements (Fulhage, 2003)

Observed parameter	Values observed over 2 years
Average sand use	66 lb/freestall-day
Sand recovery rate	73%
Best performing sand type	Graded, coarse, “concrete” sand
450 Holstein cows, average weight	1,400 lb/cow
Observed storage period/chamber	44 days for 450 cows in a freestall barn with 400 stalls.
Chamber storage volume (sand + manure solids)	2.22 ft ³ /cow-day
Estimated sand storage volume	0.55 ft ³ /freestall-day
Estimated manure solids storage volume	1.67 ft ³ /cow-day

ing walls, the methods to convey flushed manure to the basin, and the design of the outlet drain. In all of the designs studied by Meyer and Mukhtar, the weeping wall was constructed using a concrete slats. Steel or concrete pillars were used to support the porous section that was formed with tri-bar panels (fig. 4–59) or slotted concrete panels (fig. 4–63). In all cases, at least a pair of basins was used to allow one to provide primary treatment for flushed manure while the other was allowed to be unloaded. The dewatered solids were typically land applied immediately follow-

ing removal. However, additional solids storage may be needed when land is unavailable for application. Dewatered solids could also be a primary ingredient for a commercial composting operation. The limitations of a weeping wall separation system that need to be included in an evaluation are the higher capital cost than comparable earthen or lined storages and the labor needed for regular cleaning of the weep holes in the concrete or tri-bar panels (NRCS 2006).

Figure 4–61 Schematic of the two-chambered weeping wall settling basin evaluated by Meyer et al. (2004). Each chamber was 54 ft. long by 54 ft. wide and 7 ft. deep. Weeping wall sections were formed using tri-bar swine flooring with a 0.25 in. bar spacing

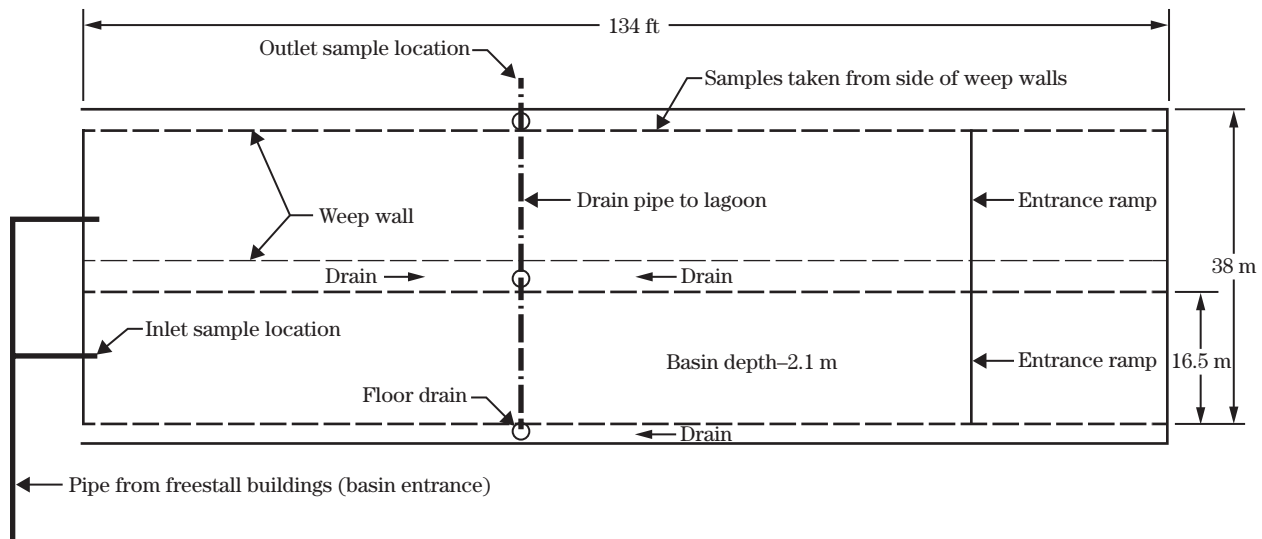


Figure 4–62 A large, multichambered primary weeping wall settling basin by Mukhtar et al. (2011)



Figure 4–63 Vertical concrete slotted panels provide 1-inch-wide vertical openings (Mukhtar et al. 2011)



One of the most critical aspects of sizing a weeping wall settling basin is provision of adequate basin volume to store dewatered solids for the desired storage period. Meyer et al. (2004) indicated that a good normalized sizing parameter is 2.0 cubic feet per cow per day. Normalized basin sizing parameters determined based on field performance are provided in table 4–72. The only basin studied that did not fit within Meyer’s recommendation was the two-stage system of basins studied by Mukhtar et al. (2011). While the discrepancy was not explained by the authors, it was apparent that the settling basins were used to treat flushed dairy manure following deposition of sand and most likely manure in the lanes that conveyed manure to the primary basin. Therefore, it appears that much of the manure did not reach the weeping wall system.

Meyer et al. (2004) and Mukhtar et al. (2011) collected extensive information concerning solids removal using weeping wall settling basins. Mukhtar also provided information on the removal of plant nutrients. The removal data from both of these studies are summarized in tables 4–73 and 4–74. The solids removals observed by Meyer were larger than those observed by Mukhtar.

In addition, the concentration reductions observed by Myers were similar to those observed by others for more traditional gravity settling. It is believed that the lower concentration reductions observed by Mukhtar et al. (2011) resulted from removal of manure and nutrients with sand prior to the weeping wall basins. The mass removal efficiency of solids and plant nutrients observed by Mukhtar et al. (2011) were quite large with the primary settling basin providing the majority of the treatment. These results suggest that the solids and plant removal efficiencies provided by a weeping wall basin are similar to those provided by a conventional settling basin.

Mukhtar et al. (2011) also provided data on the solids and nutrient content of the dewatered solids removed from weeping wall basins, and their results are given in table 4–75. The solids were very dry at 30 to 36 percent TS wet-basis and could be easily handled and stored as a solid. In addition, they were near the optimal moisture content for composting and relatively high in total nitrogen.

Table 4–72 Comparison of normalized basin sizing parameters from field studies of weeping wall settling basins

Reference	Chamber dimensions (ft)	Chamber volume using 1 ft freeboard (ft ³)	No. of cows	Dewatered solids storage period (days)	Normalized basin sizing parameter (ft ³ /cow/day)
Meyer et al. (2004)	440 × 54 × 7 ^{1/}	142,560	1,100	56 to 84	1.93 (1.54 to 2.31)
Mukhtar et al. (2011)					
Primary	300 × 40 × 8 ^{2/}	84,000	3,500	60	0.40
Secondary	80 × 40 × 8	22,400		21	0.30
				Total =	0.70
Fulhage (2003)	See fig. 4–58 ^{3/}		450	43 to 45	2.22
				Sand + manure	1.67
				Dewatered manure only	

^{1/} Weeping wall formed using 0.25 in horizontal slots formed using tri-bar swine flooring.

^{2/} Weeping wall formed using 1 in vertical slots formed using concrete slotted flooring.

^{3/} Weeping wall formed using 0.375 in horizontal slots formed using tri-bar swine flooring.

Table 4-73 Solids concentration reduction by a weeping wall settling basin used to treat flushed manure on a California dairy (adapted from Meyer et al. 2004); freestalls were bedded with dried separated manure solids

[TS _{IN}] ^{1/} (% w.b.)	[TS _{OUT}] (% w.b.)	CR _{TS} (%)	[VS _{IN}] (% w.b.)	[VS _{OUT}] (% w.b.)	CR _{VS} (%)	[FS _{IN}] (% w.b.)	[FS _{OUT}] (% w.b.)	CR _{FS} (%)
1.14	0.46	59.6	0.64	0.26	59.4	0.50	0.20	60.0
1.4	0.71	49.3	0.83	0.45	45.6	0.57	0.26	54.8
1.64	0.6	63.4	0.94	0.37	60.4	0.70	0.23	67.5
1.76	0.65	63.1	1.00	0.40	60.1	0.76	0.25	67.0

1/ TS = total solids, VS = volatile solids, FS = fixed solids (ash + sand), CR = concentration reduction

Table 4-74 Solids and plant removal using a weeping wall settling basin to treat flushed manure on a Texas dairy that used sand bedding that was removed prior to the basin (adapted from Mukhtar et al. 2011)

Constituent	Influent flushed manure [C _{IN}] (mg/L) ^{1/}	Reduction for primary chamber		Overall reduction	
		CR	MRE	CR	MRE
TS	30,130	27	67	35	88
VS	21,641	28	67	40	89
TKN	1,332	9	60	10.5	84
TP	188	2.5	55	18	86
TK	1,331	-2.6	55	7	84

1/ 1 mg/L = 0.00835 lb/1,000 gal

Table 4-75 Composition of the dewatered solids removed from a weeping wall settling basin (adapted from Mukhtar et al. 2011)

Constituent (wet-basis)	Primary settling chamber	Secondary settling chamber
TS (%)	30	36
VS (%)	20	13
TKN (lb/1,000 lb)	19.800	12.400
TP (lb/1,000 lb)	3.915	2.047
TK (lb/1,000 lb)	12.211	6.368

Example 4–11—Calculation of the storage volume for a porous-wall settling basin and sand savings

A dairy producer had a freestall barn with 300 stalls that housed 320 cows with stalls bedded with coarse sand. Alleys were flushed four times each day, and the sand use rate was 60 pounds of sand per freestall per day. Determine the chamber storage volume for a two-chambered, porous-wall settling basin for a solids storage period of 30 days. Also, estimate sand savings if the sand recovery and recycle rate is 71 percent. How much money will be saved per year if sand costs \$9.50 per ton.

Step 1: Calculate the stocking rate—

$$\begin{aligned} \text{SR} &= 320 \text{ cows} / 300 \text{ stalls} \\ &= 1.07 \end{aligned}$$

Step 2: Calculate the storage volume for one chamber using equation 4–44.

$$\begin{aligned} \text{CV} &= 300 \text{ stalls} \times 30 \text{ days} (60/120 + 1.07 \times 1.67) \\ &= 20,582 \text{ ft}^3 \text{ per chamber} \end{aligned}$$

Step 3: Determine the annual sand use.

$$\begin{aligned} \text{Sand use/year} &= \frac{60 \text{ lb sand} \times 300 \text{ freestalls} \times 365 \text{ day/yr}}{2,000 \text{ lb/ton}} \\ &= 3,285 \text{ tons of sand/year} \end{aligned}$$

Step 4: Calculate the annual purchased sand savings.

$$\begin{aligned} \text{Sand savings} &= 0.71 \times 3,285 \text{ tons of sand/yr} \\ &= 2,332 \text{ tons/yr} \end{aligned}$$

$$\begin{aligned} \text{Sand bedding cost savings} &= 2,332 \text{ tons/yr} \times \$9.50/\text{ton} \\ &= \$22,154 \end{aligned}$$

(c) Geotextile filtration

Geotextile filtration is a relatively new idea that has been investigated as a means to dewater lagoon sludge and flushed manure. Woven geotextiles have an apparent opening size (AOS) that is determined by the

diameter of the PVC threads used to form the fabric and the thread count. Fabrics with high thread counts and low AOS tend to be the most expensive. Preliminary testing by Baker (2002) indicated that apparent opening sizes ranging from 0.30 to 0.60 millimeter did not impact sludge dewatering using woven geotextiles. The characteristics of the solids that formed a filter cake on the inside of the fabric were responsible for much of the mass removal of solids and plant nutrients. Using small AOS (0.30 mm), reduced the rate of dewatering slightly and reduced the rate of evaporation through the fabric. It was concluded that woven geotextiles with an AOS of 0.60 millimeter were sufficient for constructing geotextile dewatering tubes.

Researchers at Clemson University provided an initial evaluation of the efficacy of geotextile filtration without addition of coagulants or flocculants for dewatering dairy lagoon sludge, swine lagoon sludge, fresh dairy manure (milking center wastewater), and fresh swine slurry from a pull-plug pit using the hanging bag test (Baker et al. 2002; Cantrell et al. 2008). The hanging bag test allowed a complete mass balance to be performed on a small scale geotextile tube (fig. 4–64),

Figure 4–64 Test-scale geotextile tubes (Baker 2002)



and a complete analysis of the dewatered material (fig. 4–65). The solids were removed from the tubes following three fill and dewater cycles. It was determined that geotextile filtration was effective for both lagoon sludge mixtures and the dilute fresh dairy manure (TS = 0.71%) but not for swine slurry. The oily and sticky nature of the swine slurry resulted in a film that prevented adequate dewatering.

The sludge to be dewatered was loaded into the top of the approximately 3.5 ft. by 3.5 ft. in circumference geotextile tube and the effluent was collected in the plastic container. The plastic sheets were to minimize evaporation effects over the course of the 70 day test.

The concentration reductions and overall mass removal efficiencies for the two lagoon sludges and the dilute dairy manure are provided in table 4–76. Solids and plant nutrient removal efficiencies were very similar for both the swine and the dairy lagoon sludge mixtures. Geotextile filtration removed 87.8 percent of TS, 58.4 percent of total ammoniacal nitrogen (TAN), 87.0 percent of organic-N, and 86.7 percent of total phosphorus (TP). The dewatering characteristics were also similar for both sludges. The removal efficiencies for fresh liquid dairy manure were lower than for dairy lagoon sludge. For fresh dairy manure, geotextile filtration removed 47.3 percent of TS, 25.8 percent of TAN, 43.0 percent of organic-N, and 44.9 percent of TP.

The average volume reduction and the characteristics of the dewatered sludges after removal from the geotextile tubes are summarized in table 4–77. The combination of dewatering by drainage and evaporation through the pores in the fabric resulted in a volume reduction of 16 to 21 percent for lagoon sludge mixtures. Therefore, for every 10,000 gallons of sludge mixture removed from a lagoon and dewatered with geotextile fabrics would yield 1,850 gallons (18.5%) of dewatered sludge to be land applied. Such a reduction in volume would greatly reduce the cost of transportation of lagoon sludge to remote fields. The effluent from a full size tube would be drained back into the lagoon. Geotextile filtration of the dilute fresh dairy manure would concentrate 38 percent of the solids into only 4 percent of the original volume. The solids and plant nutrient contents of the dewatered sludges and dewatered dairy solids were much higher than the influent as indicated by the concentration factors in the table. The dewatered lagoon sludges has a TS content of 15.3 and 29.9 percent and could be handled as a thick semisolid or solid manure. Dewatered dairy solids had a TS of 13.0 percent and had a consistency that would permit spreading with solid manure equipment available on most dairy farms. While treatment of dilute fresh dairy manure was successful in this test, the results indicated that geotextile filtration may be most applicable to dewatering lagoon sludge and possibly anaerobic digester sludge.

Figure 4–65 Thickened lagoon sludge and fresh dairy solids as removed from the geotextile bags. Dried solids accumulated on the inside of the fabric and wet, thick solids that accumulated near the bottom of the tubes



Dewatered dairy sludge



Dewatered swine sludge



Dewatered fresh dairy solids

Table 4-76 Performance of geotextile bags used to treat lagoon sludge and milking center wastewater (Baker et al. 2002 and Cantrell et al. 2008)

	Dairy lagoon ludge mixture TS _{in} = 5.3%		Swine lagoon sludge mixture TS _{in} = 3.6%		Fresh dairy-milking center wastewater TS _{in} = 0.71%	
	CR ^{1/}	MRE ^{2/}	CR	MRE	CR	MRE
	(%)	(%)	(%)	(%)	(%)	(%)
TS	80.6	87.8	80.8	87.3	33.3	38.4
VS	77.3	85.7	82.2	88.2	44.8	49.0
TSS	82.7	89.1	84.0	89.5	45.9	49.9
VSS	79.1	86.9	83.5	89.1	51.6	55.2
TAN	26.1	53.7	44.3	63.2	19.8	25.8
Org-N	76.3	85.1	83.2	88.9	39.0	43.0
P ₂ O ₅	77.9	86.1	80.6	87.2	40.4	45.0
K ₂ O	17.0	48.0	10.2	41.0	-8.1	0.40
Ca	78.3	86.4	83.0	88.8	28.6	34.1
Mg	69.4	80.8	78.3	85.7	28.8	34.4
S	66.9	79.2	73.8	82.7	39.4	44.2
Zn	93.6	96.0	79.9	86.8	52.3	55.8
Cu	88.6	92.8	80.7	87.3	44.2	48.4
Mn	84.5	90.2	79.3	86.4	41.2	45.5
Na	5.5	40.8	2.1	35.6	-7.6	0.77

^{1/} Average concentration reduction over three fill-dewater cycles

^{2/} Total mass removal efficiency over three fill-dewater cycles

Table 4–77 Volume reduction and composition of the separated solids removed from test-scale geotextile bags (Baker et al. 2002 and Cantrell et al. 2008)

	Dairy lagoon sludge mixture		Swine lagoon sludge mixture		Fresh dairy-milking center wastewater	
	(g/L)	$[C_{SM}]/[C_{IN}]^{1/}$	(g/L)	$[C_{SM}]/[C_{IN}]$	(g/L)	$[C_{SM}]/[C_{IN}]$
TS	299.3	5.6	152.7	4.2	129.5	17.9
VS	90.97	5.4	86.3	4.2	96.5	20.5
TAN	0.27	2.0	0.86	2.3	7.41	21.3
Org–N	3.85	4.9	6.67	4.1	4.46	17.0
P ₂ O ₅	6.72	5.2	13.6	4.1	3.83	16.0
K ₂ O	0.82	2.8	0.96	2.0	0.8	1.6
Ca	4.47	5.5	8.45	4.2	3.01	13.0
Mg	0.96	5.0	1.27	4.1	0.95	12.8
S	1.65	5.0	2.36	4.0	0.81	20.5
Zn	0.05	1.6	0.43	4.0	0.05	24.8
Cu	0.02	2.8	0.06	4.2	0.01	34.2
Mn	0.16	9.4	0.16	4.1	0.03	17.0
Na	0.14	1.8	0.18	1.6	0.26	1.2
Volume Reduction (V_{SM}/V_{IN})	0.16		0.21		0.04	
Bulk density (g/L)	1180.0		1035.3		969.8	

1/ Concentration factor = [concentration in the separated material] / [concentration of the influent sludge or manure]

Two field trials were conducted using full-scale geotextile tubes to dewater dairy lagoon sludge mixtures (fig. 4–66). One study was conducted at the University of Georgia Experiment Station (Worley et al., 2004) and the other was conducted at Texas A&M University (Mukhtar et al. 2007). In both cases, a dairy lagoon was agitated (fig. 4–67) and a sludge-lagoon water mixture was pumped into a large geotextile tube. Liquids were allowed to drain from the tube for 2 to 7 days. Several additional fill-dewater cycles (2 to 6) were carried out until the geotextile tube was filled with solids. The most significant difference between the two studies was that Mukhtar et al. (2007) injected small amounts of alum and two PAMs to help improve the rate of dewatering. Mixing of the chemicals with the sludge-supernatant mixture was achieved by pumping the chemically treated slurry through a section of pipe with a series of 8, 90 degree bends prior to filling the geotextile tube. The results for these two studies are summarized in table 4–78. The primary benefits of using alum and the PAMs was an enhancement in the removal of phosphorus and the potential for faster de-

watering with less fabric clogging. In most cases, addition of a PAM or a combination of chemicals is needed to make geotextile filtration practical for dewatering large amounts of lagoon or anaerobic digester sludge. The chemicals used and performance characteristics are very similar to those described previously in section 637.0405. The methods described in appendix D can be used to evaluate chemical effectiveness and to determine the most effective dose. A hanging bag test should be performed to evaluate the effectiveness of the chemical and dose for a particular geotextile fabric.

Geotextile filtration appears to be a viable option for lagoon sludge dewatering, especially with the addition of chemicals, but may be more difficult to use for primary manure treatment due to the large amount of time required. An advantage of the system is that it greatly reduces the volume of sludge that needs to be transported and land applied. Another advantage is

Figure 4–66 Geotextile tubes used to dewater dairy lagoon sludge mixtures in Georgia and Texas (Worley, J and Mukhtar et al. 2007)



(a) Geotextile tube used in Georgia without chemical enhancement (45 ft circumference × 100 ft long).



(b) Geotextile tubes used in Texas with alum and PAM enhancement (14 ft wide × 50 ft long).

Figure 4–67 Agitation of a lagoon with a centrifugal chopper pump to remove sludge (Clemson University Cooperative Extension)



that a geotextile tube provides a safe method to store dewatered sludge. Land application of the dewatered sludge can be scheduled to deal with poor weather conditions and to coincide with crop needs and available labor. This method gives flexibility in both timing and location of sludge application since dewatered sludge can be more economically transported greater distances than the sludge-supernatant mixture pumped from a lagoon.

Geotextile tubes can be fabricated to provide small and large storage volumes. Tubes can range in circumference from 45 to 90 feet and can be made to any length. The limitations to size are the ability to roll the tube onto a transport cylinder, like a carpet, and the

capacity of the truck used to transport geotextile tubes to the site. The tubes have two or more fill ports that are located at even intervals down the length of the tube. Long tubes may have four or more fill ports.

Filling a geotextile tube with lagoon sludge is a process that occurs over several weeks or even months. Sludge is pumped into a geotextile tube until it reaches the maximum fill height. The maximum fill height is prescribed by the manufacturer and depends on the circumference of the tube and the strength of the fabric. At this height, the tube can contain the material to be dewatered without danger of rupture. When the tube is filled to the maximum height, the weight of the slurry forces the liquid to initially drain quite rapidly out the pores in the fabric. The rate of dewatering can be observed by how quickly the top of the tube descends from the maximum fill height. As sludge dewateres, a filter cake is formed along the inside surface of the tube that improves the capture of solids and plant nutrients. Data collected by Cantrell et al. (2008) indicated that the high rates of ammonium-N removal were the result of the organic matter in the filter cake. Once the tube has dewatered sufficiently, additional sludge mixture can be pumped from the lagoon into the tube. These cycles of filling and dewatering are repeated until the tube is filled with solids. A full geotextile tube is allowed to drain slowly for several weeks until the contents can be handled as a solid. The geotextile fabric will allow water to drain and moisture to evaporate through the fabric while shedding rainwater. It is important to locate geotextile tubes so that effluent and runoff will be collected and transported to the lagoon.

Dewatered sludge is unloaded from a large geotextile tube in a manner similar to a bunker silo or silo bag. The bag can be partially cut open at one end and a skid-steer loader is used to remove the material and load it into a spreader. When application operations are suspended for a time the exposed end can be covered with plastic weighted down with used tires in a manner similar to the face of a bunker silo. A small bag can be opened by slicing it down the middle and unloading and applying the material over a short period of time (fig. 4–68). The PVC geotextile must be

Table 4–78 Results of field trials of using geotextile filtration to dewater agitated dairy lagoon sludge with and without addition of a coagulant and PAMs

	Field trial in Texas using alum + PAM ^{1/}		Field trial in Georgia without chemical addition ^{2/}
	CR (%)	MRE (%)	MRE (%)
TS	93.5	94.7	97
FS	89	90.9	
Soluble–P	84.5	88.2	
Total–P	96.5	96.9	79
TKN	84	85.1	80
Org–N			92
Total–K	42.5	47.8	36
Ca	91.5	91.2	
Mg	60	64.9	
Na	12	26.3	
Mn	94	93.7	
Fe	99	99.2	
Cu	99	99.6	

1/ Agitated dairy lagoon sludge was mixed with alum (1.65 mL alum/L) and two PAMs (PAM #1 rate = 0.069 mL/L, PAM #2 rate = 0.034 mL/L) prior to being pumped into a geotextile dewatering tube (Mukhtar et al. 2007)

2/ Agitated dairy lagoon sludge treated with geotextile dewatering tube without addition of coagulants or flocculants (Worley, et al. 2004)

disposed of properly. Fortunately, the material can be recycled if it can be cleaned and transported to the geotextile manufacturer.

(d) Sand bed filtration

A sand filtration bed is a solid-liquid separation method that has been used to dewater municipal and industrial sludge as a final treatment step prior to land filling or land application. Treated sludge is pumped out into long drying beds constructed of a layer of filter sand over layers of gravel. Liquids drain through the sand and the leachate is collected in a drainage system and is transferred to a storage pond or to additional treatment. The layer of sludge is allowed to dry in the sun and is removed using heavy loaders or specialized equipment (Vanotti et al. 2005). A few investigators have evaluated the potential for using sand bed filtration as a means to remove solids and plant nutrients from swine manure.

A preliminary study of sand bed filtration was conducted by Chastain (1999) using a two-step separation process for treating flushed swine manure. Flushed swine manure (TS = 3.3%) was first processed using a rotating drum separator, and the effluent liquid manure was treated with a test-scale, 15-inch-deep sand bed filter.

The rotating drum removed 17 percent of the total solids, 26 percent of the volatile solids, 4 percent of the ammonium-N, 23 percent of the organic-N, 12 percent of the total phosphorus, 0 percent of the total potassium, 11 percent of the zinc, and 12 percent of the copper from swine manure. After passing the separator effluent through the sand bed, the overall removal was 96 percent of the total solids, 97 percent of the volatile solids, 90 percent of the ammonium-N, 99 percent of the organic-N, 97 percent of the total phosphorus, 94 percent of the total potassium, 99 percent of the zinc, and 99 percent of the copper. While the sand bed filter provided a high rate of removal, it drained slowly and soon became clogged with manure particles. To use a sand bed filter in this way would require a great deal of back washing with water to clean the sand bed. It was concluded that the additional handling and treatment needed for the filter back wash water nullified the utility of the sand bed filter.

Vanotti et al. evaluated the use of PAM flocculants to improve drainage and filtration performance of sand filter beds used to provide primary treatment of flushed swine manure. A commercially available flocculation unit was used with two pilot-scale sand bed filters that were 20 feet long by 16 feet wide. The design of the sand beds was similar to a system used for dewatering of treated municipal sludge. The beds were designed to receive up to 12 inches of PAM-treated swine manure. It was found that flocculation with PAM greatly improved the drainage characteristics of the sand filter bed by preventing clogging and surface sealing. The sand filter beds drained within 1 to 2 hours after loading them with flocculated swine manure. The amount of time required to produce removable solids varied with the solids loading rate of the beds. It was determined that a solids loading rate of 0.41 pound TSS per square foot (2 kg TSS/m^2) or less allowed for a drying time of 10 days or less. Short drying times were found to be important to reduce fly problems. The combination of PAM treatment followed by sand bed filtration removed 97 percent of total suspended solids, 97 percent of the volatile suspended solids, 85 percent of the biochemical oxygen demand (BOD_5), and 83 percent of chemical oxygen demand from flushed swine manure. Removal of plant nutrients was of 61 percent of the TKN and 72 percent of the total phosphorus. Most of the N and P removed were in organic forms.

Figure 4-68 Unloading a small geotextile tube used to dewater dairy lagoon sludge (University of Georgia Cooperative Extension Service, Worley et al., 2004)



While PAM greatly enhanced the performance of sand bed filters, it was observed that removal of the separated solids from the sand bed and problems with odors and flies following significant rainfall present major obstacles to using sand bed filtration for primary treatment of manure. However, this method of dewatering may prove useful in the future for dewatering of anaerobically or aerobically digested sludges or for final treatment of dilute, treated wastewater.

(e) Belt solid-liquid separation system for swine manure

A belt separation system provides a completely different method of solid-liquid separation as compared to screens, presses, or gravity settling. The system provides immediate separation of manure solids and liquids (urine and wasted water) below perforated or slotted flooring that is common in swine facilities. By keeping the solid manure and urine separate, bacterial urease, which is contained in feces, has less opportunity to metabolize urea contained in urine to ammonia and carbon dioxide. Using a belt separation system has been shown to reduce ammonia emissions from swine facilities. The belt separation system also divides the manure into a dry solids component that is high in P and can be moved to remote fields where P can be used as fertilizer and a liquid fraction high in N and can be used to fertilize cropland close to the swine facility (Baird et al. 2004; Aarnink and Ogink 2007).

The design of the ventilation system is also an important component of the belt separation system. Belt separators work best when a portion of the ventilation air is drawn down through the slotted flooring and over the belt to dry the solids. In most cases, the amount of ventilation air drawn down through the floor and over the belt will be the minimum ventilation flow rate. However, drawing a larger part of the total ventilation air flow over the belt would be beneficial during warm and hot seasons.

One of the initial studies of belt separation system was conducted in North Carolina and included a conveyor belt suspended below slotted flooring of swine finishing pens. The solid manure, urine, and wasted water fell through the floor and were collected on the belt. The belt had a convex shape so that the liquids drained into gutters that were located on each side of the belt. The liquids flowed by gravity to a collection pit and the

solids remained on the belt where they were conveyed out of the animal housing at least once per day. The belt was also large enough to collect manure from the entire width and length of five pens that contained 15 pigs per pen. The average weight of the pigs when placed in the pens over four cycles was 57 pounds and the average market weight was 249 pounds per pig after a growout period of 95 days. The stocking rate of the pens was 7.95 square foot of floor space per pig.

Average manure production and nutrient content data for the study and the partitioning of solids and nutrients between the solids and liquid fractions are provided in table 4-79. The solids removed from the belt had a solids content that averaged 32.9 percent and contained 89.9 percent of the total P, and the TKN:P ratio was 1.8. The liquid fraction contained some fecal matter as indicated by a TS concentration of 3.5 percent, and 62 percent of the total N produced by the pigs was contained in the liquid fraction and the TKN:P ratio was 26. Therefore, the belt system was successful at providing an immediate partitioning of solids and plant nutrients as desired.

Researchers at North Carolina State University noted that the liquid fraction removed by the gutters contained a significant amount of organic-N. They conducted a bench scale experiment to determine how fast the organic portion would be converted to total ammoniacal nitrogen ($\text{TAN} = \text{NH}_4^+ \text{N} + \text{NH}_3^- \text{N}$). There results indicated that over 90 percent of the organic N was converted to TAN within 26 hours (table 4-80). Depending on the pH level and temperature a portion of TAN would be in the ammonia (NH_3^-) form and could be lost by volatilization from an open liquid storage.

In Europe, studies have been conducted on the use of belt separation systems below partially slotted floors (Aarnink and Ogink 2007; Alonso et al. 2008). In these types of swine buildings, a solid resting area is provided near the feeders and a slotted dunging area is located at the back of the pen. The other important difference in the Spanish study is that varying amounts of bedding were applied to the resting area and added solids to the manure. Consequently, the housing differences yielded different solids production values than would be expected for completely slotted pens used in modern facilities in the United States.

Table 4–79 Performance belt separator located below perforated flooring for finishing swine ^{1/} (data from Baird et al. 2004)

	Belt liquids		Belt solids		Total Mass produced lb/100 pigs/day	Partitioning	
	Concentration	Mass produced	Concentration	Mass produced		Liquid fraction	Solids fraction
	lb/1,000 gal	lb/100 pigs/day	lb/lb (%)	lb/100 pigs/day		(%)	(%)
TS	0.294 (3.5%)	0.024	32.91	61.213	61.236	0.04	99.96
VS	0.226	0.018	27.99	52.055	52.073	0.04	99.96
VS/TS (%)	76.81%		85.04				
TKN	51.25	4.15	1.36	2.536	6.687	62.08	37.92
TAN	9.52	0.77	0.16	0.300	1.071	72.03	27.97
Org-N	41.72	3.38	1.20	2.236	5.616	60.18	39.82
TP	1.96	0.16	0.76	1.421	1.579	10.06	89.94
OP/TP (%)	88.9						
TK	16.19	1.31	1.21	2.255	3.567	36.76	63.24
Cu	0.00	0.00	0.01	0.019	0.019	1.15	98.85
Zn	0.12	0.01	0.14	0.268	0.277	3.38	96.62

^{1/} Swine entry weight averaged 57 lb, and pigs grew to 249 lb over a period of 95 days. The belt solids production averaged 186 lb/100 pigs per day, and the separated liquids averaged 81 gal/100 pigs per day. Pens were stocked at a rate of 7.94 ft² of floor space per pig.

Table 4–80 Results from a bench scale study of conversion of organic-N to TAN in liquids obtained from a belt separation system (adapted from Baird et al. 2004)

	Elapsed time (hr)	TKN (mg/L)	TAN (mg/L)	Organic-N (mg/L)	Organic-N conversion (%)
5:45 AM	0	4,807	261	4,578	0
10:05 AM	4.33	4,567	318	4,521	1.2
12:05 PM	6.33	4,428	396	4,443	2.9
2:05 PM	8.33	4,829	537	4,302	6.0
4:05 PM	10.33	5,144	729	4,110	10.2
8:15 AM	26.5	5,261	4,487	352	92.3

Aarnink and Ogink measured performance of a belt separation system below the slotted portion of four pens of grow-finish swine for two cycles of production in the Netherlands. The amount of bedding added to the resting areas was greater for the second group of pigs than the first. For the first grow-finish cycle, the belt system collected 1.31 kilograms of solids per pig per day and 2.17 kilograms of liquids per pig per day. After adding additional bedding, the solids production for the second cycle was 1.86 kilograms per pig per day and the liquid production was 1.92 kilograms per pig per day. The nutrient partitioning between the belt solids and liquids was similar to the North Carolina study (Baird et al. 2004) in that the belt solids contained the majority of the P (93%) and a significant portion of the K (50%). The belts solids contained 67 percent of the total N and 35 percent of the TAN which was greater than observed in the fully slotted floor study (table 4–79). The belt system performed well for partially slotted floor finishing pens, but the quantitative results were different from the fully slotted floor pens. Therefore, data from a partially slotted floor facility cannot be used to make design projections for fully slotted floor facilities that are common in the United States.

637.0407 Design considerations

One of the most critical steps in the design of a solid-liquid separation process is the definition of the immediate and future goals for the system. The goals for solid-liquid separation will often include one or more of the following:

- Reduce the organic loading rate (VS, COD, or BOD) for a treatment lagoon or other method of biological treatment (anaerobic, aerobic, or facultative treatment)
- Reduce sludge build-up for a treatment lagoon or covered lagoon digester
- Reduce the size of a treatment lagoon, or covered lagoon digester needed to treat liquid manure prior to reuse for manure removal from animal production facilities
- Remove a portion of the plant nutrients (N, P, K) from liquid or slurry manure prior to storage or biological treatment
- Remove solids and plant nutrients (N, P, K) from slurry or sludge following biological treatment (e.g., anaerobically digested slurry, treatment lagoon sludge, or activated sludge from aerobic treatment)
- Remove volatile solids and organic nitrogen to reduce methane and ammonia emissions from treatment lagoons or storage structures
- Generate dewatered manure solids for composting, land application on remote fields, or for use as biomass for energy (e.g., combustion for heat or electricity, biomass gasification for heat or electric power)
- Remove a large portion of the phosphorus (60 to 98%) from liquid manure and concentrate it in a smaller volume that can be transported to places where P fertilization is needed
- Remove sand from sand-laden dairy manure to protect pumps and manure handling equipment from excessive wear and to prevent accumulation of sand in liquid storage structures, treatment lagoons, and anaerobic digesters

- Remove sand from sand-laden dairy manure that is clean enough to condition and reuse as freestall bedding
- Remove a large portion of the solids from dairy manure to yield solids that can be used as freestall bedding following drying, or composting and drying, as dictated by farm climate

In addition to definition of the separation system goals, several farm-specific variables must be considered to guide the selection of a separation method and system design. Some of the key variables that must be determined include—

- Volume and composition of manure to be treated
- Number of manure removal events per day
- Volume of manure to be treated per manure removal event
- Amount of time available for solid-liquid separation between manure removal events
- Expected solids and plant removal efficiencies for separation alternatives considered
- Land area needed for construction of separation system head works
- Land area needed for collection and storage of separated solids
- Utilization alternatives for separated solids
- Methods needed for collection and transfer of drainage and runoff from solids storage areas to a storage structure

Once the system goals and key variables have been determined the wide number of solid-liquid separation alternatives that are available can be narrowed down to a few alternatives. The best alternative will generally be the solid-liquid separation that meets current and future goals while taking into account constraints on labor and costs as well as operational and economic benefits.

(a) Single-stage primary treatment for recycle systems

Many swine and dairy farms use a flush system to remove manure from animal housing facilities. On dairy farms freestall alleys, animal traffic lanes, holding areas, and milking parlor platforms are typically flushed two to three times per day. In some cases, the frequency of flushing on dairy farms can be as high as four to eight times per day. Modern swine facilities are typically designed so as to separate the animals from manure using slotted flooring. Manure is collected in shallow channels below the perforated flooring and is removed 2 to 12 times per day using a manual or automated flushing system. Frequent manure removal by flushing aids in controlling odor emissions, reduces ammonia levels in buildings, and promotes good animal health provided that the water used to remove manure from the buildings has been adequately treated prior to reuse. In milking parlors, only fresh water is allowed to be used for floor cleaning to promote food safety and milk quality.

Another popular hydraulic method used to remove manure from beneath slotted floors in swine buildings is the gravity drain, pit-recharge system that was first described by Barker and Driggers (1985). A pit-recharge manure handling system consists of an under-floor pit with an average depth of 24 to 30 inches. The floor of the pit is typically sloped 1 inch per 20 foot toward a collection gutter that conveys manure to a drain that is located in a sump outside the building. An 8 inch outside diameter drain is plugged using a removable standpipe made of PVC. A slot is cut in the side of the standpipe to establish the liquid depth in the pits. The level is set so that the highest part of the pit floor is covered by 6 or more inches of recycled lagoon supernatant. After filling the pit, manure is allowed to accumulate in the pit for 5 to 7 days. As manure and waterer wastage accumulates a portion of the water used to fill the pit decants through the slot in the drain pipe. As a result, the volume of the pit stays the same as manure accumulates at the bottom of the pit. The pit is emptied by pulling the standpipe and allowing the pit contents to drain to a treatment lagoon. Additional cleaning can be provided by allowing the recycled water to flush out the pit for a few minutes prior to inserting the standpipe and allowing the pit to refill. The recharge pit volume varies with building design, but is often in the range of 40,000 to 50,000 gallons (Chastain et al. 2001b). As with a flush system,

well-treated wastewater is required to control odor, ammonia, and to protect animal health.

As was previously shown in section 637.0402, the total and volatile solids removed by a solid-liquid separator can be an effective means to reduce the loading rate on an existing treatment lagoon, or to reduce the size of the treatment volume needed for a proposed lagoon (tables 4-2 and 4-3). Solid-liquid separation can also reduce the rate of sludge accumulation in a treatment lagoon (tables 4-5 and 4-6) resulting in a reduction in labor and energy costs associated with periodic agitation, removal, transport, and land application of sludge.

(1) Mechanical solid-liquid separation

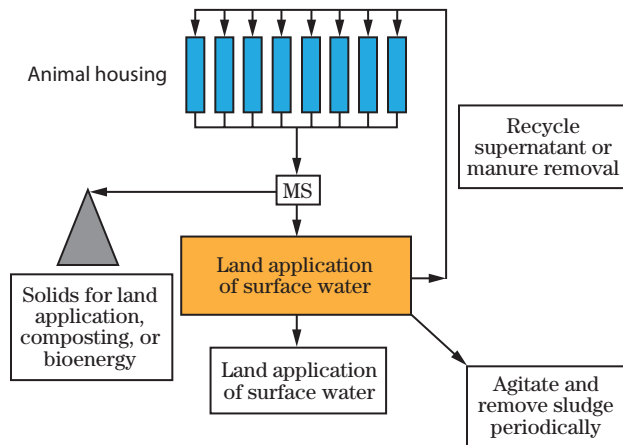
The simplest use of solid-liquid separation to improve treatment of wastewater prior to recycling is to place a single-stage of mechanical separation prior to a treatment lagoon (fig. 4-69). The amount of TS and VS removed prior to biological treatment will depend of the species, type of mechanical separator (MS) used, and the screen size. Solids removal can range from 10 to 50 percent and large amounts of removal data are provided in sections 637.0403 and 637.0404 for a wide variety of machines. The amount of solids removed by the mechanical separator will have a direct impact on the amount and frequency of sludge removal from a treatment lagoon. Use of a mechanical separator to improve treatment will also yield a substantial amount of solids that must be collected, stored, and utilized in a beneficial and environmentally responsible manner. Separated solids can be used in a variety of ways besides ordinary application to cropland. They can also be used to make high-quality compost, or as a source of biomass energy for combustion (see “Uses of separated solids” in section 637.0402).

A single-stage mechanical separation system, as shown in figure 4-69, is designed to treat all of the liquid manure that flows from the animal housing facilities. As a result, two critical factors that need to be considered are the volume capacity of the separator head works and the throughput rate of the machine (gpm). The simplest type of head works used with a mechanical separator includes the pipes or channels used to convey liquid manure from the buildings and a reception pit. The reception pit is used to contain manure while it is processed by the mechanical separator. The pipes or channels used to convey manure must be designed to maintain a mean flow velocity greater than 3 feet

per second to insure that manure solids do not settle and create a clog. The most common transfer method used is a large gravity flow pipe that top loads a reception pit. If the reception pit is to be bottom loaded, as is common in cold climates, care must be taken to ensure that the flow rate in the pipe is not reduced to the point that manure temporarily backs up in the pipe and reduces the flow rate of manure from the barns. The reception pit must be sized large enough to easily store the liquid manure volume from at least a single flush event. The throughput rate of the mechanical separator must be sufficient to treat all of the manure in the reception pit before the next manure removal event. If the throughput rate of a single separator is not sufficient to process all of the manure before the next flush event then either the reception pit must be increased in size or a second separator may be required to meet throughput demands. In some cases, a different type of mechanical separator with a higher throughput rate may be needed.

The throughput rate of a mechanical separator will vary greatly with separator type, screen opening size, screen area, solids content of the manure, and animal species. Also the size of the machine is important since larger machines can process manure at higher rates. Published values from manufacturers and from studies can provide a general idea of processing ca-

Figure 4-69 Use of a mechanical separator (MS) to reduce the organic loading on a treatment lagoon to yield treated wastewater for manure removal



capacity and are summarized in table 4–81. However, more detailed information must be obtained from the manufacturer of a particular machine. For large animal production facilities it may be difficult to obtain both a high throughput rate and high solids and plant nutrient removal efficiencies using a single stage of mechanical solid-liquid separation (section 637.0403).

Estimation of the required throughput rate is a helpful but often overlooked step when selecting a mechanical solid-liquid separator. Knowledge of the required throughput rate will often determine which machine is sufficient for the task.

Single-stage mechanical solid-liquid separation provides many advantages and disadvantages for an animal producer. The advantages include—

- A relatively small amount of space is needed for the machine and the associated reception pit.
- It can be added easily to an existing animal manure treatment system in many cases.

- The solids generated are typically dry enough to stack and they can be easily incorporated into a composting recipe or land applied using common manure spreading equipment.
- Mechanical separation capacity can be increased by adding another machine to an existing reception pit or by building another system to treat manure from new barns.

The disadvantages of using a single stage mechanical solid-liquid separator include—

- Electrical energy is required to operate pumps and conveyors.
- Mechanical separators require maintenance of screens, drive systems, motors, belts, and other parts.
- High solids and plant removal often requires low flow rates and small screen sizes.
- High solids and plant removal may generate solids that are too wet to stack easily.
- High solids and plant removal efficiencies are often difficult to achieve on large flush dairy and swine farms due to screen size and throughput constraints.

Table 4–81 Approximate throughput rates (gallons/minute) for several types of mechanical solid-liquid separators^{1/}

	High TS—slurry	Low TS—liquid
Inclined stationary screen	33–100	150–1,000
In-channel flighted conveyor screen	33–90	100–400
Rotating screen	10–175	200–1,000
Screw press	12–61	85–300
Belt press	2.5–50	
Roller press	13–67	64–1,500
Filter press		1–10
Centrifuge	10–15	30–40
Hydrocyclone		20–60
Vibrating screen	10–30	15–40

^{1/} Values are based on sources previously referenced in this document

Example 4–12—Estimation of mechanical separator throughput requirements for a swine farm that uses a pit-recharge system

A swine finishing farm has 6 houses that use a pit-recharge system to collect and remove manure from the buildings. The volume of the recharge pits are 40,000 gallons and 1 building is emptied each day, 6 days a week. The producer is considering the addition of a mechanical solid-liquid separator to reduce the loading on the lagoon. The constraints that may impact the needed throughput rate of the machine selected are: emptying a building requires 40 minutes, the average TS concentration will range from 1.5 to 2.6 percent depending on the weight of the animals in the building, and the total amount of time available for separation is 4 hours.

Calculate average manure flow rate:

The average manure flow rate will be 40,000 gallons ÷ 40 minutes = 1,000 gallons per minute. Therefore, the

separator would need a throughput rate of more than 1,000 gallons per minute if the manure is processed at the rate that manure flows from the building. A smaller separator could be used if a 40,000 gallon reception pit is used to collect the manure prior to separation.

Calculate the minimum average throughput rate:

The minimum average throughput rate needed will be 40,000 gallons ÷ 4 hours ÷ 60 minutes per hour is 167 gallons per minute. Using this value as a guide the potential types of separators that could be used are inclined screen, in-channel flighted screen, rotating screen, roller press, and possibly a screw press.

Example 4-13—Estimation of mechanical separator throughput requirements for a flushed dairy farm

A 600-cow dairy farm flushes freestall alleys each time the cows are moved to the milking center for milking. It has been determined that the flush volume (flush water + manure) is 4,850 gallons per alley with an average TS of 1.3 percent. A total of 8 alleys will be flushed during a 5-hour milking shift with a single alley being flushed every 38 minutes. The milking center is also flushed and can generate an additional 4,000 gallons at the end of a milking shift and possibly near the middle of a milking shift. What is the throughput rate needed for the mechanical separator?

Calculate the throughput rate for a single alley flush:

The throughput rate for a single alley flush is 128 gallons per minute (4,850 gal ÷ 38 min). The reception pit in this case would need to be about 4,850 gallons.

Calculate the throughput rate and reception pit volume for the parlor and an alley:

If the flush from an alley and the parlor occurs at the same time, the reception pit must be larger to allow the separator more time to process the additional manure.

If all of the manure is to be processed at the same time the reception pit should be at least 8,850 gallons (4,850 gal + 4,000 gal). The amount of time needed to process an alley flush and a parlor flush using a throughput of 128 gallons per minute would be 69 minutes. Since two alley flushes will occur every 76 minutes, this combi-

nation would be sufficient. Expanding the reception pit to an active volume of 9,700 gallons would allow two alleys to be flushed at the same time if needed.

Example 4-14—Calculation of minimum reception pit volume when mechanical separator throughput is less than the manure flow rate

A dairy producer has determined that the total flush volume from his 600-cow dairy freestall barns will be 38,800 gallons for each 5-hour milking period (4,850 gal/alley × 8 alleys). The flush volume from the milking center will also be 8,000 gallons per 5-hour milking period (4,000 gal/flush × 2). The producer has determined that to use a small screen in a screw press (0.50 mm) the throughput will average 116 gallons per milking. How large does the reception pit need to be to allow the screw press to complete processing of the manure after the 5-hour milking period and will all of the manure be processed in less than 7 hours? How large would the reception pit need to be if flushed manure from the milking center was excluded from this stage of primary treatment?

Determine total volume to be treated and the amount of time the screw press must run per milking period:

The total volume of manure to be processed is 46,800 (38,800 + 8,000) gallons/milking. Total process time is 403.4 minutes (46,800 ÷ 116 gal. per milking) or 6.72 hours per milking period. Therefore this screw press can meet the processing time constraint of 7 hours.

Estimate the minimum volume for the reception pit:

The minimum volume of the reception pit, S_{PIT} , can be calculated using the following mass balance (assuming density is constant):

$$S_{PIT} = f_s \times (Q_{IN} - STR) \times \Delta t_{IN} \quad (\text{eq. 4-45})$$

where—

- f_s = safety factor, 1.1 – 1.2.
- Q_{IN} = manure flow rate into the reception pit, gpm
- STR = separator throughput rate, gpm
- Δt_{IN} = The total time interval that manure flows into the reception pit at the rate Q_{IN} , min.

For this example, $Q_{IN} = 46,800$ gallons / (5 hr \times 60 min/hr) is 156 gallons per minute, STP = 116 gallons per minute, $\Delta t_{IN} = 300$ minutes, and a safety factor of 1.1 was used. Therefore, the minimum volume for the reception pit is 13,200 gallons. Also note that the reception pit volume in this case could also be calculated as 12,850 gallons (one alley flush + two milking center flushes = 4,850 + 8,000).

Estimate the minimum volume for the reception pit if only freestall manure is treated using the screw press:

The value of Q_{IN} for only the flushed freestall barns is 129.3 gallons per minute (38,800 gal/300 min). Using equation 4-45 with a safety factor of 1.1, the minimum reception pit volume would be 4,389 gallons. However, a reception pit that holds at least one full alley flush is recommended to ensure that any delays in starting the separator would not cause an overflow or reduce the flow rate in the pipes that convey manure to the pit.

In all of the examples, a minimum freeboard of one foot should be added to the reception pit. In addition, a reception pit should have an outlet that prevents overflow. The outlet would convey excess volume to the treatment lagoon.

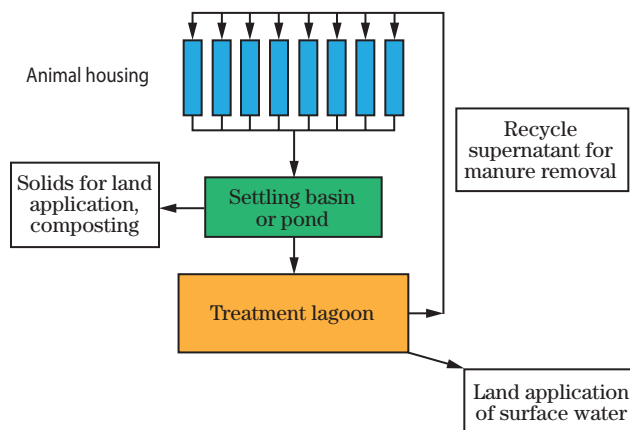
(2) Gravity solid-liquid separation

On flush dairy and swine farms a gravity settling basin or storage pond can be designed to handle the high throughput rate needed while providing solid and plant nutrient removals that are often twice that of many single-stage mechanical separators. A general layout for this type of single-stage system is provided in figure 4-70.

The two types of gravity settling structures most often used to reduce loading on a treatment lagoon are a draining type settling basins or a settling pond. A draining settling basin is designed to allow free water to drain slowly from the settled solids providing a high level of dewatering. Evaporation also provides additional dewatering, but will vary with the depth of the solids and the weather. Many types of screened outlets and riser pipe configurations have been used to allow liquids to drain from the settled solids (AWMFH, ch. 12). One of the more recent ideas is the weeping or porous wall structures described in section 637.0406. Depending on farm location and solids utilization plan, a drain-dry type settling basin can be sized to

provide solids storage for a period that ranges from two weeks to several months. These types of basins are typically dewatered to the point that solids can be removed using a front-end loader. They can be handled and land applied as semisolids or solids. As a result, concrete bottoms and ramps must be incorporated into the design. On dairy farms located in relatively dry climates (western Texas, Kansas, or California) the solids will often be dry enough to stack on a concrete pad prior to composting or land application. A settling pond is a structure that is designed to provide the maximum amount of settling while maintaining the settled solids in a consistency that can be agitated and pumped (3 to 8% TS). The structure functions as a manure storage with the liquid level controlled by a screened, outlet pipe. The liquid effluent from the storage pond flows into the treatment lagoon where additional treatment is provided prior to reuse. The solids agitated and pumped out using techniques similar to a slurry storage pond (AWMFH 2012). Settling ponds are designed to contain the settled solids for a defined storage period (3 to 12 months) plus a layer of liquid that is sufficient to cover the solids and maintain them in a pumpable condition. Application of solids from a settling pond are most often used to offset purchased fertilizer on fields that are remote from the animal

Figure 4-70 Use of a settling basin or pond to reduce organic loading on a treatment lagoon and to eliminate sludge accumulation in a treatment lagoon



facility. However, they are generally too wet to use for composting directly. They need to be dewatered and mixed with large amounts of organic matter to provide an acceptable C_T:N ratio (25 to 40) and moisture content (50 to 60%). Single-stage primary treatment

using a settling basin or pond has several advantages and disadvantages summarized in table 4-82. They need to be considered and evaluated during the planning process.

Table 4-82 Advantages and disadvantages of using draining settling basins and settling ponds for single-stage primary treatment

Settling method	Advantages	Disadvantages
<i>Draining settling basin</i>	<p>Greatly reduces organic loading in a treatment lagoon</p> <p>Greatly reduces or eliminates sludge buildup in a treatment lagoon</p> <p>Eliminates need to agitate manure prior to removal</p> <p>Greatly reduces the volume of solids that must be utilized</p> <p>Concentrates organic plant nutrients</p> <p>Can be used with sand bedding on dairy farms</p> <p>Much smaller than the equivalent settling pond</p> <p>Reduction in methane, ammonia, and odor emissions from an anaerobic treatment lagoon</p>	<p>Use of a loader to remove solids may require more labor than pumping for large farms</p> <p>Dry solids may provide material suitable for fly propagation</p> <p>Uncovered solids may not dry well in a wet climate</p> <p>Odor may be a problem if sufficient drying does not occur (common in wet climates)</p>
<i>Settling pond</i>	<p>Greatly reduces organic loading in a treatment lagoon</p> <p>Eliminates sludge buildup in a treatment lagoon</p> <p>Agitation and removal of solids is more efficient than removal of sludge from a treatment lagoon</p> <p>Concentrates organic plant nutrients</p> <p>Removal of settled solids with pumps may be more cost effective than using a frontend loader on large farms</p> <p>Persistence of a liquid layer above the settled solids will reduce fly propagation</p> <p>Reduction in methane, ammonia, and odor emissions from an anaerobic treatment lagoon</p> <p>Permeable or impermeable covers can be used to reduce emissions of odor, ammonia, and other gases</p>	<p>A larger volume of settled solids must be removed, transported to remote fields and land applied due to higher water content</p> <p>A portion of the settled solids may resuspend and be washed into the treatment lagoon</p> <p>Odor and ammonia emissions from an uncovered settling pond will often be greater than for a draining settling basin.</p> <p>May require several concrete ramps and pad around the perimeter of the settling pond to facilitate solids removal.</p>

Example 4–15—Calculate settling pond volume requirements for a swine farm that uses a pit-recharge system

A swine finishing farm has 6 houses that use a pit-recharge system to collect and remove manure from the buildings. The volume of the recharge pits are 40,000 gallons and one building is emptied 6 days a week. The total volume of liquid manure that flows from the buildings in a week is 240,000 gallons per week. The average TS concentration of the manure ranges from 1.5 to 2.6 percent depending on the weight of the animals in the building. The farm is located in a warm climate that permits crop production about 8 months per year. As a result, the settling basin needs to store settled solids for 26 weeks (6 months). Calculate the storage volume needed for settled solids.

Determine settled volume fraction (SVF):

The average TS content on this farm is 2.0 percent. Use the equation given in table 4–26 to determine the settled volume fraction to use for sizing the settling pond:

$$\text{Linear hindered settling } SVF_{LHS-f} = 0.0513 e^{0.9056 TS} = 0.32$$

$$\text{Compression settling } SVF_{CS-f} = 0.0464 e^{0.6640 TS} = 0.18$$

The SVF for compression settling is used since manure will be contained over 24 hours (figs. 4–35).

Calculate settled solids storage volume:

The volume of settled solids to store per week is—

$$0.18 \times 240,000 \text{ gal/week} = 43,200 \text{ gal/week}$$

The storage volume needed for 26 weeks (6 months) is—

$$43,200 \text{ gal/week} \times 26 \text{ weeks} = 1,123,200 \text{ gal}$$

The recommended liquid depth above the solids is 1.5 to 2.0 feet. All rainfall that falls on the storage will be contained in the treatment lagoon. A freeboard of a least 1 foot is required and 2 feet may be required to meet regulatory requirements in some States.

Example 4–16—Calculate draining settling basin volume requirements for a swine farm

Estimate the storage volume requirements for a draining settling basin that removes 53 percent of the TS from liquid swine manure, and allows the solids to drain and dry to a TS content of about 10 percent. What is the total settled solids storage needed per day and for 182 days (26 weeks)? A previous gravity settling mass balance determined that 0.85 pound of total solids is removed per hog per day (ex. 4–9). The total number of hogs housed in the finishing buildings is 4,800.

Estimate the settled TS generated per day:

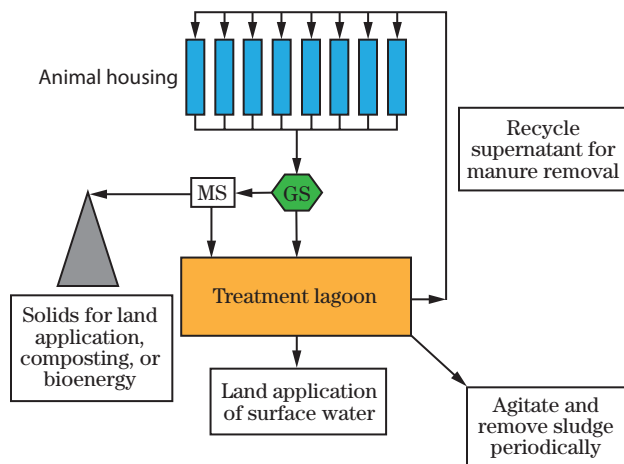
The mass of dry matter (TS) removed by settling is—

$$0.85 \text{ lb settled TS/hog/day} \times 4,800 \text{ hog} = 4,080 \text{ lb settled TS/day}$$

Determine the volume occupied by the settled solids in a single basin:

The first step is to convert the 10 percent TS to pound per gallon.

Figure 4–71 Use of a gravity settling basin (GS) to settle and thicken solids prior to a high-removal mechanical separator (MS)



Convert TS in percent to g TS/L:

$$\begin{aligned} (\text{TS, g/L}) &= (\text{TS, \%}) \times 10 \\ &= 10\% \times 10 \\ &= 100 \text{ g TS/L} \end{aligned}$$

Convert the TS content in g/L to pound per gallon as—

$$\begin{aligned} [\text{TS, lb/gal}] &= [\text{TS, g/L}] \times \frac{3.78541 \text{ L/gal}}{453.592 \text{ g/lb}} \\ &= 100 \text{ g/L} \times \frac{3.78541}{453.592} \\ &= 0.835 \text{ lb TS/gal} \end{aligned}$$

The second step is to calculate the volume of settled solids:

$$\begin{aligned} \text{Volume of settled solids/day} &= \frac{\text{lb settled TS/day}}{[\text{TS, lb/gal}]} \\ &= \frac{4,080 \text{ lb settled TS/day}}{0.835 \text{ lb TS / gal}} \\ &= 4,886 \text{ gal/day} \end{aligned}$$

The volume of settled storage needed for 180 days is—

$$4,886 \text{ gal/day} \times 182 \text{ days} = 889,252 \text{ gal}$$

(b) Multiple-stage primary treatment for recycle systems

Screen type mechanical solid-liquid separators have the advantage that they can be manufactured in sizes that are sufficient to process liquid manure at the high throughput rates needed on large dairy and swine farms. They also produce separated solids that stack easily (TS = 20% or more), release minimal odor, and do not support fly propagation if they remain dry. The challenge is that modern farms require high removal rates for solids and plant nutrients while maintaining high throughput rates. To address this challenge, several manufacturers have developed a variety of inclined static screen separators or in-channel flighted separators that combine smaller screen openings with a secondary dewatering method into a single machine or system. Some of the available combinations include—

- An in-channel flighted stacking screen conveyor combined with a small screw press prior to stacking (fig. 4–13).
- Combination of an inclined screen with a roller press on the outlet.
- Combination of a fine sloping screen with a low-pressure screw press and stacking screen conveyor (fig. 4–14 and example 4–8).
- Combination of an inclined screen and a centrifuge or hydrocyclone.
- Combination of screw press with a centrifuge.

Some of the mechanical separators that provide the highest removal efficiencies are presses with a small screen or belt openings, and centrifuges. However, as removal efficiency increases separator throughput rate falls to 50 gallons per minute or less. One of the options to utilize these types of machines is to add multiple separators to the system to meet the flow rate requirements. This is often an undesirable option, since treatment costs may double or triple. Another option is to combine a high-rate mechanical separator with a gravity settling (GS) basin that is designed to allow the settleable solids to accumulate and thicken into a smaller liquid volume while allowing the supernatant from the settling process to flow to the treatment lagoon as shown in figure 4–71. The effluent from the mechanical separator also will flow into the lagoon for additional treatment.

The solids removed by any mechanical separator are the large solids that will float or the solids that will settle. Many of the high-removal separators that use fine screens (e.g., screw press, belt press, fine inclined screens combined with a screw press, etc.) perform better when the influent manure has a TS content that is greater than associated with flush systems. Settling and thickening in a GS basin prior to mechanical separation will increase the TS content of the manure processed by the separator from the range of 0.5 to 2.5 percent to 3.5 to 7 percent. Consequently, the combination of a settling basin followed by a high-removal mechanical separator will provide the same or better performance as if the entire flow was processed by multiple separators of the same design. A screened outlet should also be provided for the settling basin to retain floating solids that are to be removed by the machine. This arrangement will allow use of a single

machine to treat manure from a larger number of animals resulting in less upfront costs and lower operating costs.

Example 4-17—Determination of minimum separator throughput rate when combined with settling

A settling basin was designed to provide treatment for flushed manure from an 8,000 head finishing swine farm in example 4-3. The daily flow of flushed manure from the 10 buildings was 152,891 gallons per day with a mean TS of 1.0 percent. A settling basin was designed, using a 1 hour detention time, that would contain all of the settlable solids in only 17 percent of the daily flow volume. Therefore, only 26,000 gallons would need to be processed by the separator each day. The storage volume of the settling basin was set at 6,500 gallons and the settled slurry is to be removed and treated using a high-removal mechanical separator at least four times each day. If the desired processing time is 3 hours, determine the required throughput rate for the machine and the minimum throughput rate that could be used.

Figure 4-72 Combination of a mechanical separator (MS) and a two-chambered weeping wall settling basin to provide a high-rate of primary treatment for a flush dairy that uses composted or dried solids as bedding

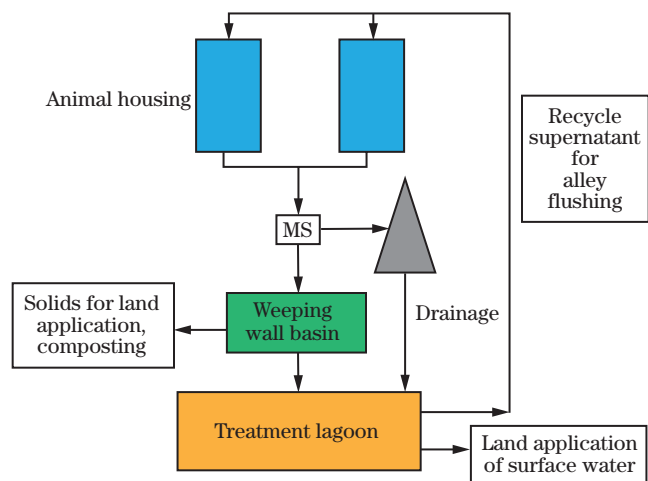


Figure 4-73 Combination of sand lanes and a two-chambered weeping wall settling basin to provide a high-rate of primary treatment for a flush dairy that uses recycled sand to reduce sand bedding costs. For information on sand lanes refer to section 637.0406

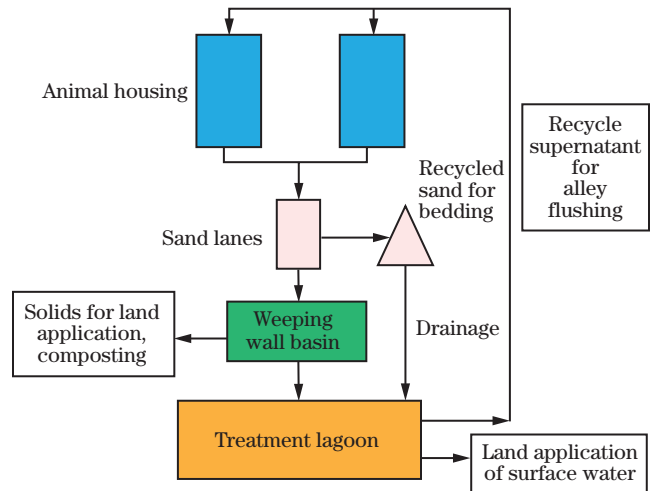
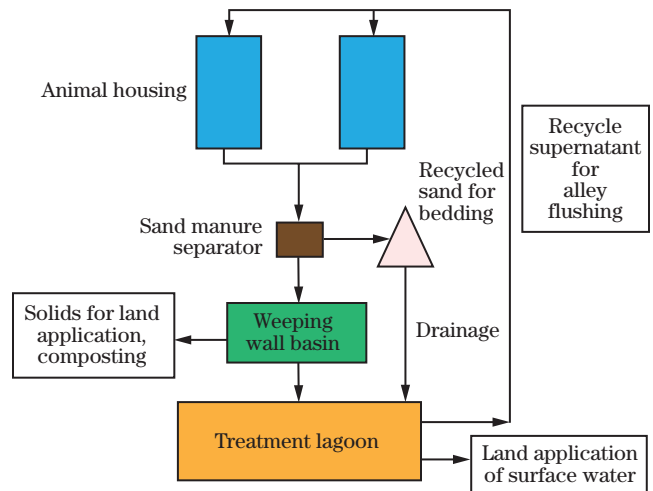


Figure 4-74 Combination of mechanical sand-manure separator and a two-chambered weeping wall settling basin to provide a high-rate of primary treatment for a flush dairy that uses recycled sand to reduce sand bedding costs. For information on a sand-manure separator refer to section 637.0406



If three hours of processing time are used four times per day, the separator throughput rate needed for one machine is—

$$\frac{6,500 \text{ gal}}{3 \text{ hr}} \div 60 \text{ min/hr} = 36 \text{ gpm}$$

The minimum separator throughput rate is the set by the accumulation rate of settled solids. In this case, the solids accumulate at a continuous rate of—

$$Q_{\text{SETTLED SOLIDS}} = \frac{26,000 \text{ gal}}{24 \text{ hr}} \div 60 \text{ min/hr} \\ = 18 \text{ gpm}$$

The theoretical minimum separator throughput rate is the rate that matches the solids accumulation rate. However, this rate would not allow much time for the settled solids to thicken. In addition, the bottom of the basin would need to be conical in design to allow the solids to flow to the pumping point. Doubling this rate would provide a more conservative design value of 36 gallons per minute. This value is 66 percent slower than the 106.2 gallons per minute that would be required if all of the flushed manure was treated continuously with a single mechanical separator.

Large flush freestall dairy facilities have unique treatment needs due to the large amount of manure solids

generated and the need for freestall bedding. In some cases, a mechanical separator is used to remove solids from flushed manure that can be treated by drying or composting. The dried solids are then reused for freestall bedding. As a result, the main goal of mechanical solid-liquid separation would be to reduce bedding costs. In such a case, additional treatment can be provided by adding a settling basin between the mechanical separator and a treatment lagoon. Figure 4-72 provides a possible layout using a weeping wall settling basin. In most cases, the weeping wall basin will include two or more chambers as described in section 637.0406. Similar layouts are shown in figures 4-73 and 4-74 and where sand-manure separation is combined with a weeping wall basin to enhance treatment to provide recycled water for flushing alleys and to yield recycled sand to reduce bedding costs.

(c) Primary treatment using flocculants and coagulants for recycle systems

The performance of most any type of solid-liquid separation method can be enhanced by the use of the proper dose of coagulants, flocculants, or both. Chemical enhancement of the separation process is often motivated by the need to control odor generation by greatly reducing the loading rate on a biological treatment process. Another reason to use chemicals is to consolidate a large portion of the phosphorus and

Figure 4-75 Use of coagulants and flocculants to enhance removal efficiencies for a two-chambered gravity settling basin

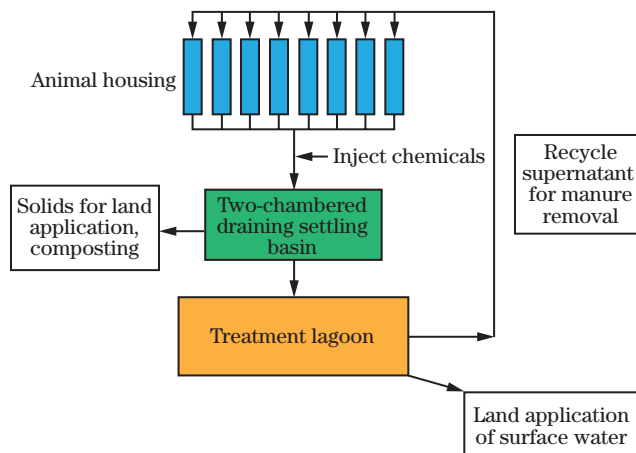
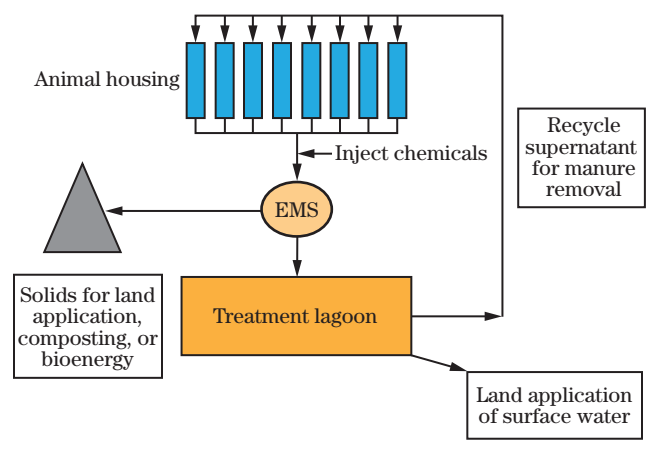


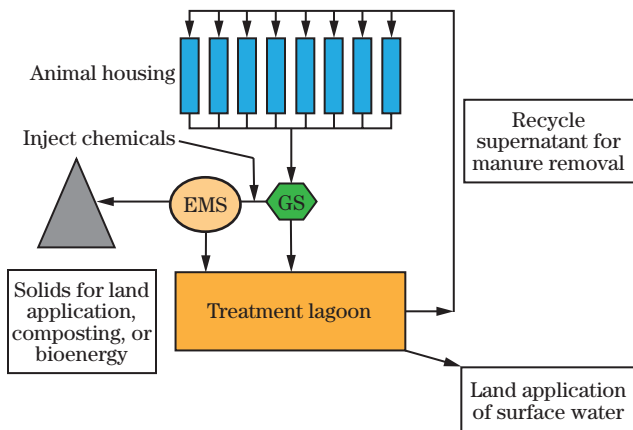
Figure 4-76 Use of coagulants and flocculants to enhance solids and plant removal efficiencies for single-stage mechanical separation (EMS)



other plant nutrients in the separated solids to facilitate composting or other offsite uses of P. The lower volume and moisture content of the separated solids makes transport of the consolidated plant nutrients to distant fields less costly than transport of thin slurry or liquid manure. Separated solids from chemically enhanced solid-liquid separation are richer in plant nutrients than ordinary separated solids, and can be used to make compost products with high nutrient value (Chastain et al. 2006).

The most common method used to enhance solid-liquid separation is to inject and mix the proper dose of coagulants and/or flocculants prior to a settling basin (fig. 4-75) or mechanical separator (fig. 4-76). The exact chemical dose needed will depend on the type of chemical used, manure type, and the amount of mass removal of solids or plant nutrients desired. Results from several laboratory and field experiments were summarized previously in section 637.0405. However, more specific information is often needed and can be developed with assistance of the chemical manufacturer, performance data collected from a farm using the same method of separation and chemical, or from preliminary testing (appendix 4D). The amount needed can be calculated by the amount (dose) of chemical per gallon of manure, and the total volume of manure to be treated per day. The chemicals are injected into the flushed manure for the two solid-liquid separation systems shown in figures 4-75 and 4-76.

Figure 4-77 Use of (GS) to reduce chemical costs for enhanced removal of solids and plant nutrients using a mechanical separator (EMS)



Example 4-18—Calculation of chemical needed to enhance mechanical separation of flushed swine manure

A swine producer is considering the addition of a chemically enhanced mechanical separator to greatly reduce sludge buildup in the lagoon and to capture a large portion of the phosphorus. The system that he is considering is shown in figure 4-76. Based on information from similar facilities, it has been determined that addition of 100 milligrams of PAM per liter of flushed manure will provide close to 90 percent removal of the total suspended solids, and about 50 percent of the total-P. The daily flow of flushed manure from the 10,000-head facility is 152,891 gallons per day using four flushes per day with an average TS content of 1 percent. How many pounds of PAM will be needed per day and per year? What would be the annual chemical cost if the PAM can be obtained for \$1,000 per ton?

The PAM dose of 100 milligrams PAM per liter is equivalent to 0.83 pound PAM per 1,000 gallons. The amount of PAM needed per day is—

$$0.83 \text{ lb PAM}/1,000 \text{ gal} \times 152,891 \text{ gal}/\text{day} = 126.9 \text{ lb PAM}/\text{day}$$

The facilities will be in full operation about 46 weeks per year or 322 days. The annual PAM needs would be—

$$126.9 \text{ lb PAM}/\text{day} \times \frac{322 \text{ days}/\text{year}}{2,000 \text{ lb}/\text{ton}} = 20.4 \text{ tons PAM}/\text{year}$$

The annual chemical cost would be about—

$$20.4 \text{ tons PAM}/\text{year} \times \$1,000/\text{ton} = \$20,400/\text{year} \\ \text{or } \$2.04 \text{ /hog-space}/\text{year}$$

As can be seen, use of chemicals to improve solid-liquid separation for high-volume flush systems can be expensive. To reduce the chemical cost, the producer must reduce the volume of manure that is treated. This can be achieved by reducing the flushing frequency. In this example the producer flushed the buildings four times a day. It would be possible to reduce the chemical needs by 25 percent by reducing the number of flushes to three times per day. Thus, the total volume to be treated would be 114,668 gallons per day. The amount of PAM needed per year would be reduced to 15.3 tons of PAM per year or \$1.53/hog-space/year

assuming that a dose of 100 milligrams PAM/L is still sufficient to meet treatment goals.

The volume of liquid manure to treat with PAM can be reduced greatly by using gravity settling to concentrate the solids into a smaller volume prior to the mechanical separator. Supernatant would be allowed to decant and flow to the treatment lagoon. Periodically, the settled volume would be pumped to the separator and PAM would be injected to enhance removal of solids and phosphorus. A layout of this alternative enhanced treatment system is shown in figure 4-77.

If the buildings are flushed four times each day, 152,891 gallons per day with an average TS content of 1 percent must be treated by the system. In a previous example on settling basin design, example 4-3, it was determined that the settled volume fraction removed each day was 17 percent of the total flushed manure volume. Therefore, the volume to be treated by injection of PAM followed by mechanical separation for this example is 0.17 times 152,891 gallons per day equals 26,000 gallons per day. Settling will increase the TS concentration from about 1 percent to about 4 percent. Therefore, data from previous studies (section 637.0405) indicate that the dose would need to be increased by 20 percent to 120 milligrams PAM/L or 1.0 pound per 1,000 gallons. Therefore, the amount of PAM needed for this system would be—

$$1.0 \text{ lb PAM}/1,000 \text{ gal} \times 26,000 \text{ gal}/\text{day} = 26.0 \text{ lb PAM}/\text{day}$$

The annual PAM use would be—

$$26.0 \text{ lb PAM}/\text{day} \times 322 \text{ days}/\text{year} \div 2,000 \text{ lb}/\text{ton} = 4.2 \text{ tons PAM}/\text{year}$$

The annual chemical cost would be—

$$4.2 \text{ tons PAM}/\text{year} \times \$1,000/\text{ton} = \$4,200/\text{year} \text{ or } \$0.42 / \text{hog-space}/\text{year}$$

Therefore, use of gravity settling basin to reduce the amount of manure that received enhanced mechanical separation reduced chemical costs by 79 percent in this case.

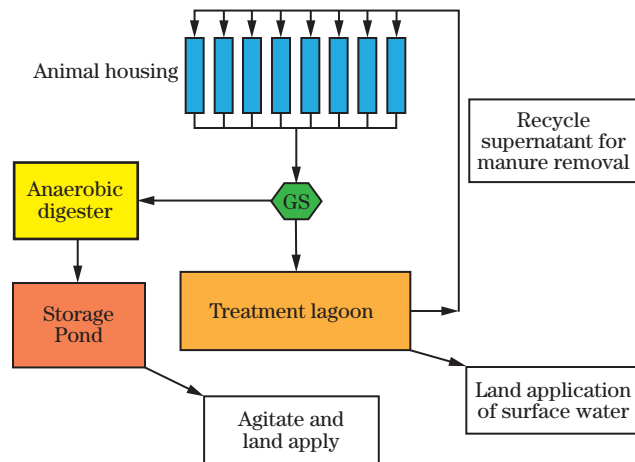
Providing chemical treatment for well-treated recycled lagoon water provides little additional removal of the solids and plant nutrients produced by the animals between manure removal events. A treatment lagoon

that provides adequate treatment will yield recycled lagoon supernatant with a TS on the order of 0.3 to 0.7 percent. On-farm tests have shown that after manure removal, the supernatant of the manure flowing from the building had a TS of only 0.6 percent, while the lagoon supernatant used to clean the barns was 0.5 percent (Chastain et al. 2001b). It was observed that the majority of the solids and plant nutrients produced by the animals were located in the settled solids. Therefore, the other key factor in reducing chemical treatment costs is provision of high levels of biological treatment prior to recycle of supernatant for manure removal.

(d) Gravity settling prior to anaerobic digestion

An anaerobic digester is designed to provide a chemical and thermal environment that promotes the destruction of volatile solids by acid-forming and methane-forming bacteria. The highest VS destruction rates occur at digester temperatures of about 95 degrees Fahrenheit. During the late fall, winter, and early spring heat must be supplied to maintain the digester temperature at this temperature if maximum VS destruction is to be maintained year round. In most

Figure 4-78 Use of gravity settling (GS) to concentrate volatile solids prior to loading a heated anaerobic digester. Digester effluent is not stored in the treatment lagoon to maintain a high level of treatment for the water that is recycled for manure removal



cases, a portion of the biogas (60 to 65% methane) is burned as a source of heat or heat is reclaimed from an engine that drives an electric generator. While a flush system provides a convenient means of frequent barn cleaning, it adds a large amount of water which results in high heat requirement for maintaining the needed temperature for anaerobic digestion. In fact, performing a heat and mass balance on a 95 degrees Fahrenheit reactor indicates that the amount of heat needed to raise the entire mass of water and manure from ambient temperature to 95 degrees Fahrenheit can require more heat energy than can be generated by the methanogens from the VS in the manure during much of the year. As a result, large dairy and swine farms in warm climates, such as South Carolina, Texas, and California, can only use unheated covered lagoon digesters if the entire volume of flushed manure is treated.

A gravity settling basin can be used to provide primary treatment prior to a treatment lagoon as well as a means to settle and thicken volatile solids prior to loading a heated digester (see example 4-3). The volume loaded into the digester will vary with the volume

of thickened manure loaded. This can range from 17 to 30 percent of the total flush volume, depending on the TS content, amount of thickening time allowed, and animal type (section 637.0403 and 637.0404). A diagram of this concept is provided in figure 4-78.

During the anaerobic digestion process, a portion of the volatile solids will be destroyed, resulting in a decrease in the total solids in the digester effluent, and the potential for strong odors will be diminished. However, digested manure will still have a TS content that is much greater than flushed manure. In addition, the undigested solids could still contribute to sludge buildup in a treatment lagoon. Consequently, storage of digested manure in a treatment lagoon is not recommended. Instead a separate storage pond should be provided for the digester effluent (fig. 4-78).

The other significant change that will occur during the digestion process is that a large amount of the organic nitrogen (30 to 40%) will be converted to ammonium nitrogen. If the digester is operated in such a way that an equal volume of manure flows into and out of the digester each day then no nitrogen will be lost during

Figure 4-79 Use of chemically enhanced gravity settling (EGS) to concentrate 80% or more of the volatile solids prior to loading a heated anaerobic digester and to provide a high level of treatment prior to the lagoon. Digester effluent is not stored in the treatment lagoon to maintain a high level of treatment for the water that is recycled for manure removal

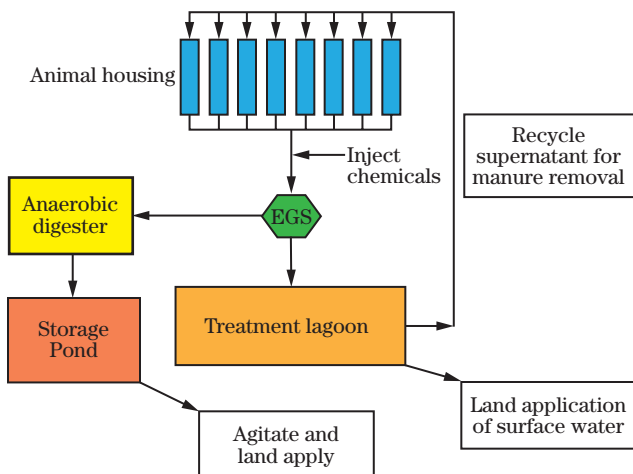
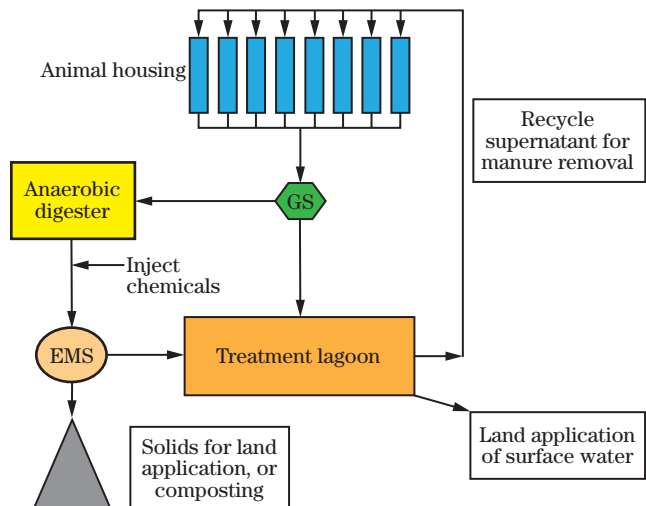


Figure 4-80 Use of chemically enhanced mechanical separation (EMS) to remove the majority of the solids from digester effluent prior to storing liquids in a treatment lagoon. Gravity settling (GS) is used as primary treatment prior to digestion



digestion. Therefore, anaerobic digestion does not reduce the nitrogen content of manure but it increases its availability to plants. The disadvantage of mineralizing organic-N to ammonium-N is that a larger portion of the nitrogen can be lost to ammonia volatilization in an uncovered storage pond. The amount of total ammoniacal-N that will be in the ammonia form depends on manure pH and temperature (fig. 4-45). In most cases the pH will be near 8.0 and the fraction of the total ammoniacal-N (TAN) that will be lost is on the order of 5 to 8 percent. A permeable or impermeable geotextile cover could be used on the digester effluent storage pond to reduce ammonia emissions by 50 to 90 percent.

Biodegradable PAM flocculants can be used to enhance settling of suspended volatile solids and COD. Settling of 90 percent or more of the VS can be attained if the correct chemical and dose are used (section 637.0405 and appendix D). Injection of these chemicals prior to gravity settling can allow 80 to 90 percent of the particulate VS (VSS) to be loaded into a heated digester if a flush system is used (fig. 4-79). Use of the PAM will also greatly reduce the organic loading rate and the fraction of total-P that enters the treatment lagoon. Odor and ammonia emissions from the lagoon will also be greatly reduced. However, a cover may be desirable to reduce ammonia losses from the digester effluent storage structure.

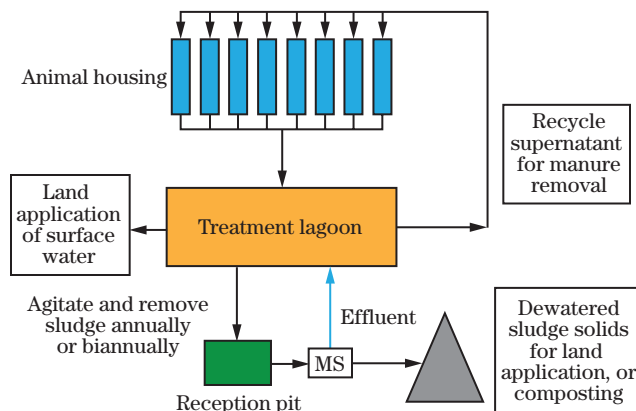
In most applications of PAM flocculants, pumping after flocculation and settling should be avoided due to destruction of the flocs. However, in this case, floc destruction will only occur as the settled and thickened solids are pumped into the anaerobic digester and may enhance biodegradability if particle sizes are sufficiently reduced by a chopper pump.

Chemical flocculation, combined with a high-removal mechanical separator, can be used to separate a large portion of the solids and plant nutrients from digester effluent as shown in figure 4-80. The high-rate mechanical separation system should be used with a chemical dose that will provide high TS removal so as to greatly reduce sludge buildup in the lagoon that receives the liquid fraction from the mechanical separator. The enhanced mechanical separation system will remove only the TAN that is associated with the moisture in the separated solids. This option may result in a modest increase in the TAN concentration in the lagoon supernatant.

(e) Use of solid-liquid separation to dewater sludge

Sludge management is an important, but often overlooked, factor in the maintenance of a treatment lagoon or covered anaerobic lagoon digester. These types of structures are sized to treat the volatile fraction of the manure solids by anaerobic decomposition (see section 637.0402). The solids that are stored near the bottom of a lagoon by settling that will not decompose (fixed solids or ash) or decompose slowly are called sludge. If the volume of inert sludge is allowed to build up excessively, the treatment volume will be significantly reduced, and the quality of the supernatant will be impaired to the point that it should no longer be used to remove manure from animal facilities. In extreme cases, the treatment volume can be reduced to the point that the lagoon or covered lagoon digester becomes overloaded, and the methanogens cease to function properly. If this happens in a treatment lagoon, the supernatant will be dark in color, have a strong odor, and will be elevated in solids and ammonium-N content. Excessive sludge buildup in a covered lagoon digester (CLD) can result in a reduction and eventually a failure to produce methane.

Figure 4-81 Use of a reception pit and mechanical separator (MS) to dewater sludge from a treatment lagoon. If flocculation is desired to enhance removal efficiencies, inject chemicals between the reception pit and the mechanical separator



A portion of the sludge should be removed at planned time intervals (every 1 to 5 years) to maintain proper levels of biological treatment and settling in a lagoon or CLD. Sludge removal typically involves removal of a portion of the supernatant, agitation of the solids and remaining liquid, pumping the sludge-supernatant mixture into a tank-type spreader or injection system, and applying the sludge to distant fields at the appropriate agronomic rate for a key major plant nutrient (N, P, or K). The characteristic of the sludge mixture varies greatly depending on animal species and the loading rate. Typical solids contents can be in the range of 4 to 12 percent TS, and phosphorus and organic-N are typically the plant nutrients in the highest concentrations.

Sludge that is removed from a treatment lagoon often must be transported to remote fields that do not receive plant nutrients from annual applications of lagoon supernatant. Sludge that is pumped from a lagoon is still mostly water and cannot be stored temporarily in a stacking area. As a result, wet sludge must be hauled to remote fields and land applied as soon as it is pumped from the lagoon into a tank type spreader. Solid-liquid separation can be used to dewater lagoon sludge mixtures to the point that sludge solids can be stored in a well-drained stacking area prior to land application, and the volume and weight of solids that must be transported to remote fields can be significantly

reduced (fig. 4–81). Separated sludge solids could also receive additional treatment by including them in a composting operation.

Mechanical separators, such as a screw press with a fine screen, are often one of the easiest methods of sludge dewatering to use since the main requirements are a reception pit to hold the sludge during processing, a structure to hold the machine and controls, and a stacking pad to receive and store the sludge solids (fig. 4–81). Thick sludge, TS of 6 percent or more, would be processed in batch mode. The reception pit would be filled with sludge and the machine would be allowed to process the sludge for several hours. Key factors that need to be considered are: the screen size needed to remove the desired quantity of solids, the size of reception pit needed to accommodate the volume of sludge to be dewatered each day, the throughput rate of the mechanical separator, the number of hours per day that will be used for sludge dewatering, and the size of drained stacking area needed for storage.

Example 4–19—Estimation of sludge dewatering time using a mechanical separator

A dairy producer is considering the use of a mechanical separator to dewater treatment lagoon sludge. The

Figure 4–82 Use of geotextile tubes to dewater sludge from a treatment lagoon

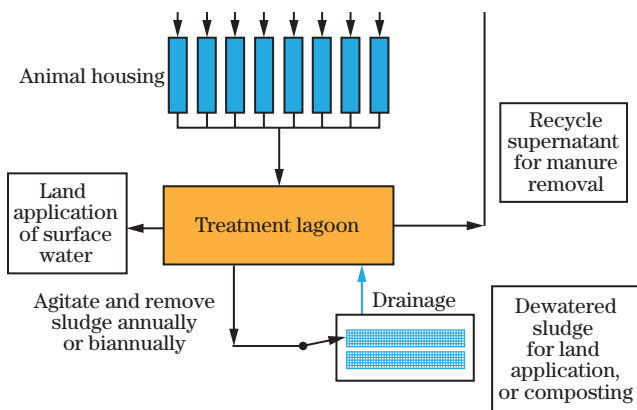


Figure 4–83 Use of flocculants and geotextile tubes to dewater sludge from a covered lagoon digester

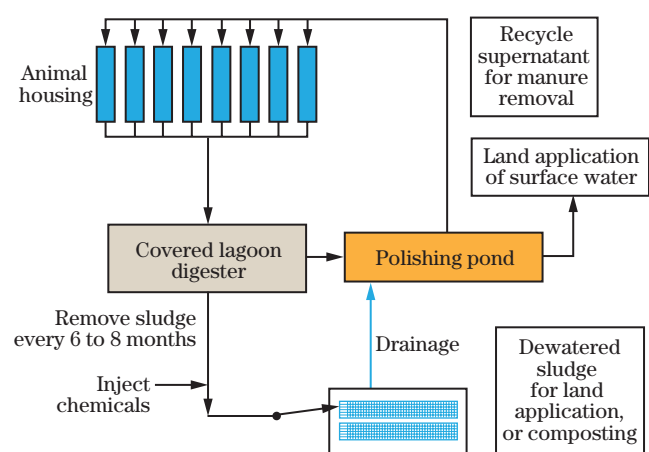


Figure 4–84 Use of chemically enhanced mechanical solid-liquid separation (EMS) to dewater effluent from a heated anaerobic digester

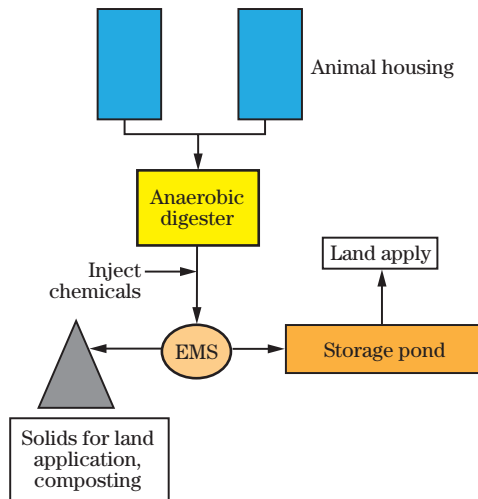


Figure 4–85 Separation without chemical enhancement using a mechanical separator (MS) with small screen openings

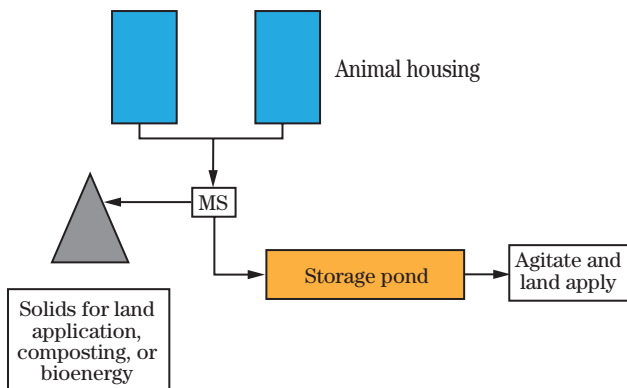
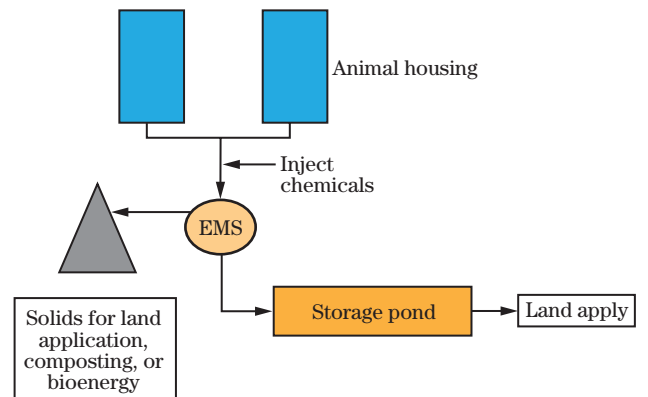


Figure 4–86 Mechanical separation of slurry using chemical enhancement (EMS)



objective will be to agitate and fill a large reception pit that will hold a single batch of 100,000 gallons of sludge. The plan is to dewater 100,000 gallons on a weekly basis a few months prior to spring planting. After filling, the pit separator will be allowed to process the sludge prior to refilling the pit again. The fine-screen separator that is being considered will process slurry at a rate of about 40 gallons per minute. How long will it take to process a 100,000 gallon batch?

The amount of time needed to process a 100,000 gallons batch of sludge is—

$$100,000 \text{ gal/batch} \div 40 \text{ gpm} \div 60 \text{ min/hr} = 42 \text{ hr/batch}$$

Geotextile dewatering tubes with or without chemical flocculants offer another option for dewatering and storing sludge from treatment lagoons and covered lagoon digesters. The layouts are shown in figures 4-82 and 4-83. The advantages of the geotextile tubes are that they can provide long-term storage for dewatered sludge at relatively high solids content (15 to 30 percent TS, Cantrell et al. 2008). The result is that lagoon sludge can be removed and processed during periods of the year when cropland is not available for spreading. Dewatered sludge can be used for land application on remote fields using a time frame dictated by

cropping needs. Thus, the need for a large amount of cropland during a short period of time is removed.

Mechanical liquid solid separators can also be used to dewater effluent from heated anaerobic digesters (fig. 4-84). Separators with small screens (0.50 mm or less) can provide high rates of solids removal (ex. 4-6 and 4-7). The liquid effluent is still very high in plant nutrients, and is typically stored in a lined pond. The storage period will vary from 4 to 12 months depending on the climate and the crops grown.

Figure 4-87 Use of a sand-manure separator prior to slurry storage pond on a dairy farm that uses sand for freestall bedding

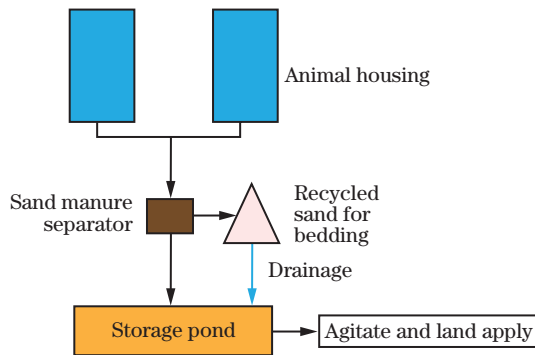
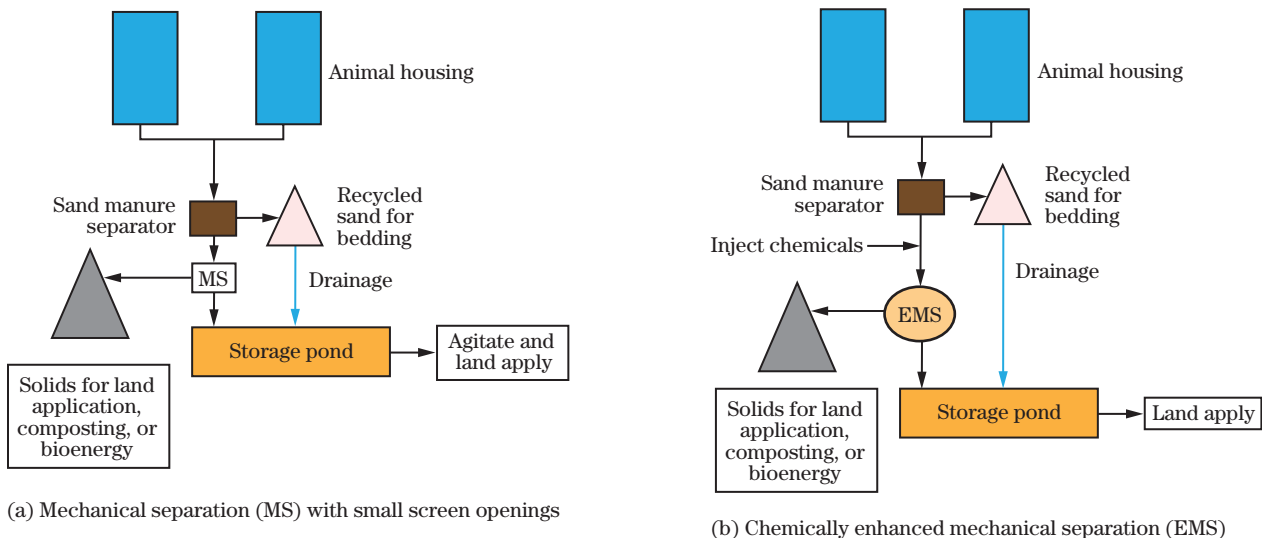


Figure 4-88 Use of high-rate liquid solid separators downstream from a sand-manure separator



(f) Solid-liquid separation on farms that use manure storages

Many swine and dairy facilities are designed to remove manure from the animal housing area as slurry. Examples of slurry manure removal methods include mechanical scraping of manure from alleys in dairy freestall barns, and gravity-drain hairpin gutters used below slotted floors in swine facilities. Most often slurry manure is stored in a lined pond or below ground tank for 8 to 12 months. The entire contents of the storage are agitated and land applied to meet crop needs for N, P, or K. The phosphorus (expressed as P_2O_5) content in slurry manure is often much higher than the nitrogen content. The most common methods used to land apply slurry manure are tank-type splash plate applicators or direct injection. The goals for solid-liquid separation on these types of farms are to remove solids to improve pumping characteristics of the manure and remove a significant amount of phosphorus from the slurry to reduce P application rates on cropland near the farm. The two most common types of systems are shown in figures 4–85 and 4–86. To achieve significant phosphorus removal (greater than 20%), presses with small screen sizes and slow throughput rates are needed. The highest rates of P removal (50% or more) generally requires injection of coagulants and flocculants. The advantage of using

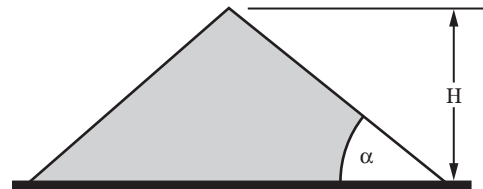
chemicals with slurry systems is that a relatively small volume of manure must be treated per 1,000 pounds of animal weight which reduces chemical use. The disadvantage is that it is more difficult to mix the chemicals with slurry. On dairy farms, separated solids can be used for stall bedding if they are adequately dried, or composted and dried before reuse.

Many dairy producers choose to use sand as bedding for dairy freestalls to enhance cow comfort and milk quality (low somatic cell counts). However, storing sand-laden manure in a pond for 8 to 12 months makes unloading and land application of sand-laden manure difficult and costly. Use of a sand-manure separator to remove the majority of the sand from the manure yields slurry that can be stored and applied to land like conventional dairy manure (fig. 4–87). Often, a large portion (80% or more) of the recovered sand is clean enough to be reused as bedding after a period of draining and conditioning (section 637.0406). Sand-manure separation is also a required prerequisite if high-rates of solids and plant nutrient removal are needed to deal with excess P or other plant nutrients (fig. 4–88).

Figure 4–89 Temporary storage of mechanically separated solids in a conical pile below a stacking conveyor with windrows for longer term storage in the background



Figure 4–90 Angle of repose of a pile of granular material that forms a circular cone. The angle of repose, α , is a property of the material, H is the height of the cone, and the radius of the circle that forms the base is r



(g) Considerations for storage of mechanically separated solids and sand

One of the advantages of using a mechanical solid-liquid separator over a gravity settling basin is that it yields separated solids that can be stacked and stored immediately following separation (fig. 4–89). Separated solids can be moved using a loader to form windrows on a stacking pad to provide longer term storage. The stacking area needs to be a well-drained, constructed of an impervious material (typically concrete), and designed so as to route drainage and runoff to a storage pond or lagoon.

Use of a mechanical sand-manure separator also requires short-term storage in a conical pile below the sand outlet as shown previously in figures 4–52 and 4–54. Separated sand requires additional storage area to allow it to be drained and conditioned for at least 30 days prior to reuse for stall bedding.

Sizing of the stacking area for short- and long-term storage of separated manure solids or sand requires design values for two physical characteristics: angle of repose and bulk density. The angle of repose, α , is a property of the granular material being stored that defines the slope of the cone or windrow as shown in figure 4–90. The value of α depends on a variety of factors that include density of the granular particles, the shape of the particles, the static coefficient of friction, the cohesive properties of the granular particles, and the moisture content. Prediction of the exact value of α is complicated; however, mean values are sufficient for most designs. Design values of the angle of repose

for mechanically separated manure solids and sand are provided in table 4–83.

The bulk density of granular materials depends on particle shape, particle density, volume of void spaces, moisture content, and degree of compaction. Values of bulk density to be used for calculating storage volumes for separated solids or sand should be restricted to values measured where the weight of the material provides the only compaction. The wet bulk density of sand varies from 110 to 120 pounds per cubic foot depending on the moisture content. For design purposes a wet sand bulk density of 110 pounds per cubic foot is often used. However, site-specific values should be used if available. The wet bulk density of manure solids varies greatly with respect to moisture content. As a result, average dry matter bulk densities (ρ_{DB} , lb DM/ft³) are more useful than wet bulk densities. The wet bulk density (ρ_B , lb wet/ft³) can be estimated based on a reasonable estimate of the TS content (percent, wet basis) of the separated solids as—

$$\rho_B = \frac{\rho_{DB}}{(TS/100)} \quad (\text{eq. 4-46})$$

Where the quantity (TS/100) is the dry matter fraction of the separated solids. Values of the dry matter bulk density for separated manure solids and lagoon sludge are provided in table 4–84. There was very little difference in ρ_{DB} for separated dairy or swine solids. However, the presence of soil in the dewatered sludge from a dairy lagoon doubled the value of ρ_{DB} when compared with dewatered sludge from a treatment lagoon on a swine farm. Dairy cattle often track soil from pastures

Table 4–83 Angle of repose, α , for separated manure solids and sand

Material	α
Separated manure solids	40° to 48°
Dry sand	32° to 35°
Wet sand	40° to 45°
Saturated, water-filled sand	15° to 30°

Table 4–84 Dry matter bulk density, ρ_{DB} , of noncompacted separated solids and lagoon sludge

	Dry matter bulk density (lb DM/ft ³)
Separated dairy solids	8.24 to 9.34
Separated swine solids	7.94 to 8.68
Separated swine lagoon sludge	10.4
Separated dairy lagoon sludge with soil	23.0

and dry lots into the freestall area and results in a larger dry-matter bulk density.

The amount of separated solids or sand that can be stored in a conical pile below the separator outlet will depend on the maximum height possible for the cone, H , and the angle of repose. The radius of the circular base of the cone, r , can be calculated from the height and the angle of repose as $r = H / \tan(\alpha)$. The volume of the cone is $V_{\text{CONE}} = 1/3 \pi r^2 H$. Calculated values of r , and V_{CONE} for a practical range of H and α are provided in table 4–85.

Separated solids or sand is often removed from below the separator and are stored in long windrows. The volume of the windrow is calculated using an assumed geometry. A common geometry used is a triangular windrow that can be formed by allowing the material to flow freely from an elevated bucket onto the storage pad. The internal length of the windrow will have a triangular cross-section with two half-cones on each end. A plan view showing the nomenclature for the planar dimensions of a triangular windrow is provided in figure 4–91. The volume of the interior section with length L is $V_L = r H L$. The total volume of the windrow is $V_{\text{TL}} = r H L + 1/3 \pi r^2 H$.

Example 4–20—Long- and short-term storage for separated dairy solids

A dairy facility houses 500 cows and the anticipated TS removal efficiency for a high-rate mechanical separator is 50 percent. It was estimated, based on performance data, that the mechanical separator will yield 30,000 pounds of separated solids per day with a TS content of 22.7 percent. Short-term storage of the separated solids will be in a conical pile below a stacking conveyor. It has been determined that the maximum height of the cone will be 16 feet (H). Once a week the dairy producer will move separated solids to a triangular windrow to provide storage for 30 days. How many days of storage can be provided below the stacking conveyor? How long will the windrow need to be if the peak height is 10 feet?

Short-term storage—The maximum height of the conical pile below the stacking conveyor is 16 feet and the

Figure 4–91 Dimensions used to calculate the volume of a triangular windrow of separated solids or sand with two halves of a cone on each end

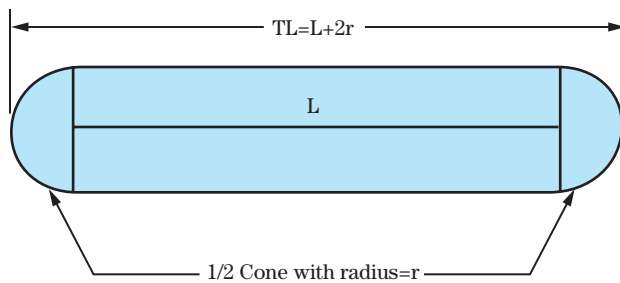


Table 4–85 Variation of radius, r , and volume of a circular cone, V_{CONE} , as a function of cone height, H , and angle of repose, α

H (ft)	$\alpha = 30^\circ$		$\alpha = 35^\circ$		$\alpha = 40^\circ$		$\alpha = 45^\circ$	
	r (ft)	V_{CONE} (ft ³)	r (ft)	V_{CONE} (ft ³)	r (ft)	V_{CONE} (ft ³)	r (ft)	V_{CONE} (ft ³)
8	13.86	1,608	11.43	1,094	9.53	762	8.00	536
10	17.32	3,142	14.28	2,136	11.92*	1,487*	10.00	1,047
12	20.78	5,429	17.14	3,691	14.30	2,570	12.00	1,810
14	24.25	8,621	19.99	5,861	16.68	4,081	14.00	2,874
16	27.71	12,868	22.85	8,749	19.07*	6,092*	16.00	4,289
18	31.18	18,322	25.71	12,456	21.45	8,674	18.00	6,107
20	34.64	25,133	28.56	17,087	23.84	11,899	20.00	8,378

* See example 4–20.

angle of repose was assumed to be 40 degrees (table 4–83).

1. Determine r and cone volume.
Using table 4–85, the radius of the circular base will be 19.07 feet and the volume will be 6,092 cubic feet.
2. Determine dry matter bulk density.
The average dry matter bulk density was assumed to be 8.79 pounds of DM per cubic feet (mean of range in table 4–84). The wet bulk density was determined to be: $\rho_B = 8.79$ pounds DM per cubic foot divided by $(22.7/100)$ is 38.7 pounds wet per cubic feet.
3. Determine volume of separated solids produced in a day.
The volume of separated solids was estimated as 30,000 pounds per day divided 38.7 pounds wet per cubic foot is 775 cubic feet of separated solids per day.
4. Calculate short-term storage period in the conical pile.
The short-term storage period that will be provided below the stacking conveyor will be 7.86 days $(6,092 \text{ ft}^3/775 \text{ ft}^3/\text{day})$. Therefore, separated solids will only need to be moved to long-term storage one time per week. The area of the stacking pad below the pile will be 1,142.5 square feet. Additional area will be needed to allow for operation of the loader and other equipment.

Long-term storage—The height of the triangular windrow will be 10 feet with the same angle of repose ($\alpha = 40^\circ$).

1. Determine base width of the triangular windrow.
The base width of the windrow will be $2r$, where r is determined in the same manner as for a cone. From table 4–85, half of the base width = $r = 11.92$ feet. The base width will be $2r = 23.84$ feet.
2. Determine volume contained in the two one-half cone sections at the ends of the windrow (fig. 4–91).
Using table 4–85, the volume of the 2, half cones with H is 10 foot and α is 40 degrees is 1,487 cubic feet.

3. Determine length of the internal section of the windrow (L in fig.4–91).

The volume of separated solids to be stored in the internal section is—
775 cubic feet of separated solids per day times 30 days minus 1,487 cubic feet (volume in conical ends) is 21,763 cubic feet.

The volume of the section with length L is $V_L = r H L = 21,763$ cubic feet.

The required value of L is—

$$L = \frac{V_L}{r H}$$

$$= \frac{21,763 \text{ ft}^3}{(11.92 \text{ ft} \times 10 \text{ ft})}$$

$$= 182.6 \text{ ft}$$

4. Calculate total windrow length, TL .

$$TL = 182.6 \text{ ft} + 2 \times 11.92 \text{ ft}$$

$$= 206.4 \text{ ft}$$

The total area of the base of the windrow is—

$$\text{Base Area} = 182.6 \text{ ft} \times 23.84 \text{ ft} + \pi (11.92 \text{ ft})^2$$

$$= 4,800 \text{ ft}^2$$

Example 4–21—Volume of separated sand conditioning windrow

A dairy freestall barn contains 480 stalls and 60 pounds of sand is added per stall per day. A sand-manure separator is being used to recover about 80 percent of the sand. How large of a windrow is needed to provide 30 days of sand conditioning if the windrow height will be 10 feet?

1. Calculate amount of sand that will be recovered with the sand-manure separator each day.

$$480 \text{ freestalls} \times 60 \text{ lb sand/stall/day} \times 0.8 = 23,040 \text{ lb of sand recovered/day.}$$

$$\text{Volume of recovered sand} = 23,040 \text{ lb/day} \div 110 \text{ lb sand/ft}^3 = 209.5 \text{ ft}^3 \text{ sand/day.}$$

- Calculate the volume of sand to be conditioned in a windrow for 30 days.

$$209.5 \text{ ft}^3 \text{ sand/day} \times 30 \text{ days} = 6,285 \text{ ft}^3 \text{ sand/windrow.}$$

- Determine volume of sand contained in the two half cone sections at the ends of the windrow (fig. 4–91). Use an angle of repose of 35 degrees (table 4–83).

Using table 4–85, the volume of the two half cones with H is 10 feet and α is 35 degrees is 2,136 cubic feet.

The radius of the conical sections will be 14.28 feet.

- Determine the volume and dimensions of the triangular section of the windrow (L, r, H).

The total volume of sand in the windrow will be 6,285 cubic feet with 2,136 cubic feet contained in the conical end sections. The triangular section will contain 4,149 cubic feet (6,285 – 2,136) with r is 14.28 feet and H is 10 feet. The length of this section needs to be—

$$\begin{aligned} L &= \frac{V_L}{r H} \\ &= \frac{4,149 \text{ ft}^3}{14.28 \text{ ft} \cdot 10 \text{ ft}} \\ &= 29.05 \text{ ft} \end{aligned}$$

The total length of the windrow will be—

$$\begin{aligned} \text{TL} &= 29.05 \text{ ft} + 2 \times 14.28 \text{ ft} \\ &= 57.6 \text{ ft} \end{aligned}$$

The total area of the base of the windrow is—

$$\text{Base Area} = 57.6 \text{ ft} \times 28.56 \text{ ft} + \pi (14.28 \text{ ft})^2 = 2,286 \text{ ft}^2$$

(h) Cost-benefit considerations

In many modern animal manure management systems, solid-liquid separation is a necessary component to achieve manure treatment goals for a farm. A common example is the high level of treatment needed to recycle liquids for manure flushing. Another goal may be to capture a large portion of the phosphorus in

the manure to reduce P application on the fields that normally receive manure as a fertilizer substitute. In such a case, the separated solids allow phosphorus to be moved in a smaller compact form. In many cases, manure treatment is part of the cost of modern, efficient animal production facility that is just as necessary as the barn, ventilation system, or milking system. However, the costs and benefits can vary greatly depending on the amount of treatment required, the type of system used, and the potential to realize income benefits from potential by-products, such as freestall bedding, composting ingredients, P-rich fertilizers, or bioenergy. Obviously, not all of the potential benefits are available on every farm. For example, a swine producer does not have the potential to use separated solids or sand to reduce bedding costs. Such a benefit would only apply to dairy facilities. However, composting of separated solids with other ingredients may provide an opportunity if the swine farm is located in a region that produces high-value fruit crops. A listing of cost and potential benefit categories is shown for gravity settling and mechanical solid-liquid separation systems in table 4–86. Each cost category or potential benefit has been classified as very low (€), low (\$), medium (\$\$), or high (\$\$\$). A third category is also shown for the chemical enhancement of any type of separator using coagulants and flocculants. The costs for this category would be added to either a mechanical or gravity system. The categories in this table are only relative and serve as a beginning point to evaluate the costs and benefits for an actual case. However, the simple evaluation does indicate that a mechanical separation has more total costs than a gravity system. The value of a benefit such as using separated solids for bedding or compost may offset the cost differential between the two options. A planner can use the categories in the table as a guide to the development of costs and potential benefits when advising a producer on system selection.

When looking at fixed and variable costs, the total relative cost differential between gravity and mechanical systems may not be significant. Whereas chemical enhancement for either type of waste separation system can substantially increase overall costs. As a result, the selection of a waste separation system is dependent on the most important controlling factors as outlined in table 4–86 for the owner or operator.

Table 4–86 Cost and benefit categories to consider when planning a solid-liquid separation system

Category	Gravity settling	Mechanical separation	Chemical enhancement
Fixed costs			
Construction of separation system	\$\$\$	\$	\$
Machinery and controls	\$	\$\$\$	\$\$
Land area for separation system	\$\$\$	\$	¢
Solids storage	\$	\$	¢
Variable costs			
Labor	\$\$	\$	\$
Energy for the separation system	¢	\$\$	\$
Energy for handling separated solids	\$	\$\$	
Maintenance	\$	\$\$	\$\$
Coagulants and flocculants			\$ to \$\$\$
Relative total costs ^{1/}	12\$	13\$	8\$ to 10\$
Relative total costs with chemical enhancement ^{2/}	20\$ to 22\$	21\$ to 23\$	
Potential separated solids benefits			
Bedding	NA	\$\$\$	NA
Fertilizer	\$\$	\$	\$\$\$
Compost	\$	\$\$	\$\$\$
Biogas production potential	\$\$	¢	\$\$\$
Energy Content	¢	\$\$	\$\$\$
Potential separated liquids benefits			
Fertilizer Content	\$\$	\$\$\$	\$
Removal of P	\$\$	\$	\$\$\$
Biogas from liquid effluent	\$	\$\$	¢

^{1/} Relative total cost = Sum of the dollar signs for fixed + variable costs

^{2/} Relative total cost with chemical enhancement = Sum of the relative total costs for the system + chemical enhancement costs

¢ = very low, \$ = low, \$\$ = medium, \$\$\$ = high

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APPENDIX A Nomenclature

A_P	Projected particle area in the direction of fall
A_S	Surface area of the settling zone
AU	Animal unit = 1,000 pounds of live animal weight
A_X	Cross-sectional area of a settling basin
BOD_5	5-day biological oxygen demand
C_D	Drag coefficient of a falling particle
CS	Compression settling
CV	Chamber storage volume
CR_C	Concentration reduction of a manure constituent
C_T	Total carbon
[C]	General symbol of a constituent concentration on a volume basis
$[C_{EFF}]$	Constituent concentration in the liquid effluent, volume basis
$[C_M]$	General symbol of a constituent concentration on a mass basis
$[C_{MSS}]$	Constituent concentration on a mass basis in separated solids
$[C_{IN}]$	Influent constituent concentration
CLD	Covered lagoon digester (typically unheated)
COD	Chemical oxygen demand
d	Equivalent spherical diameter of a falling particle
d_{50}	Median particle diameter
D_A	Depth of the settling zone
D_T	Total depth of a settling basin that includes the settling zone and the depth to allow settled solids to accumulate
D_{SM}	Depth of settled material
DM	Dry matter
DVS	Dissolved volatile solids
E	Entrainment factor
FS	Fixed solids or ash
f_s	Safety factor
f_{TSR}	Fraction of the total solids removed
f_{VSR}	Fraction of volatile solids removed
g	Acceleration of gravity
G	Velocity gradient
h(t)	Height of the solid-liquid interface at the end of a time interval
h(0)	Initial height of manure prior to settling
H	Height of a conical pile
L_s	Length of the settling zone
LHS	Linear hindered settling
LR	Loading rate (of a treatment lagoon)
m	Mass flow of solid manure, general
m_C	Mass flow of C (manure constituent)
m_F	Mass flow of liquid manure (fluid)
m_{SS}	Mass flow of separated solids
MRE_C	Mass removal efficiency of a manure constituent
MTS	Mass of total dry solids produced per day

MVS	Mass of volatile solids produced per day
N_{FS}	Number of freestalls in a dairy freestall building
NH_4^+-N	Ammonium nitrogen based on chemical analysis of a manure sample.
PAN	Plant available nitrogen sum of the ammonium-N, and organic-N that is available to the plant plus all nitrate-N contained in animal manure.
PAM	Water soluble organic polymers formed from acrylamide
Q	Fluid flow rate, general
Q_i	Intermittent flow rate
Q_{IN}	Influent manure flow rate
r	Radius
R_{SAND}	Sand recovery rate
Re-p	Particle Reynolds number $U-p d / \nu$
SAR	Sludge accumulation rate
S_{PTT}	Volume of a reception pit
SG_p	Specific gravity of a particle
SP	Design storage period, days
SR	Stocking rate number of cows/number of freestalls
SU	Sand use rate
SV	Sludge storage volume of a treatment lagoon
STR	Separator throughput rate
SVF	Settled volume fraction
SVF(t)	Settled volume fraction at time, t
SSV	Sand storage volume
SLDM	Sand-laden dairy manure
T	Detention time
TAN	Total ammonical nitrogen = $(NH_4^+-N + NH_3-N)$
THS	Transitional hindered settling
TL	Total length of a solids storage windrow
TS	Total solids
TSR	Total solids removed
TV	Treatment volume
$U-i$	Interface settling velocity
$U-i_{CS}$	Interface settling velocity during compression settling
$U-i_{LHS}$	Linear hindered settling velocity
U_F	Mean flow velocity in a settling basin
U_O	Overflow rate of a settling basin
$U-p$	Discrete particle settling velocity
$U-p_{CR}$	Flow rate of the smallest particle
V_I	Initial manure volume prior to settling
V_P	Particle volume
VD	Total volume of liquid manure removed from an animal facility per day
V_{CONE}	Volume of a conical pile
V_M	Volume of manure

V_R	Volume of recycled lagoon water
VS	Volatile solids
VSS	Suspended volatile solids
$V_{SM}(t)$	Volume occupied by the settled material at time, t
V_{SZ}	Volume of the settling zone
W	Width of a rectangular settling basin
α	Angle of repose
Δt	Time interval
ρ_B	Wet bulk density
ρ_F	Fluid density
ρ_{DB}	Dry matter bulk density
ρ_{SAND}	Sand density
ρ_P	Particle density
ν	Kinematic viscosity of a fluid
μ	Dynamic viscosity of a fluid

Appendix 4B Additional Solid-Liquid Separation Performance Data

Table 4B-1 Summary of separation efficiency data for incline screen separators (static and in-channel flighted conveyor) treating beef and swine manure (concentration reduction)

Animal type	Opening size (mm)	Influent TS (%)	Separation efficiency (%)					TS in solids (%)
			TS	VS	COD	TKN	TP	
Beef ^{1/}	0.5	0.97–4.41	1–13	—	—	—	—	13–22
Swine	1.0 ^{2/}	1.0–4.5	6–31	5–38	0–32	3–6	2–12	5.0
Flow = 33 gpm	1.0 ^{3/}	0.2–0.7	35	—	69	—	—	9
Flow = 62 gpm	1.5 ^{3/}	0.2–0.7	9	—	24	—	—	6

1/ Solids from an oxidation ditch treating beef manure, Hegg et al. (1981)

2/ Piccinini and Cortellini (1987) as reported by Zhang and Westerman (1997)

3/ Shutt et al. (1975)

Table 4B-2 Summary of separation efficiency data for rotating screen separators (concentration reduction)

Animal type	Opening size (mm)	Influent TS (%)	Separation efficiency (%)					TS in solids (%)
			TS	VS	COD	TKN	TP	
Beef	0.75 ^{1/}	1.56–3.68	4–6	—	11–16	—	—	9.5–12.4
Dairy	0.75 ^{1/}	0.52–2.95	0–14	—	3–5	—	—	6.4–11.0
Swine	0.75 ^{1/}	2.54–4.12	4–8	—	3–5	—	—	16–17
	0.8 ^{2/}	1.0–4.5	5–24	9–31	2–19	5–11	3–9	12

1/ Hegg et al. (1981)

2/ Piccinini and Cortellini (1987) as reported by Zhang and Westerman (1997)

Table 4B-3 Summary of separation efficiency data for incline screen separators (static and in-channel flighted conveyor) treating dairy manure (concentration reduction)

Separator type	Chastain et al. (2001a)	Fulhage and Hoehne (1998)	Auvermann and Sweeten (1992)	AWMFH (2012)		Graves et al. (1971)
	----- In-channel flighted conveyor -----			----- Static -----		
Opening size (mm)	1.5	1.5	--- ^{1/}	0.557	1.68	0.51
Influent TS (%)	3.83	---	1.50	2.8	4.6	---
TS removed (%)	60.9	45.5	19.4	68	49	55–74
VS removed (%)	62.8	50.1	24.3	---	---	57–75
TKN removed (%)	49.2	17.1	13.3	---	---	---
Org.-N removed (%)	52.2	19.0	---	---	---	33–52
NH ₄ ⁺ -N removed (%)	45.7	8.3	---	---	---	18–33
TP removed (%)	53.1	11.0	18.4	---	---	---
TK removed (%)	50.8	9.9	7.6	---	---	---
COD removed (%)	66.5	---	27.0	---	---	41–68
BOD ₅ removed (%)	---	---	21.6	---	---	---

Separated solids						
TS (%)	20.3	23.1	18.6	6.0	12.1	---
lb solids /cow/day	46.1	30.9	---	---	---	---
lb solids /1,000 lb /day ^{2/}	51	23				---

1/ --- = not reported

2/ Computed assuming Jersey cows have an average weight of 900 lb and Holsteins have an average weight of 1,350 lb

Table 4B-4 Removal of solids, COD, plant nutrients, and minerals from flushed dairy manure using a 1.5-mm inclined stationary screen separator (Chastain et al. 2001a)

	Flushed manure	After inclined stationary screen	Concentration reduction
	----- (mg/L) ^{1/} -----		(%)
Total solids	38,258	14,959	60.9
Total suspended solids	29,575	11,051	62.6
Volatile solids	32,073	11,937	62.8
Suspended volatile solids	28,137	9,760	65.3
Chemical oxygen demand	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 ₂ O ₅	930	436	53.1
K ₂ O	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

1/ To convert from mg/L to lb/1,000 gal divide by 119.826

Table 4B-5 Performance of an inclined screen and settling basin in series treating flushed dairy manure ($TS_{IN} = 3.8\%$, CR = concentration reduction, adapted from Chastain et al. 2001a)

	Flushed manure	After inclined stationary screen	After settling basin		
	----- (mg/L) ^{1/} -----		CR (%)	(mg/L)	CR (%)
Total solids ^{2/}	38,258	14,959	60.9	11,470	23
Volatile solids	32,073	11,937	62.8	8,705	27
Ammonium-N	661	359	45.7	389	0 ^{3/}
Organic-N	772	369	52.2	304	18
TKN	1,433	729	49.2	703	3.6
P ₂ O ₅	930	436	53.1	373	14
K ₂ O	921	453	50.8	495	0 ^{3/}
Ca	953	488	48.8	423	13
Mg	337	168	50.2	158	6.0
S	179	104	41.6	86	17
Zn	14	7	50.0	5	28
Cu	11	12	0	7	42
Mn	12	6	50.0	5	17
Na	288	140	51.2	148	0 ^{3/}

1/ To convert from mg/L to lb/1,000 gal divide by 119.826

2/ Large amounts of wood shavings were used for freestall bedding and increased solids and nutrient removal

3/ Influent and effluent concentrations of soluble constituents were not significantly different, hence CR = 0

Table 4B-6 Summary of separation efficiency data for roller and belt presses (concentration reduction)

Press type	Opening size (mm)	Influent TS%	Separation efficiency (%)					TP	TS in solids (%)
			TS	VS	COD	TKN	TP		
Belt press									
Dairy	1.0–2.0 ^{1/}	7.1	32.4	—	—	10	15	15.3	
Swine	1.0–2.0 ^{1/}	5.66	22.3	—	—	10	20	19.2	
	0.1 ^{2/}	3.0	47	—	39	32	18	18	
	0.1 ^{2/}	8.0	59	—	40	35	21	14	
Roller press									
Beef	3.2 & 3.2 ^{3/}	7.2	33.3	36.3	—	13.9	14.3	16.3	
Dairy	3.2 & 3.2 ^{3/}	5.2	36	40.6	—	14.7	15.3	13.9	
	— ^{4/}	4.5	9.5	—	—	—	—	26	
	— ^{4/}	9.9	25	—	—	—	—	30	
	— ^{4/}	10.3	39.9	44.8	—	17.9	13.4	23.9	
Swine	1.6 & 1.6 ^{5/}	6.3	20.6	24.8	—	6.2	6.1	20	
Filter press									
Swine	Membrane ^{6/}	1.8	26–51	—	—	11–31	7–42	—	

1/ Moller et al. (2000) as reported by Ford and Fleming (2002)

2/ Fernandes et al. (1988)

3/ Pos et al. (1984)

4/ Rorick et al. (1980)

5/ Gooch et al. (2005)

6/ Pieters et al. (1999)

Table 4B-7 Summary of separation efficiency data for vibrating screen separators (concentration reduction)

Animal Type	Opening Size (mm)	Influent TS (%)	Separation efficiency (%)					TS in Solids (%)
			TS	VS	COD	TKN	TP	
Beef	0.595 ^{1/}	1.60	11	—	7	—	—	15.4
	0.595 ^{1/}	3.19	16	—	5	—	—	16.4
	0.841 ^{1/}	1.55	6	—	7	—	—	15.9
	0.841 ^{2/}	6.8	26	—	—	—	—	24
	1.68 ^{1/}	1.59	12	—	—	—	—	14.8
Dairy	0.595 ^{1/}	1.02	10	—	9	—	—	12.1
	0.595 ^{1/}	1.73	16	—	5	—	—	5.7
	0.841 ^{1/}	1.05	12	—	3	—	—	12.6
	0.841 ^{1/}	1.84	12	—	—	—	—	9.7
	1.68 ^{1/}	0.95	8	—	8	—	—	12.3
	1.68 ^{1/}	1.90	12	—	12	—	—	14.8
Swine	0.104 ^{3/}	3.6	58	62	53	42	46	5
	0.39 ^{4/}	0.2–0.7	22	28	16	—	—	16
	0.516 ^{5/}	3.6	36	40	33	18	25	13
	0.595 ^{1/}	1.83	27	—	24	—	—	20.9
	0.44 ^{5/}	1.0	15	18	13	2	1	13
	0.44 ^{5/}	4.5	25	38	26	5	15	13
	0.841 ^{1/}	1.52	10	—	1	—	—	18.4
	0.841 ^{1/}	2.86	10	—	14	—	—	19.3
	1.68 ^{1/}	1.55	3	—	6	—	—	16.9
	1.68 ^{1/}	2.88	5	—	4	—	—	20.9

1/ Hegg et al. (1981)

2/ Gilbertson and Nienaber (1978)

3/ Holmberg et al. (1983)

4/ Shutt et al. (1975)

5/ Piccinini and Cortellini (1987) as reported by Zhang and Westerman (1997)

Table 4B–8 Summary of separation efficiency data for screw presses (concentration reduction and mass removal efficiency)

Animal type	Opening		Separation Efficiency (%)						
	Size (mm)	Influent TS (%)	TS	VS	TKN	Organic N	NH ₄ -N	TP	TS in solids (%)
Dairy	0.50 ^{1/}	2.6	24.6	—	7.7	13	2.1	5.7	26.1
	0.75 ^{2/}	9.96	70.5	76.9	24.1	29.3	20.2	23.9	25.3
	2.38 ^{3/}	2.0	15.8	—	—	—	—	8.6	26.3
	2.38 ^{3/}	10.0	47.0	—	—	—	—	28.9	33.9
	2.38 ^{1/}	4.9	33.1	—	13.3	20	3.1	9.7	28.9
	3.0 + 1.0 ^{4/}	5.2 ^{5/}	48.2	—	22.7	—	—	12.5	23.1
	3.0 + 1.0 ^{4/}	5.4 ^{6/}	51.4	—	25.71	—	—	15.1	19.4
Digested ^{7/}	0.50 ^{2/}	7.45	49.6	55.7	16.0	18.2	13.8	24.3	23.7
	0.50 ^{2/}	8.32	46.5	52.5	16.8	19.6	14.5	20.1	24.6
	2.25 ^{2/}	5.50	3.9	4.7	1.2	1.5	0.7	1.2	29.3
Swine	0.50 ^{3/}	1.5–5.3	15–29.7	—	< 8	—	—	3–5	23.5–34.5
	0.50 ^{8/}	3.0	7.3	9.8	5	7	4	7.5	22.6–34.4
	0.50 ^{8/}	5.0	15.7	28.7	12	15.5	10	16	22.6–34.4
	0.50 ^{8/}	7.0	24.1	31.7	20	23.5	17	24	22.6–34.4
	0.50 ^{8/}	Pit ^{9/}	14.9	19.6	9.2	16.0	7	14.8	27.5

1/ Converse et al. (2000), concentration reduction

2/ Gooch et al. (2005), mass removal

3/ Converse et al. (1999),

4/ Wu (2007), Screw press used had two inline cylindrical screens with a common auger. The first screen had 3.0 mm openings and the second had 1.0 mm openings, concentration reduction

5/ Chastain et al. (2001b), concentration reduction

6/ Press operated with additional weights on pressure plate to produce solids for use as freestall bedding.

7/ Press operated with less weight on pressure plate to produce solids for land application.

8/ All three of these machines were processing effluent from anaerobic digesters on dairy farms.

9/ Calculated separation efficiency for processing manure from a recharge pit on a swine finishing farm based on the manure added by the animals only (TS of the influent to press varied from 0.5% TS to 5.5% TS).

Table 4B-9 Summary of separation efficiency data for centrifuges and hydrocyclones (concentration reduction)

Type	Influent TS (%)	Separation efficiency (%)					TS in solids (%)
		TS	VS	COD	TKN	TP	
Centrifuge							
Beef	3.6–6.2 ^{1/}	51–61	60–65	52–60	23–28	43–48	19–26
In-flow = 10.8 gpm	7.5 ^{2/}	25	—	35	—	—	18.4
Swine	1.0–7.5 ^{1/}	15–61	18–65	7.8–44	3.4–32	58–68	16–27
Decanter Centrifuge							
Beef							
Flow = 8 gpm	6.0 ^{2/}	45	—	56	—	—	26.1
Flow = 3.5 gpm	6.9 ^{2/}	64	—	72	—	—	22.1
Swine							
Flow = 2.6 gpm	7.58 ^{3/}	66	—	52	—	—	37.4
	1.9 ^{4/}	47.4	—	—	—	—	29–31
	8.0 ^{4/}	56.2	—	—	—	—	25.9
Hydrocyclone							
Dairy ^{5/}							
Cone diameter = 3"	1.2	16.3	21.1	8.8	—	—	12.5
Cone diameter = 10"	1.4	7.9	10	5.5	2.7	5.4	2.0
Swine manure after passing through a 1 mm screen ^{6/}							
6° cone, 23 gpm	0.10–0.50	26.5	—	—	—	—	8.4
Swine							
Flow = 66 gpm	1.5–2.0 ^{7/}	8.0	—	—	—	—	—

1/ Piccinini and Cortellini (1987) as reported by Zhang and Westerman (1997)

2/ Chiumenti et al. (1987) as reported by Ford and Fleming (2002). The two different flow rates represent results for machines made by two different companies.

3/ Glerum et al. (1971) as reported by Ford and Fleming (2002)

4/ Sneath et al. (1988) as reported by Ford and Fleming (2002)

5/ Auvermann and Sweeten (1992)

6/ Shutt et al. (1975) as reported by Ford and Fleming (2002)

7/ Pietters et al. (1999) as reported by Ford and Fleming (2002)

Table 4B–10 Performance of gravity settling treating flushed dairy manure with $TS_{IN} = 4.2\%$ (adapted from Chastain et al. 2001a)

Constituent	Influent (mg/L) ^{1/}	After settling for 30 minutes		After settling for 60 minutes	
		Effluent (mg/L)	Concentration reduction (%)	Effluent (mg/L)	Concentration reduction (%)
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 ^{2/}
Organic-N	923	681	26.2	524	43.3
TKN	1,464	1,107	24.4	1,113	24.0
P ₂ O ₅	1,061	766	27.8	661	37.7
Elemental-P	467	337	27.8	291	37.7
Inorganic-P	136	138	0	137	0 ^{2/}
K ₂ O	958	952	0.6	954	0.4
Zn	15	11	26.7	9	40.0
Cu	6	4	33.3	4	33.3

1/ To convert from mg/L to lb / 1,000 gal divide by 119.826.

2/ Influent and effluent concentrations of soluble constituents were not significantly different, CR = 0.

Table 4B–11 Plant nutrients in separated dairy solids and lagoon sludge (Chastain et al. 2001a)

	Solids from stationary screen	Solids from settling basin	Lagoon sludge and supernatant mixture
Total solids (%)	20.3	10.9	7.0
	----- (mg/kg, wet basis) ^{1/} -----		
Ammonium–N	100	200	1,840
Organic–N	2,370	2,885	8,950
TKN	2,470	3,085	10,790
P ₂ O ₅	1,530	2,010	11,945
K ₂ O	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

1/ To convert to lb/ton divide by 500

Table 4B-12 Performance of gravity settling treating milking center wastewater with $TS_{IN} = 0.7\%$ (adapted from Chastain et al. 2005) Detention time = 60 min and $SVF = 0.093$

Constituent	Influent (mg/L) ^{1/}	Supernatant (mg/L)	Concentration reduction (%)	Mass removal efficiency (%)
TS	7,165	4,645	35	41
VS	4,621	2,690	42	47
TAN	354	375	0 ^{2/}	9 ^{3/}
Org-N	252	153	39	45
TKN	607	528	13	21
P ₂ O ₅	255	146	43	48
K ₂ O	508	533	0 ^{2/}	9 ^{3/}
Ca	237	195	18	25
Mg	77	48	38	43
S	39	25	36	42
Zn	2.1	1.2	50	55
Cu	0.4	0.2	50	55
Mn	1.7	1.1	50	55
Na	214	228	0 ^{2/}	9 ^{3/}

1/ To convert from mg/L to lb/1,000 gal divide by 119.826.

2/ Influent and effluent concentrations of soluble constituents were not significantly different, CR = 0.

3/ Mass removal efficiency = $100 \times SVF$ if concentration reduction is not significantly different from zero.

Table 4B-13 Performance of gravity settling treating milking center wastewater with $TS_{IN} = 1.7\%$ (adapted from Chastain et al. 2005) detention time = 60 min, and SVF = 0.254

Constituent	Influent (mg/L) ^{1/}	Supernatant (mg/L)	Concentration reduction (%)	Mass removal efficiency (%)
TS	17,024	8,960	47	61
VS	13,373	6,049	55	66
TAN	756	785	0 ^{2/}	25 ^{3/}
Org-N	452	167	63	73
TKN	1,207	951	21	41
P ₂ O ₅	402	296	26	45
K ₂ O	917	961	0 ^{2/}	25 ^{3/}
Ca	321	286	11	34
Mg	133	102	23	43
S	65	47	28	46
Zn	4.2	3.0	29	47
Cu	1.2	0.6	50	63
Mn	3.0	2.4	20	40
Na	161	167	0 ^{2/}	25 ^{3/}

1/ To convert from mg/L to lb / 1,000 gal divide by 119.826.

2/ Influent and effluent concentrations of soluble constituents were not significantly different, CR = 0.

3/ Mass removal efficiency = $100 \times SVF$ if concentration reduction is not significantly different from zero.

Table 4B-14 Composition of settled solids following 30 and 60 minutes of settling of milking center wastewater (adapted from Chastain et al. 2005)

Constituent	[TS _{IN}] = 17,024 mg/L (1.7%)				[TS _{IN}] = 7,165 mg/L (0.7%)			
	T= 30 min		T= 60 min		T= 30 min		T= 60 min	
	SVF(T) = 0.279		0.254		0.105		0.093	
	C _{SM} ^{1/} (mg/L) ^{2/}	C _{SM} /C _{IN} ^{3/}	C _{SM} (mg/L)	C _{SM} /C _{IN}	C _{SM} (mg/L)	C _{SM} /C _{IN}	C _{SM} (mg/L)	C _{SM} /C _{IN}
TS	37,894	2.23	40,658	2.39	28,554	3.99	31,800	4.44
VS	32,328	2.42	34,838	2.61	21,011	4.55	23,498	5.09
TAN	771 ^{4/}	1.0	771 ^{4/}	1.0	365 ^{4/}	1.0	365 ^{4/}	1.0
Org-N	1,190	2.63	1,288	2.85	1,092	4.33	1,220	4.84
TKN	1,869	1.55	1,957	1.62	1,278	2.10	1,379	2.27
P ₂ O ₅	676	1.68	713	1.77	1,180	4.63	1,321	5.18
K ₂ O	939 ^{4/}	1.0	939 ^{4/}	1.0	521 ^{4/}	1.0	521 ^{4/}	1.0
Ca	413	1.28	425	1.32	593	2.50	648	2.73
Mg	214	1.61	224	1.69	323	4.20	361	4.68
S	112	1.71	118	1.81	158	4.05	176	4.51
Zn	7.3	1.74	7.7	1.84	10.5	5.24	11.8	5.89
Cu	2.7	2.29	3.0	2.47	2.1	5.24	2.4	5.89
Mn	4.5	1.52	4.8	1.59	10.5	5.24	11.8	5.89
Na	164 ^{4/}	1.0	164 ^{4/}	1.0	221 ^{4/}	1.0	221 ^{4/}	1.0

1/ C_{SM} = Concentration of a constituent in the settled material

2/ To convert from mg/L to lb/1,000 gal divide by 119.826

3/ C_{SM}/C_{IN} = ratio of C_{SM} to concentration of a constituent in the influent milking center wastewater

4/ Mean of initial and supernatant concentrations, Concentrations not significantly affected by sedimentation, therefore C_{SM}/C_{IN} = 1.0

Table 4B-15 Performance of gravity settling treating a mixture of dairy lagoon sludge and supernatant with $TS_{IN} = 1.9\%$ (adapted from Chastain and Darby, 2000) detention time = 7 hr, and SVF = 0.385

Constituent	Influent (mg/L) ^{1/}	Supernatant (mg/L)	Concentration reduction (%)	Mass removal efficiency (%)
Total solids	19,340	3,558	81.6	88.7
Fixed solids	8,116	1,345	83.4	89.8
Volatile solids	11,223	2,212	80.3	87.9
TAN	75	57	24.0	53.3 ^{3/}
Organic-N	755	217	71.3	82.3
Nitrate-N	1	2	0 ^{2/}	38.5 ^{4/}
TKN	830	273	67.1	79.8
Total-N	831	275	66.9	79.6
P ₂ O ₅	547	174	68.2	80.4
K ₂ O	410	325	20.6	51.3
Zn	20	3	82.6	90.8
Cu	19	4	79.3	87.1

1/ To convert from mg/L to lb/1,000 gal divide by 119.826

2/ Influent and effluent concentrations of soluble constituents were not significantly different, CR = 0

3/ Data indicated that TAN was lost by ammonia volatilization

4/ Mass removal efficiency = $100 \times SVF$ if concentration reduction is not significantly different from zero

Table 4B-16 Performance of gravity settling treating a mixture of dairy lagoon sludge and supernatant with $TS_{IN} = 3.98\%$ (adapted from Chastain and Darby 2000) detention time = 7 hr and SVF = 0.423

Constituent	Influent (mg/L) ^{1/}	Supernatant (mg/L)	Concentration reduction (%)	Mass removal efficiency (%)
Total solids	39,862	2,398	94.0	96.5
Fixed solids	12,714	1,165	90.8	94.7
Volatile solids	27,148	1,232	95.5	97.4
TAN	240	187	22.1	55.0 ^{3/}
Organic-N	1,395	200	85.7	91.7
Nitrate-N	1	2	0 ^{2/}	42.3 ^{4/}
TKN	1,635	387	76.3	86.3
Total-N	1,636	389	76.2	86.3
P ₂ O ₅	1,116	234	79.1	87.9
K ₂ O	392	378	3.6	44.4
Zn	18	1	96.0	96.8
Cu	4	0.2	95.1	97.1

1/ To convert from mg/L to lb/1,000 gal divide by 119.826

2/ Influent and effluent concentrations of soluble constituents were not significantly different, CR = 0

3/ Data indicated that TAN was lost by ammonia volatilization

4/ Mass removal efficiency = $100 \times SVF$ if concentration reduction is not significantly different from zero

Table 4B-17 Solids and plant nutrient content in thickened dairy lagoon sludge (Chastain and Darby 2000)

Settling time (hr) SVF(T)	Thickened sludge from [TS _{IN}] = 19,340 mg/L (1.93%)		Thickened sludge from [TS _{IN}] = 39,862 mg/L (3.98%)	
	7		7	
	0.385		0.423	
	C _{SM} ^{1/} (mg/L) ^{2/}	C _{SM} / C _{IN} ^{3/}	C _{SM} ^{1/} (mg/L)	C _{SM} / C _{IN}
Total solids	40,985	2.12	88,499	2.22
Fixed solids	18,929	2.33	28,446	2.24
Volatile solids	25,609	2.28	62,452	2.30
TAN	104	1.39	313	1.30
Organic-N	1,615	2.14	3,023	2.17
TKN	1,719	2.07	3,336	2.04
P ₂ O ₅	1,143	2.09	2,318	2.08
K ₂ O	544	1.33	411	1.05
Zn	46	2.30	41	2.28
Cu	44	2.32	9	2.25

1/ C_{SM} = Concentration of a constituent in the settled material

2/ To convert from mg/L to lb/1,000 gal divide by 119.826

3/ C_{SM} / C_{IN} = ratio of C_{SM} to concentration of a constituent in the influent sludge and lagoon water mixture

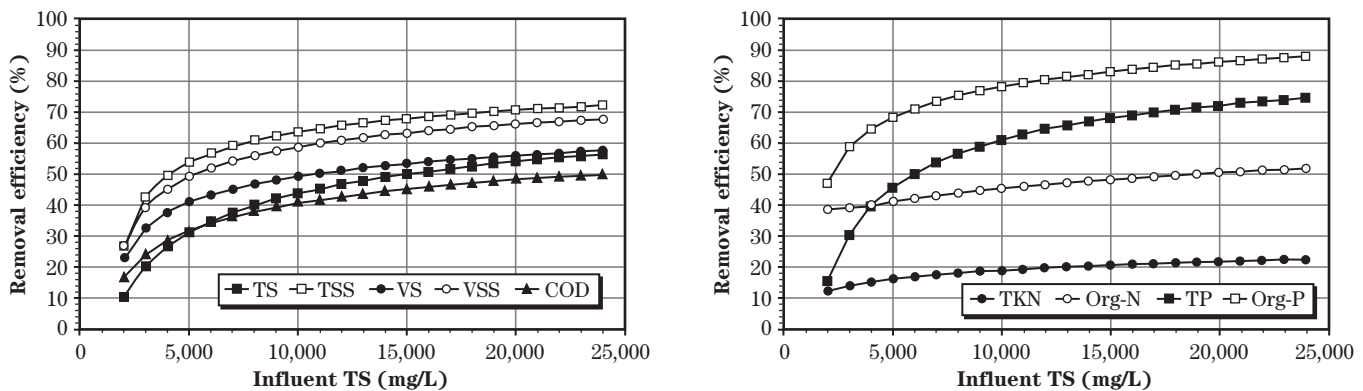
Table 4B-18 Influent and supernatant concentrations of liquid finishing swine manure treated by 60 min. of gravity settling (adapted from Chastain and Vanotti 2003)

Influent concentrations (mg/L) ^{1/}	R ²	Supernatant concentrations (mg/L)	R ²
$[TS_{IN}] = 1,730 \text{ to } 23,850$ ^{2/}	NA	$[TS_{OUT}] = 8.12 [TS_{IN}]^{0.71}$	0.9757
$[TSS_{IN}] = 0.832 [TS_{IN}] - 1073$	0.9939	$[TSS_{OUT}] = 4.38 [TSS_{IN}]^{0.72}$	0.9763
$[VS_{IN}] = 0.699 [TS_{IN}] - 698$	0.9910	$[VS_{OUT}] = 2.67 [VS_{IN}]^{0.81}$	0.9896
$[VSS_{IN}] = 0.580 [TS_{IN}] - 579$	0.9910	$[VSS_{OUT}] = 3.81 [VSS_{IN}]^{0.74}$	0.9726
$[COD_{IN}] = 0.936 [TS_{IN}] - 381$	0.9779	$[COD_{OUT}] = 3.34 [COD_{IN}]^{0.81}$	0.9613
$[TKN_{IN}] = 0.112 [TS_{IN}]$	0.8899	$[TKN_{OUT}] = 1.15 [TKN_{IN}]^{0.95}$	0.9926
$[TAN_{IN}]^1 = 0.554 [TKN_{IN}] + 29$	0.9508	$[TAN_{OUT}] = 1.00 [TAN_{IN}]$	0.9994
$[Org-N_{IN}] = [TKN_{IN}] - [TAN_{IN}]$	NA	$[Org-N_{OUT}] = [TKN_{OUT}] - [TAN_{OUT}]$	NA
$[TP_{IN}] = 0.052 [TS_{IN}]$	0.9044	$[TP_{OUT}] = 7.87 [TP_{IN}]^{0.52}$	0.8988
$[Org-P_{IN}] = 0.894 [TP_{IN}] - 59$	0.9945	$[Ortho-P_{OUT}] = 1.00 [Ortho-P_{IN}]$	0.9874
$[Ortho-P_{IN}] = [TP_{IN}] - [Org-P_{IN}]$	NA	$[Org-P_{OUT}] = [TP_{OUT}] - [Ortho-P_{OUT}]$	NA
$[TK_{IN}] = 0.049 [TS_{IN}] + 185$	0.8881	$[TK_{OUT}] = 0.98 [TK_{IN}]$	0.9915

1/ To convert from mg/L to lb/1,000 gal divide by 119.826.

2/ Range of concentration of total solids in swine manure as removed from pit-recharge and flush swine finishing buildings.

Figure 4B-1 Concentration reduction of solids, COD, and major plant nutrients following 60 min of gravity settling of liquid swine manure (Chastain and Vanotti 2003)



APPENDIX C

Demonstration Projects Funded by FPPC that Include Liquid-solid Separation

Farm Pilot Project Coordination, Inc. (FPPC) (<http://www.fppcinc.org/index.html>) has provided funding for several demonstration projects that include evaluation of liquid-solid separation technologies. The purpose of this appendix is to provide short summaries of the project results. The reader is encouraged to review the complete project reports that are available online. The URL for each project is given.

(a) Belt press for dairy waste nutrient removal, animal waste solutions, Coral Springs, FL

Available at http://www.fppcinc.org/projects_aws.html

This demonstration project provides detailed information concerning the use of a novel belt press to provide primary treatment of anaerobically digested and raw dairy manure with and without the use of a cationic PAM with a medium charge density. The authors of this study provide a valuable comparison of a screw press and the newly developed belt press on one of the three dairy farms (New York, Vermont, and Georgia) included in the study. A detailed analysis of the annual costs including PAM costs is included. Key results from this study are summarized below.

- Solids removal provided by the belt press ranged from 36 to 73 percent. When manure was pre-mixed with PAM at a dose in the range of 500 to 750 milligrams per liter, the TS removal ranged from 75 to 99 percent.
- Use of the belt press to separate PAM treated manure provided a total nitrogen (TKN) removals ranging from 50 to 60 percent. The total-P removed ranged from 79 to 92 percent.
- Separated solids could be easily handled as a solid as indicated by a TS contents of 26.2 to 36.3 percent
- Using a PAM dose of 500 milligrams per liter and a chemical cost of \$2 per pound the chemical cost was \$8.34 per 1,000 gallons of dairy manure processed.
- The electrical energy used by liquid-solid separation was 3.57 kilowatts per hour per 1,000 gallons of manure (\$0.25/1,000 gal at \$0.07/kWh).

- Total annualized cost of PAM and mechanical separation varied based on farm size and ranged from \$51 to \$200 per year per steady-state live animal weight.

(b) Ohio dairy waste separation and wastewater treatment project: Andreas and Royer Dairy Farms, Crossroads RC&D Council & Wastewater, Inc., Beach City, OH

Available at http://www.fppcinc.org/projects_crossroadsrkd.html

The goal of this project was to demonstrate that a mechanical liquid-solid separation system could be used to remove 99 percent of the solids and plant nutrients from dairy manure and yield a liquid fraction with a TS content less than 1 percent. The effluent from the liquid-solid separator was to receive additional treatment to meet discharge standards. The types of mechanical separators considered included a drum brush screen, belt press, and screw press. Pretreatment of dairy manure with polymers was also considered. Several machine and polymer combinations were considered. The total-P removals observed ranged from 89 to 92 percent with TKN removal of 67 percent and BOD removal of 44 percent. However, none of the systems studied provided the required solids and plant nutrient removal to meet discharge requirements. The cost of polymer for treatment was also judged to be too expensive.

(c) Struvite formation pilot study conducted at Fisher Dairy, Reaction Energy Corporation, Yantis, TX

Available at http://www.fppcinc.org/projects_reactionenergycorporation.html

The goal of this project was to use a struvite precipitator to remove 75 percent of the total phosphorous (TP) from dairy manure. It was determined that only 25.5 to 42.3 percent of the TP could be removed on the first day of treatment. A process time of 3 weeks was required to reach a TP removal of 74.7 percent. It was determined that the high amounts of calcium in dairy manure greatly altered the anticipated reaction kinetics.

(d) Reducing dairy manure phosphorous content through solid separation and phosphorus recovery by struvite precipitation, Virginia Dairyman’s Association and Dr. J.A. Ogejo, Bio-systems Engineering, Virginia Tech, Blacksburg, VA

Available at http://www.fppcinc.org/projects_virginia-dairymensassoc.html

The purpose of this project was to evaluate the potential to combine liquid-solid separation of dairy manure with a screw press and phosphorous removal from the separator effluent by struvite precipitation. The screw press used for the first step in the treatment process was fitted with a 0.5 millimeter screen. The dairy manure that was processed was slurry with a TS of 5.7 percent. The screw press was observed to remove (concentration reductions) 30 percent of the TS, 6 percent of the total P, 11 percent of the calcium, and trace amounts of nitrogen. The pH of the separator effluent varied from 7.8 to 9.6 prior to treatment with the cone fluidized bed struvite reactor. The amount of P removed by the reactor ranged from 2.8 to 8.4 percent. It was determined that high calcium concentrations interfered with the struvite reaction. It was found that the effects of calcium could be removed by treating the manure with a process that included addition of chemicals to react with the calcium (oxalate or EDTA) combined with acidification and treatment with a centrifuge.

(e) Decentralized nutrient reduction, centralized energy production, Agricultural Waste Solutions, Westlake Village, CA

Available at http://www.fppcinc.org/projects_agriculturalwastesolutions.html

This project evaluated using a high-cationic polymer with an advanced centrifuge to treat dairy manure. The solids removed by the centrifuge were used as a biomass energy source. As a part of the study the authors used the polymer and centrifuge to remove solids and plant nutrients from lagoon water, and flushed swine and dairy manure. The concentration

reductions provided in this study for influents with TS contents ranging from 0.6 percent to 2.7 percent are summarized in table 4C–1. The average moisture content of the centrifuged solids was 67 percent. It was also determined that the polymer costs were \$1.44 per 1,000 gallons treated and 3.31 kilowatts per 1,000 gallons treated.

(f) Watson Dairy Project, Agrimond, Cape Canaveral, FL

Available at http://www.fppcinc.org/projects_ajtagrimond.html

The project demonstrated the implementation of a total manure treatment system on an 800-cow dairy in Florida. The system included the following technologies: sand trap, inclined screen separator, biological treatment using the activated sludge process, sedimentation of activated sludge, and use of sludge drying beds. The project report did not provide performance data concerning the individual separation or biological treatment processes. However, the

Table 4C–1 Solids and nutrient removals (concentration reduction, %) observed using a centrifuge to separate polymer flocculated lagoon water and manure (from Agricultural Waste Solutions)

	Swine lagoon	Dairy lagoon	Flushed dairy manure	Flushed swine manure
TS	81	83	81	85
TSS	99	99	97	99
TKN	62	64	70	71
TP	85	87	91	93
COD	85	90	91	97
K	38	36	42	51
Cu	99	93	90	99
Zn	99	99	99	99

treatment system reduced the concentrations of TKN by 88 percent, TP by 67 percent, BOD by 88 percent, and COD by 95 percent. This project demonstrated that a waste treatment process similar to those applied to food processing and municipal waste treatment can provide similar results on a dairy farm. The report also contains many photographs and diagrams that depict the construction and installation of the various unit operations.

(g) Capturing and utilizing struvite from an on-farm dairy operation, Applied Chemical Magnesium-Texas, L.L.C., Loveland, CO, M.S. Massey, J.G. Davis, and R.E. Sheffield

Available at http://www.fppcinc.org/projects_appliedchemicalmagnesiums.html

The use of struvite precipitation to remove phosphorous from dairy manure was evaluated on 4 dairy farms in Colorado. The phosphorous removal ranged from only 9 to 14 percent. High concentrations of calcium were observed which consistently interfere with the formation of struvite crystals.

(h) Pilot Project Program North Williston Cattle Company, BioProcessH2O, LLC, Portsmouth, RI

Available at http://www.fppcinc.org/projects_bioprosesstechnologies.html

In this project the goal was to use liquid-solid separation to treat slurry dairy manure prior to a biofiltration and digestion process. The evaluators tried several methods including two screw presses, a belt press, and sedimentation. The first screw press was only able to reduce the solids content of the effluent to only 4 to 5 percent solids. The desired TS content was 1 percent or less. No details were given concerning influent TS concentration or screen size. Sedimentation was attempted, but the manure removed from the animal facilities was too thick. A second screw press and belt press were used in series to treat the manure and provided sufficient TS reduction to allow the evaluators to test the downstream treatment processes.

(i) High volume geotextile dewatering, EnviroWaste Technology Inc., Carroll, IA

Available at http://www.fppcinc.org/projects_envirowastetechnologies.html

The effectiveness of using chemical coagulants and polymers with geotextile tubes to dewater fresh pit manure from a swine building and agitated swine lagoon sludge was evaluated at Rensing Farms in Illinois. The study included preliminary tests to evaluate the best doses of ferric sulfate and polymer needed to treat both waste streams. Detailed information is provided on the field methods used and the composition of the manure loaded into the tubes, the filtrate, and the dewater solids. A summary of the concentration reductions for TS and major plant nutrients is provided in table 4C–2.

This study also included a detailed summary of the costs and is provided in table 4C–3. The costs to dewater lagoon sludge was higher than for raw manure because the initial TS (5.86%) was much greater than for raw manure (1.75%).

Table 4C–2 Concentration reductions (%) of solids and major plant nutrients provided by addition of ferric sulfate and polymer followed by dewatering with a geotextile tube

	Pit manure from swine barn, TS = 1.75%	Agitated lagoon sludge, TS = 5.86%
TS	52	88
Total–N	57	33
Total–P	86	91
Total–K	1.4	0

(j) Pork nutrient reduction project Marshalltown, IA, Global Resource Recovery Organization, Bradenton, FL

Available at http://www.fppcinc.org/projects_grro1.html

The purpose of this project was to demonstrate that 75 percent of the plant nutrients could be removed from raw swine manure using a two-stage treatment system. The first stage was a mechanical separator (screw press). The effluent from the separator flowed to a surge tank where it was fed to a novel process called the induced cyclonic separation process (IC-SEP). The IC-SEP unit utilized coagulants and polymers with a dissolved air floatation unit. The unit produced a dry bagged product that could be land applied in a similar manner as solid manure. The high amounts of labor, management, and chemicals rendered the concept impracticable for on-farm use. The chemical costs were \$80/1000 gal of manure treated.

(k) Farm pilot program at Geerlings Hillside Farm – Overisel Hog Facility, Overisel, MI, Phase 3 Developments & Investments, LLC, Cincinnati, OH

Available at http://www.fppcinc.org/projects_phase3developments.html

This project focused on the technical and economic feasibility of using a screw press to dewater anaerobic digester effluent. Additional solids and plant nutrients were removed from the separated liquids using a dissolved air flotation system with a combina-

tion of polymers and coagulants. The floating solids were removed and combined with the fibrous solids removed by the screw press. The mixed solids were dried and pelleted. The pellets could be stored in a pile or bagged prior to land application as a plant nutrient source. The process was able to capture more than 50 percent of the nutrients in swine manure. The high cost of chemicals and energy needed for drying prior to pelleting rendered the process unaffordable. The chemical costs were about \$110 per 1,000 gallons of manure processed as compared to only \$15 per 1,000 gal for hauling the digester effluent for conventional land application.

(l) Florida dairy nutrient management demonstration project, Royal Consulting Services, Inc., Altamonte Springs, FL

Available at http://www.fppcinc.org/projects_royalconsultingservices1.html

This project provided detailed data and evaluation of a dairy manure treatment system that had as its goal the removal of 75 percent of major plant nutrients from flushed manure. The system included 3 treatment ponds arranged in series combined with final treatment using a novel ion exchange process that was targeted at phosphate removal. The first pond provided a zone for sand settling and storage followed by a zone for manure solids settling and storage. The liquids from pond 1 were conveyed to pond 2 that was aerated to provide biological treatment using the activated sludge process. Periodically, oxygen-rich water from pond 2 was recycled through pond 1 to suppress

Table 4C-3 Costs for using chemicals and geotextile tubes to treat pit swine manure and lagoon sludge

	Pit manure from swine barn	Agitated lagoon sludge
Polymer	\$5.36/1,000 gal treated	\$8.13/1,000 gal treated
Ferric sulfate	\$0.71/1,000 gal treated	\$3.93/1,000 gal treated
Total costs including site preparation, geotextile tubes, chemicals, labor, and equipment	\$12.98/1,000 gal treated	\$26.76/1,000 gal treated

odor emissions. The supernatant from pond 2 was also used as a source of water for flushing freestall alleys. Pond 3 received the excess water from pond 2 where a chemical flocculent was added to provide additional treatment by settling. The settled solids following flocculation were stored in pond 3. Much of the water in pond 3 was irrigated onto nearby cropland at agronomic rates as a fertilizer substitute. Excess water from pond 3 received additional phosphate removal using the ion change unit. The system exceeded the target removal rate of 75 percent for TP and TN after pond 3 as shown in table 4C-4. However, the total cost to treat manure was \$87.88/1000 gal.

(m) Solids removal system for reducing environmental impact of swine production, Super Soil Systems USA, Inc., Clinton, NC

Available at http://www.fppcinc.org/projects_supersoilssystemusa.html

This project evaluated the performance of a modular, movable liquid-solid separation unit on a commercial swine farm in North Carolina. The separation module included influent homogenization, polymer injection and mixing, screening, dissolved air floatation treatment (DAF), dewatering with a belt press, and removal of the separated solids. Effluent from the multistage separation process was returned to the existing lagoon. Solids were transported to a central processing facility where they were composted to stabilize nutrients, kill pathogens, and manufacture soil amendment,

fertilizer, potting soil, and container mix. The system was monitored over a 6-month period and provided removal of 90 percent of the total suspended solids. The plant nutrient reductions were 47 percent of the total Kjeldahl nitrogen, 90 percent of the organic nitrogen, 74 percent of the total phosphorus, 92 percent of the organic phosphorus, 93 percent of the copper, and 91 percent of the zinc. The least beneficial component of the multistage separation module was dissolved air floatation providing only 2 to 3 percent of the solids, nitrogen, and phosphorus removal. Therefore, elimination of the DAF step was recommended to reduce initial and operating costs. Detailed cost data are provided in the report and a third generation system is being developed based on these data to further reduce costs.

(n) Solid liquid separation and nutrient removal from dairy manure using comparisons from anaerobic digestion, a screw press separator, a two-stage solid-liquid separator, electrocoagulation and settling ponds, Conley Hansen, Ph.D., Utah State University, Logan, UT

Available at http://www.fppcinc.org/projects_utahstateuniv.html

Table 4C-4 Summary of concentration reductions and component costs for a multistage dairy manure treatment system in Florida

System component	Cumulative reduction in TP concentration (%)	Cumulative reduction in TN concentration (%)	Cost to treat 1,000 gallons (\$/1,000 gal)
Pond 1 – sand & manure settling	39	43	10.01
Pond 2 – activated sludge	55	64	7.85
Pond 3 – flocculation and settling	96	72	26.11
Ion exchange system	99	78	23.50
		Total system costs =	87.88

The following is a direct quotation of the project abstract provided by Dr. Hansen:

Manure from a 1,000 cow dairy near Ogden, Utah, was treated first through anaerobic digestion in an Induced Blanket Reactor (IBR) to stabilize the waste, after which the effluent passed through several treatment methods to determine the effectiveness of each system in removing solids and/or nutrients from the anaerobically treated waste stream. Systems studied included anaerobic digestion, mechanical liquid-solid separators, (both a screw press separator and a two-stage dewaterer), electrocoagulation, and natural settling of solids and nutrients. Natural settling was used after some of the treatments to determine its value in removing nutrients in combination with each treatment system. Nitrogen and phosphorus levels in the manure were measured after each stage of treatment to determine the efficacy of the particular treatment system in concentrating and removing these nutrients from the waste stream.

Anaerobic stabilization removed an average 40 percent and 46 percent of the TS and VS respectively, and increased the settleability of the manure significantly. Any P difference before and after anaerobic digestion was due to P storage in the anaerobic digester. Solids in the raw influent manure did not settle. Concentration of nutrients through natural sedimentation was only possible with manure that had been anaerobically stabilized and even better

if also passed through the two-stage dewaterer before settling. Raw or treated manure had to be relatively dilute (2–3 percent) to settle probably due to hindered (> type II) settling. Following anaerobic digestion, the screw press only removed 6 percent of the remaining TS (3 percent of the original TS level). The screw press would only remove those solids that would settle. The screw press was not effective at removing nutrients from the waste stream.

The two-stage dewaterer was able to remove 38 percent of the TS in the anaerobically stabilized waste, resulting in a total TS removal of 66 percent (TS in the waste before entering the lagoon were reduced from 52 g/L to 18 g/L). The two-stage dewaterer was unable to remove nitrogen from the liquid waste, but was able to remove 25 percent of the phosphorus.

Electrocoagulation (EC) treatment resulted in 85 percent and 94 percent removal of the TS and VS respectively from anaerobically treated manure. EC was also effective in removing nitrogen and phosphorus; removing 74 percent and 93 percent respectively but expensive to operate. The cost of operation for our unit was near \$16 per thousand gallons of anaerobic effluent. The manufacturer claimed he could reduce these costs dramatically with a different type of electronic system. The more efficient system was never supplied to us.

APPENDIX D

Guidelines for Evaluating Coagulant and Polymer Dose

Research based information related to the optimum dose of metal salt coagulants and polymer flocculants were provided in NEH637.0405. However, the optimum dose needed for a particular manure treatment system will vary with the composition of the manure, the characteristics of the chemicals to be used, and the desired removal of solids and plant nutrients. In addition, chemical companies have a wide variety of products that have different characteristics than those available in the literature. Therefore, more specific information is often needed to make dose recommendations for a particular metal salt, polymer, or combination of chemicals. Sometimes the information needed can be provided by a chemical manufacturer based on results obtained for a similar type of facility. In many cases, the best way to determine the optimum dose is to perform a laboratory technique called a jar test. The purpose of this appendix is to provide a method to determine the optimum dose of a chemical or chemicals needed to enhance liquid-solid separation.

(a) Collect a large representative sample

The first step in the evaluation process is the collection of a sample of the manure that is large enough to conduct the desired tests and is representative of the manure that will be treated by the liquid-solid separator. The sample used in the evaluation must contain the same average solids and plant nutrient content that will flow from the animal facilities. Therefore, the sample used must be collected from a reception pit, gutter, transfer pipe, or other location while manure is being removed from the animal production facility. If the separation system is being added to an existing facility, the sample should be obtained from a building on that farm that houses animals that are near the maximum weight. If the separation system will be for a new farm, the sample should be collected from a facility that is as similar in design to the proposed facility as possible. The animals in the facility must be the same type and size that will be in the proposed facility. For example, if the liquid-solid separation system is being planned for a swine finishing farm that produces animals for a particular company, the sample should be collected from a building that uses the same type of manure collection system, houses the same size animals, and receives feed from the same feed mill.

One of the simplest locations to obtain a sample is from a reception pit that is used to collect manure

from a building prior to pumping the manure into a lagoon or storage pond. The basic steps are:

1. Have the producer completely empty the reception pit the day before the sample is to be collected.
2. Allow the manure to accumulate in the pit until the volume is sufficient to yield a valid sample. This may require several hours depending on the pit volume. Pump controls may need to be changed to allow accumulation.
3. Agitate the pit contents until it is well-mixed. Maintain agitation while the sample is being collected.
4. Use a long-handled sampling cup to remove 0.5 to 1 liter samples and combine them in a large bucket. Continue sampling until an amount sufficient to carry out all tests and analyses. A total volume of 2 to 5 gallons is common.

Many swine and dairy producers that could benefit from use of a liquid-solid separator use a flush or pit-recharge system to remove manure from the animal facilities. In most cases, the composition varies greatly as manure flows from the building. In all cases, a representative sample of manure should be collected while manure is being removed from a building by taking samples (≈ 500 to 1000 mL/sample) over time using a long handled sampling cup. The samples collected with respect to time are then combined in a large container to yield the required large composite sample (2 to 5 gal). The time interval between samples will depend on the time required to empty a recharge pit or to flush an alley. The duration of a flush can range from 15 seconds to a few minutes. As a result, sampling will occur continuously during a single flush and sampling from more than one flush event may be required to obtain a large sample. The time required for a recharge pit to empty can range from 30 to 40 minutes and the required sampling interval can range from 1.5 to 2.0 minutes if a 1,000 milliliter sampling cup is used. The most critical part of obtaining a valid composite sample is the determination of the sampling point. The best sampling point will vary with building design and plumbing installation. Common sampling locations for flush or pit recharge systems are—

- Where the flushed manure flows off of the alley into a collection gutter.

- From an open gutter that conveys flushed manure to a lagoon or separator.
- From the outlet of a gravity flow pipe.
- From a rectangular sump located inside or outside of the building where the plug is pulled to allow manure to flow from a recharge-pit.
- From a manhole in the pipe that conveys flushed manure to a lagoon.

In all cases, be prepared to store the large samples on ice in large coolers until the jar tests will be conducted. The cold temperature will greatly decrease biological activity that could alter the sample composition and will decrease generation of gases that could build up in the container and cause it to burst.

(b) Composition of as removed manure

The first step to evaluate the effectiveness of a chemical is to determine the average composition of the manure that was removed from the animal facility. Two to three well-mixed subsamples are to be collected from the large sample obtained from the building. One of the most convenient ways to mix a large manure sample in the field or in a laboratory is to transfer the manure to a clean, 5 gallon bucket. Have a coworker mix the manure continuously using a paint stirrer attached to a variable speed drill. Once the bucket contents are well-mixed use a sampler to extract two to three 500 milliliter samples and pour them into separate labeled sample jars. Stir the manure sample continuously while the sub-samples are extracted. Send these subsamples to an appropriate testing laboratory for analysis. Many land-grant universities have laboratories that can provide the required analysis for a reasonable fee. Have the samples analyzed to determine concentrations of at least: total solids (TS), total nitrogen (TN), ammonium nitrogen (TAN), total phosphorous (TP or P_2O_5), and total potassium (TK or K_2O). Other constituents that may be helpful are volatile solids, total suspended solids, organic nitrogen, soluble phosphorous, and key minor plant nutrients such as sulfur, magnesium, and manganese. Use the average constituent concentrations, [C], obtained from the two to three replicate subsamples as the mean concentrations of the manure to be treated with liquid-solid separation.

In most cases the volume used to evaluate a chemical treatment will be 1 liter. Therefore, the mass of TS, TN, TP, and any other constituent, $M\text{-in}_c$, prior to treatment will be: $M\text{-in}_c \text{ (mg)} = [C\text{-in (mg/L)}] \times 1L$.

(c) Suggested jar test procedure for sedimentation

The most basic ways to evaluate the effectiveness of a dose of a particular chemical or combination of chemicals is to observe the degree of separation provided by sedimentation. Large flocs that readily settle can also generally be removed with a screen. The apparatus used for a jar test can range from a simple setup that allows one dose to be evaluated at a time to dedicated laboratory equipment that allows several doses to be evaluated at one time using multiple mixers with independent speed controls. The basic equipment needs are a variable speed mixing device, a clean 1 liter graduated cylinder; a clean 1.5 liter beaker for each dose; a clean 500 milliliter sample jar for each test; a timer; and prepared doses of the chemicals to be evaluated. The number of doses to be evaluated will vary from 2 to 5 depending on the available treatment information. However, it is important to remember to include a zero-dose control for each study to determine the enhanced removal of solids or plant nutrients provided by the chemicals.

The basic procedure for a jar test should be repeated for the control (no chemical) and for all chemical doses and combinations to be evaluated.

1. Obtain a well-mixed one liter sample of the manure removed from the building and pour it into a graduated beaker.
2. Begin stirring the manure in the beaker at a high rate (≈ 100 rpm) and then add the chemical dose to be evaluated. If more than one chemical is to be used add them in the same manner as will be used in the field (at the same time or sequentially).
3. Mix the chemicals at high speed (≈ 100 rpm) for about two minutes to provide complete mixing and coagulation to occur.
4. Reduce the speed to slow speed (≈ 30 rpm) and mix for about five minutes to allow flocculation to occur.

5. Stop mixing and pour the chemically treated manure into a one liter graduated cylinder and record the total volume.
6. Begin the timer and allow the sample to settle for 60 minutes. Observe the contents of the graduated cylinder and make notes concerning floc size, settling or floating characteristics, and the clarity of the supernatant.
7. After 60 minutes record the volume of the supernatant and the settled material.
8. Slowly decant the supernatant into a 500 milliliter sample jar making sure that none of the settled material is allowed to enter the jar.
9. Store the properly labeled sample jar in a refrigerator or ice chest until all tests are completed.

Once all of the jar tests have been completed, have all of the supernatant samples analyzed for the same constituents as the manure that was removed from the animal facility using the same laboratory. These sample analyses will provide the means to calculate concentration reductions as—

$$CR_{\text{settle}} = 100 \times \left(\frac{[C - \text{in}] - [C - \text{sup}]}{[C - \text{in}]} \right)$$

The mass removal efficiency for each constituent will be—

$$MRE_{\text{settle}} = 100 \times \left(\frac{M - \text{in}_c - [C - \text{sup}] \times \text{Vol} - \text{sup}}{M - \text{in}_c} \right)$$

The chemical dose that provides the desired removal of TS and TP is most likely the best option.

(d) Suggested jar test procedure for screening

Addition of a metal salt or a polymer is a way to greatly enhance the removal of solids and plant nutrients by screens and presses. Therefore, determination of the removal using a standard screen close to the size that will be used in a mechanical separator is often more beneficial than a sedimentation test (table 4D-1). Furthermore, some chemicals will cause large flocs to

form that will not settle but can be removed by screening.

The first five steps for a screened jar test are the same as for a settling jar test. The new steps are provided below.

6. Slowly pour the contents of the graduated cylinder through a standard screen and collect the liquid effluent in a clean container.
7. After all of the liquid has passed through the screen use a clean graduated cylinder to measure the effluent volume (Vol-eff).
8. Mix the supernatant and collect a 300 to 500 milliliter sample and pour into a clean, labeled sample jar.
9. Store effluent sample jars in an ice chest or refrigerator until all tests are completed.

Table 4D-1 Selected opening sizes for standard screens

Mesh	mm	inch
No. 10	2.00	0.0787
No. 12	1.68	0.0661
No. 14	1.41	0.0555
No. 16	1.19	0.0469
No. 18	1.00	0.0394
No. 20	0.841	0.0331
No. 30	0.595	0.0234
No. 35	0.500	0.0197
No. 40	0.420	0.0165
No. 50	0.297	0.0117
No. 60	0.250	0.0098
No. 70	0.210	0.0083
No. 80	0.177	0.0070
No. 100	0.149	0.0059

After all of the jar tests have been completed, have all of the screen effluent samples analyzed for the same constituents as the manure that was removed from the animal facility using the same laboratory. These sample analyses will provide the means to calculate concentration reductions as—

$$\text{CR} - \text{screen} = 100 \times \left(\frac{[\text{C} - \text{in}] - [\text{C} - \text{eff}]}{[\text{C} - \text{in}]} \right)$$

The mass removal efficiency for each constituent will be—

$$\text{MRE} - \text{settle} = 100 \times \left(\frac{\text{M} - \text{in}_c - [\text{C} - \text{eff}] \times \text{Vol} - \text{eff}}{\text{M} - \text{in}_c} \right)$$

The chemical dose that provides the desired removal of TS and TP is most likely the best option.