SOLID-LIQUID SEPARATION OF ANIMAL MANURE FOR ODOR CONTROL AND NUTRIENT MANAGEMENT

R. H. Zhang, P. W. Westerman

ABSTRACT. *Solid-liquid separation can be an effective manure treatment method for producing nutrient-rich organic solids for multiple uses and potentially reducing the odor generation rate and nutrient contents in liquid manure storage and treatment units. This article discusses the characteristics of animal manure relevant to solid-liquid separation for odor control and nutrient management, reviews the basic concepts used in different separation processes, and presents the design and operational principles and performance data of several major types of separation equipment as compiled from an extensive literature review. Such information is very useful for agricultural and sanitary engineers and animal producers to select solid-liquid separation equipment for animal enterprises. The needs for further research and development in the area of solid-liquid separation are identified.*

Keywords. *Manure, Solid-liquid separation, Odor control, Nutrient management.*

Liquid manure handling systems are popularly used on various types of confinement animal operations (including swine, dairy, beef, and poultry) because of ease of mechanization and low labor requirement for manure management. They are also a cause of much environmental concern because of their inherent odor generation potential (White, 1980). Solid-liquid separation has been historically studied and used as an alternative manure treatment method from the standpoint of improving manure handling properties and producing manure solids for animal feeding, energy generation, and compost production (Jett et al., 1974; White, 1980; Hegg et al., 1981; Sievers et al., 1981; Holmberg et al., 1983; Lo et al., 1993). Continuing trends of animal industry consolidation and expansion and increasing public concerns with odors and excess nutrients that may be generated at large animal operations, however, demand a close examination of the solid-liquid separation as a method to help reduce manure odors and facilitate nutrient management, in addition to the benefits stated above. Effective solid-liquid separation that is capable of removing a substantial amount of organic solids from fresh liquid or slurry manure will potentially offer the benefits of production of nutrient-rich organic solids, odor reduction in subsequent liquid manure storage pits (or tanks) and anaerobic lagoons, and improvement in the economics of subsequent liquid manure treatment processes due to reduced organic loading rates on an annual basis. The separated solids can be utilized on farms near animal operations or can be economically exported to other areas as fertilizer and soil conditioning products.

Solid-liquid separation has been widely used for treating municipal and industrial wastewaters. Because of the associated costs, however, it has not become a popular unit operation for animal manure management, even though a number of studies have been reported in developing and testing different types of separation equipment with animal manure. The objective of this article is to discuss the characteristics of animal manure relevant to solid-liquid separation, especially for the purposes of odor control and nutrient management, review the basic concepts used in different separation processes, present the design and operational principles and performance data of several major types of separation equipment, and identify future needs for research and development. Such information can be very helpful for agricultural and sanitary engineers and animal producers to select separation equipment to meet their own needs.

CHARACTERISTICS AND PARTICLE SIZE DISTRIBUTION OF ANIMAL MANURE

Animal manure contains complex organic compounds originated from the undigested and wasted feed as well as simple organic and inorganic compounds produced in the gastric intestinal track of animals. Once excreted from animals, the manure will naturally undergo anaerobic decomposition, producing a number of odorous gases and compounds. Manure production and characteristics on an actual farm are largely affected by the feed rations, species, and growth stages of animals, manure collection methods, and the amount of water added into the manure collection systems.

The chemical constituents of the manure are distributed between suspended solids (SS) and dissolved solids (DS). Total solids (TS) is the sum of suspended solids (SS) and dissolved solids (DS). Each solids fraction (TS, SS, or DS) is further divided between a volatile solids fraction (VS) and a fixed solids fraction (FS). The volatile solids (VS) is a

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measure of the amount of organic matter present in that solids fraction and the fixed solids (FS) is a measure of the amount of inorganic matter present (also called the ash content). The corresponding volatile solids fractions of TS, SS, and DS are total volatile solids (TVS), suspended volatile solids (SVS), and dissolved volatile solids (DVS), respectively, and the corresponding fixed solids fractions are total fixed solids (TFS), suspended fixed solids (SFS), and dissolved fixed solids (DFS). The amount of organic matter contained in the manure can also be measured by the chemical oxygen demand (COD), which is defined as the quantity of oxygen required to chemically oxidize the organic matter in the manure. Due to the fact that not all the organic matter in the manure is biodegradable, the amount of biodegradable organic matter contained in the manure is measured by the biochemical oxygen demand (BOD), which is defined as the quantity of oxygen required to biochemically oxidize the organic matter in the manure. Five-day biochemical oxygen demand (BOD_5) is typically used as a standard measurement in wastewater engineering. In practical applications, COD is usually preferred to BOD_5 because the laboratory analysis procedure for COD is less time-consuming.

Understanding of the particle size distribution of manure solids and distribution of various chemical constituents among the particles of different sizes in different types of animal manure is important for design and selection of proper solid-liquid separation equipment to achieve the purposes of solid-liquid separation. Lindley (1970) studied the particle size distribution of fresh dairy manure and determined the effects of particle size on aerobic decomposition of the manure. He found that the finest fraction of the manure was decomposed to the greatest extent and the coarsest fraction was the least decomposed. This finding should equally apply to the anaerobic decomposition process. We can reasonably say that easily biodegradable fine fractions would have more contribution to the odor generation than coarse fractions during the natural decomposition of the manure .

Chang and Rible (1975) determined the particle size distribution in fresh dairy, beef, and poultry manure by using a set of six ASTM standard wire screen sieves with the openings of 1.000, 0.500, 0.250, 0.105, and 0.053 mm. Table 1 gives the distribution of total solids (TS), volatile solids (VS), crude protein, fat, and crude fiber in different size ranges as derived from the original data of Change and Rible (1975) by making appropriate calculations. The TS and VS in the fresh manure are almost equally divided between the sizes greater than 1.000 mm and the sizes smaller than 0.053 mm, with usually less than 25% of the TS distributed in the intermediate ranges. Most of the crude protein is contained in the fine particles, e.g., 60% for dairy, 65% for beef, and 65% for poultry in the particles smaller than 0.053 mm and most of the crude fiber is concentrated in the coarse particles, e.g., 69% for dairy and 70% for poultry in the particles larger than 1.000 mm. Fat has different distributions in different manure. Most fat is deposited in the fine particles in the dairy manure (70% in the particles smaller than 0.053 mm), while the fat in the beef manure is almost equally distributed between the coarse and the fine particles, and the fat in the poultry manure is more concentrated in the coarse particles (39% in the particles larger than 1.000 mm and 77% in the particles larger than 0.250 mm).

Table 1. Particle size and chemical constituent distribution of dairy, beef, and poultry wastes as derived from the published data by Chang and Rible (1975)

		Content of Constituent (%) Within a Given Size Range (mm)					
Animal Species	Constituent	> 1.000	1.000-0.500	0.500-0.250	0.250-0.105	0.105-0.053	< 0.053
Dairy	TS	41.8	7.1	7.2	3.9	2.0	38.0
	VS	43.2	7.4	7.4	4.0	1.8	36.2
	Protein	25.7	4.7	3.9	3.6	2.6	59.5
	Fat	19.4	3.0	3.2	2.2	2.2	70.0
	Fiber	68.7	9.5	10.0	4.3	0.9	6.6
Beef	TS	30.7	9.0	6.7	6.1	3.6	43.9
	VS	32.7	9.3	6.9	6.5	3.6	41.0
	Protein	15.8	6.0	5.0	4.9	3.1	65.2
	Fat	39.5	7.2	6.4	6.9	3.3	36.7
	Fiber	48.6	19.0	8.0	6.0	2.2	16.2
Poultry	TS	23.6	11.6	16.3	8.3	4.6	35.6
	VS	22.6	12.3	17.8	8.6	6.3	32.4
	Protein	15.8	6.0	5.1	4.9	3.0	65.2
	Fat	39.2	19.9	17.9	16.0	5.9	1.1
	Fiber	69.7	19.0	13.5	5.8	1.7	0.3

*Protein - crude protein, Fiber - crude fiber.

Powers et al. (1995) studied the distribution of TS, nitrogen (total Kjeldahl nitrogen, TKN) and phosphorus (total phosphorus, TP) in different fractions of the particles in dairy manure, using a set of five standard sieves with the openings of 3.350, 2.000, 1.400, 1.000, and 0.500 mm, respectively. They found that 60% of TS, 86% of TKN, and 94% of TP passed through the 0.500 mm sieve.

Jett et al. (1974) studied the size distribution and nutritional value of separated swine manure solids obtained from three rations containing different size feed particles. They used a set of six standard sieves with 4.760, 3.360, 2.000, 1.190, 0.595, and 0.250 mm openings, respectively. Their results showed that approximately 83% of the crude protein and 93% of the fat in the original manure samples were contained in the materials which passed the 0.250 mm sieve for all three rations. Hill and Toller (1980) studied the characteristics of flushed swine manure after screening with a set of five standard sieves with the openings of 3.000, 2.000, 1.000, 0.500, 0.250, and 0.105 mm, respectively. Their results showed that 46% of TS , 40% of VS, 47% of COD, 70% of TKN and 75% of TP passed the sieve with 0.105 mm openings. Their finding also showed that COD increased as the particle size decreased, which indicated that the reduced organic compounds were contained in the fine particles. This agrees with the finding of Lindley (1970).

Review of previous research results as above allows us to conclude that fine particles in the manure decompose faster than the coarse particles and most of the reduced carbon compounds, protein, and nutrient elements (especially nitrogen and phosphorus) are contained in the fine particles. Because these compounds are the precursors for odor generation and the carriers of organic nitrogen and phosphorus, solid-liquid separation processes should be designed to remove fine particles effectively (at least smaller than 0.250 mm) as well as coarse particles from fresh liquid or slurry manure in order to cause a significant impact on reducing the odor generation potential and nutrient contents in subsequent manure storage and/or treatment units.

Solid-Liquid Separation Techniques and Equipment

Physical Separation with Sedimentation Basins and Mechanical Separators

The solid-liquid separation processes include sedimentation, screening, centrifugation, and filtration (or pressing). Sedimentation and screening are the most commonly used techniques for animal manure treatment. Sedimentation is most effective for treating dilute wastewaters, such as flushed manure or feedlot runoff (Miner and Smith, 1975). Detailed descriptions and design procedures of sedimentation basins can be found in several handbooks, including *Livestock Waste Facilities Handbook* (MWPS, 1985) and *Agricultural Waste Management Field Handbook* (USDA, 1992). The screen separators that have been used with animal manure include stationary screen, vibrating screen, and rotating screen separators. Stationary screen separators use slow relative motion between the manure and the screen as caused by the gravity of the manure to facilitate the separation. A stationary inclined screen separator (fig. 1) has a screen mounted on an incline with the liquid or slurry manure pumped to the top edge of the screen, having the liquids to pass through the screen and drain away while having the solids to move down the face of the screen and drop to a collection area. Stationary screen separators are widely used on dairy farms in the United States for removing fibrous coarse particles from dairy manure to ease the manure handling in storage and land application. The most attractive feature of the stationary screen separators is the lack of moving parts and therefore low maintenance and no power requirement. Some operators have found it necessary to install a wash-down system to follow use to prevent solids from blinding the screen (Moore, 1989). Vibrating screen and rotating screen separators use continuous motion screens to aid in separation. A vibrating screen separator uses a rapid vibrating motion to aid the movement of the separated solids across the screen and reduce clogging of the screen. One configuration uses a flat circular screen (fig. 2). The manure is pumped onto the center of the screen at a controlled rate and the separated solids remaining on the screen are slowly discharged at the periphery and the liquids passing through the screen are collected into a pan beneath the screen. A rotating screen separator (fig. 3) uses a rotating screen. The manure is deposited to the top of the screen at a controlled rate. The solids retained on the screen are scraped into a collection area and the liquids passing through the screen are collected into a tank.

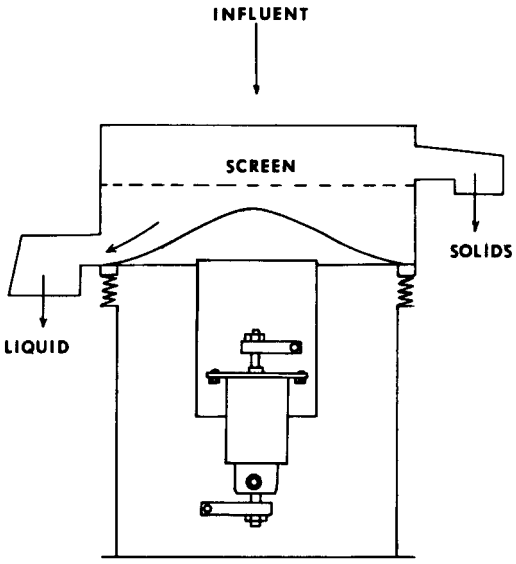


Figure 2–Vibrating screen separator (Shutt et al., 1975).

Centrifuges and hydrocyclones use centrifugal forces to cause separation. There are vertical and horizontal types of centrifuges. A horizontal decanter centrifuge (fig. 4) uses a closed cylinder of continuous turning motion. The centrifugal force separates liquids and solids on the wall in two layers. An auger, turning at a slightly higher speed than the cylinder, moves the solids to the conic part where they are discharged. The liquids leave the cylinder at the other end. Hydrocyclones, unlike centrifuges, have no moving parts and the necessary vortex motion is performed by the liquid itself. A hyrocyclone (fig. 5) consists of a cone tangentially to the circle near the top. The manure slurry is pumped tangentially through the inlet near the top and a strong swirling motion of the liquid, developed as a result, will accelerate the gravity settling of solid particles to the

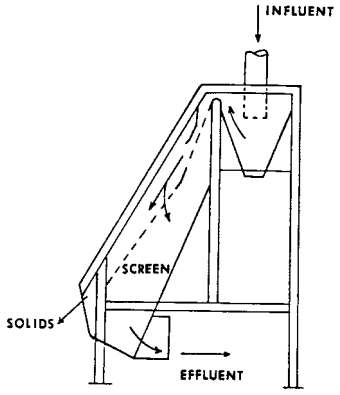


Figure 1–Stationary inclined screen separator (Shutt et al., 1975).

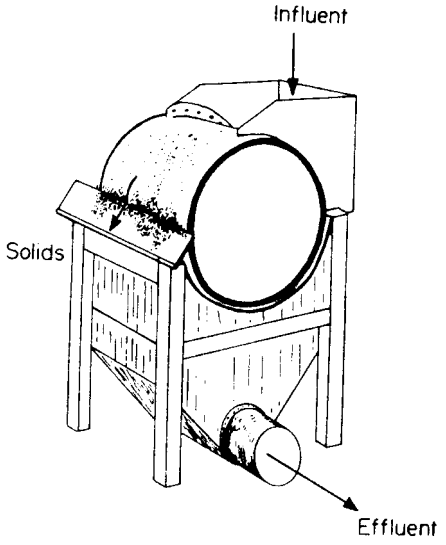


Figure 3–Rotary screen separator (Hegg et al., 1981).

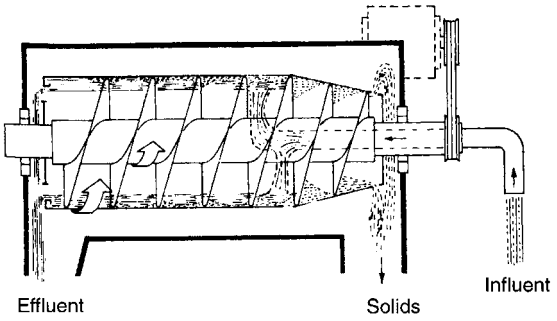


Figure 4–Horizontal decanter centrifuge (Glerum and Poelma, 1971).

bottom or apex of the cone while the liquid is discharged through a cylindrical tube fixed in the center of the top.

Sedimentation, screening, and centrifugation are usually used as the primary separation unit operations. The separated solids generated from these separators, also called solid cakes, contain high moisture contents (85-95%) and need to be further dewatered for further uses, such as composting. Presses are designed for solids dewatering. The presses use the principle of pressurizing solids with rollers or screws against an opposing screen or a perforated belt, through which the liquid is removed. They mainly include roller press, belt press, and screw press. The roller press uses two concave screens and a series of brushes and rollers (fig. 6). The manure slurry is firstly deposited onto the first screen and then moved across the two screens with brushes and squeezed by the rollers. The belt press (fig. 7) uses a flat, woven fabric belt that runs horizontally between squeezing rollers. The liquid is pushed through the belt by the rollers and the solids are carried along on the belt and dropped to a solids collection chamber. The screw press (fig. 8) uses a central screw conveyor housed in a cylindrical screen. The screen is used to retain the solids in the manure slurry which is pumped into the screen chamber and the screw is used to convey the solids to the discharge chute. During the transport, the solids are compacted and dewatered.

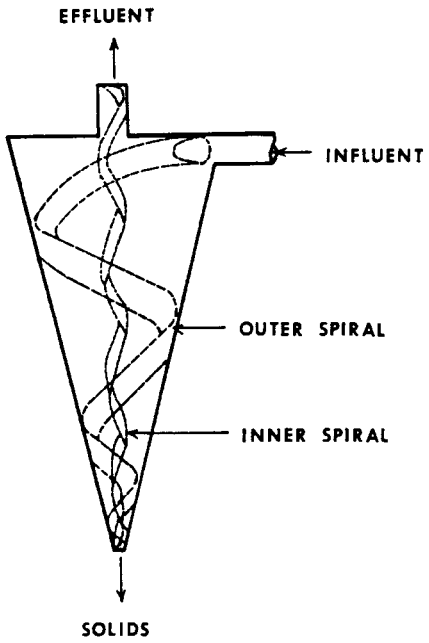
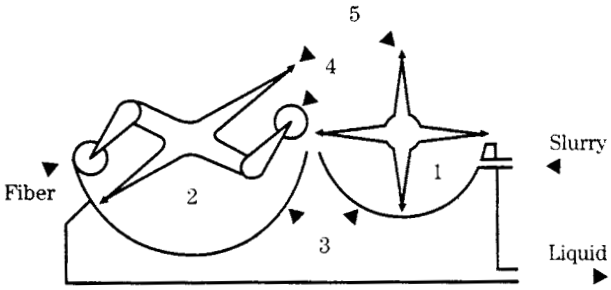


Figure 5–Hydrocyclone (Shutt et al., 1975).

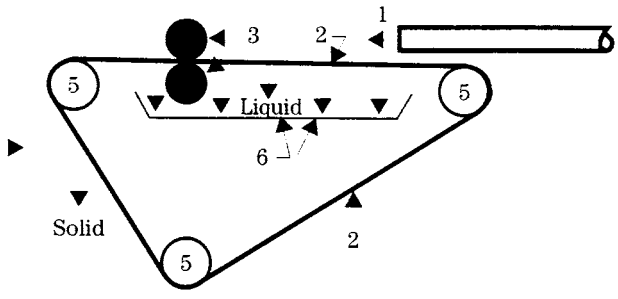
CHEMICAL TREATMENT

Chemical treatment of wastewater involves addition of chemicals to alter the physical state of dissolved and suspended solids and to facilitate their removal by physical separation processes. It includes chemical precipitation and particle coagulation and flocculation. Chemical precipitation is formation of insoluble precipitate through the chemical reactions between the dissolved ions in the wastewater, such as phosphate, and the metal ions added, such as calcium (Ca^{2+}), iron (Fe^{2+} or Fe^{3+}), or aluminum (Al^{+3}). The chemical precipitation is mostly used for removal of dissolved phosphorus in the wastewater. The commonly used chemicals include chloride or sulfate salts of these metals. Besides forming precipitates with dissolved phosphorus, these chemicals also induce coagulation of suspended particles. Coagulation is the destablization of colloidal particles by neutralizing their surface charges to form small visible flocs. Flocculation is the further agglomeration of coagulated particles upon addition of a polyelectrolyte which absorbs the particles in



1 Screening stage
2 Roller pressing stage
3 Screens
4 Spring loaded press roller
5 Brushes

Figure 6–Roller press separator (USDA, 1992).



1 Slurry input
2 Polyester mesh belt
3 Press rollers
4 Rotary brush
5 Belt guide rollers
6 Liquid collection trough

Figure 7–Belt press separator (USDA, 1992).

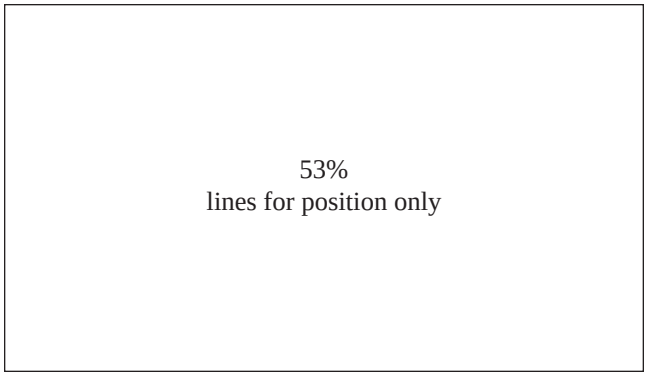


Figure 8–Screw press separator.

the liquid and bridges the particles to allow them to form large flocs. Many natural polymers, such as modified starches and chitoson (a product made from fish shells) and synthetic polymers, such as the polymers derived from polyacrylamide (PAM), are commercially available as flocculants. The metal salts and polymers can be used separately or in combination.

The chemical treatment can be performed either as a continuous process in manure transport pipelines where the chemicals are added and mixed into the manure continuously or as a batch process in a mixing tank where the chemicals are added and mixed into the manure in batches. The equipment for batch chemical treatment usually include a chemical metering and injection device, such as a metering pump, and a mixing and settling tank. Detailed descriptions of theories and applications for coagulation and flocculation are included in several books (Dobias, 1993).

Performance and Economics of Solid-liquid Separators

The percentage of suspended solids (SS) in total solids (TS) of fresh manure is 45 to 65% for swine, 62 to 83% for beef and dairy, and 47 to 57% for poultry (Loehr, 1974). The ultimate goal of solid-liquid separation is to remove all the suspended solids in the manure and also part of the dissolved solids which are absorbed in the suspended solids. Generally, the separation efficiency for a particular constituent is expressed in terms of the percent of the constituent removed from the influent manure. Theoretically speaking, the maximum total solids separation efficiency for the liquid or slurry manure by physical separation (sedimentation, screening, filtration, and centrifugation) is in the range of 48 to 70% for swine, 64 to 84% for beef and dairy, and 50 to 59% for poultry, if removal of 5% dissolved solids along with the suspended solids is assumed. The separation efficiency can be improved significantly to a level of 85% or higher if additional dissolved solids can be removed by means of chemical treatment. The characteristic parameters of animal manure that affect the solid-liquid separation performance mainly include particle size distribution and initial total solids content.

Sedimentation Basins and Mechanical Separators

The performance of sedimentation basins and mechanical separators is evaluated by the percent of total solids removed from the influent manure and moisture content of the solids separated. A high percentage of solids removal and a low moisture content of the solids separated are desirable. Different types of separation processes and equipment have been evaluated with animal manure by a number of researchers.

Sedimentation basins, which are either concrete or earthen, have been mostly used for solids removal from feedlot runoff or flushed manure (Moore et al., 1975; Oatway et al., 1975; Lorimore et al., 1995). Their performance is largely determined by the settling behavior and rate of solid particles in the manure which is in turn affected by the density and concentration of the particles. Sobel (1966) found that sedimentation was hindered and solids settling rate was reduced when the concentration of suspended solids in the manure exceeded about 1.0%. Manure flow rate, solids settling rate and detention time are the primary design parameters for a sedimentation basin (MWPS, 1985). Moore et al. (1975) examined the solids settling characteristics in the liquid manure of 0.1 to 1.0% initial TS from several animal species (beef, dairy, swine, poultry and horse) and suggested a detention time of 10 to 100 min to be used for designing sedimentation basins. The performance data of sedimentation basins are scarce in the literature. Lorimore et al. (1995) conducted a two-year monitoring study on the performance of two sedimentation basins at two feedlots (concrete swine feedlot and earthen beef feedlot) and concluded that both basins removed a significant portion of the solids carried by the feedlot runoff. The amount of total solids removal was 64.2% for concrete swine feedlot and 39.0 to 52.9% for earthen beef feedlot.

Various mechanical separators have been evaluated in recent years (Shutt et al., 1975; Pain et al., 1978; Gilbertson and Nienaber, 1978; Hegg et al., 1981; Holmberg et al., 1983; Piccinini and Cortellini, 1987; Fernandes et al., 1988). Table 2 compiles the performance data of several major types of mechanical separators as reported in the literature.

Screens are the most extensively tested separators thus far. The performance of screen separators is mainly determined by screen opening size, flow rate, and the characteristics of manure to be separated, such as the initial solids content and particle size distribution. Smaller screen openings will generally yield a higher percentage of solids removal but the separated solids may have higher moisture content, because screen openings smaller than a certain size tend to retard the flow of manure through the openings due to adherence interactions between solid particles, water, and screen surfaces, resulting in retainment of more water on the screen together with solids. Higher flow rate and higher solids content of the manure will make this effect more expressed. This observation is clearly reflected in the results of Holmberg et al. (1983) who tested a vibrating screen separator using five sizes of screens (8, 18, 30, 60, and 150 mesh) with flushed swine manure of an average 3.6% TS. At the same flow rate (150 L/min), the moisture content of the separated solids increased from 82.7% with the 8 mesh screen to 97.6% with the 150 mesh screen. The TKN and TP of the solids increased from 2.0% to 5.2% of the TS and from 0.5% to 2.1% of the TS,

Table 2. Performance of mechanical separators

Separator - Animals	Screen Opening (mm)	TS in Raw Manure (%)	Separation Efficiency (%) TS	VS	COD	TKN	TP	TS in Solids (%)	Liquid Flow Rate (L/min)	Reference
Stationary S.										
Swine	1.5	0.2-0.7	9	-	24	-	-	6	235	A
	1.0	0.2-0.7	35	-	69	-	-	9	123	A
	1.0	1.0-4.5	6-31	5-38	0-32	3-6	2-12	5	-	E
Dairy	1.68	4.6	49	-	-	-	-	12	-	G
Beef	0.5	0.97-4.1	9-13	-	-	-	-	13-22	-	C
Vibrating S.										
Swine	1.7	1.5	3	-	6	-	-	17	37-103	C
	0.841	1.5-2.9	10	-	1-14	-	-	18-19	15-103	C
	0.516	1.8	27	-	24	-	-	20	37-57	C
	0.516	3.6	21-52	25-55	17-49	5-32	17-34	9-17	38-150	D
	0.39	0.2-0.7	22	28	16	-	-	16	67	A
	0.44	1-4.5	15-25	18-38	13-26	2-5	1-15	13	-	E
	0.104	3.6	50-67	54-70	48-59	33-51	34-59	2-8	38-150	D
Dairy	1.7	0.9-1.9	8-12	-	-	-	-	12-15	35-103	C
	0.841	1-1.8	12-13	-	-	-	-	18-19	15-76	C
	0.6	1.0-1.7	10-16	-	-	-	-	12	14-54	C
Beef	1.7	1.6	12	-	-	-	-	15	40-114	C
	0.841	1.6	6	-	7	-	-	16	38-108	C
	0.6	1.6-3.2	11-16	-	5-7	-	-	15-16	19-63	C
	0.841	6.8	26	-	-	-	-	24	71	B
Rotating S.										
Swine	0.75	2.5-4.12	4-8		4			16-17	80-307	C
	0.8	1-4.5	5-24	9-31	2-19	5-11	3-9	12	-	E
Belt Press										
Swine	0.1	3-8	47-59	-	39-40	32-35	18-21	14-18	-	F
Centrifuge										
Swine	-	1-7.5	15-61	18-65	7.8-44	3.4-32	58-68	16-27	-	E
Beef	-	3.6-6.2	51-61	60-65	52-60	23-28	43-48	19-26	-	E

* References: A- Shutt et al.,1975; B- Gilbertson and Nienaber, 1978; C- Hegg et al., 1981; D- Holmberg et al., 1983; E- Piccinini and Cortellini, 1987; F- Fernandes et al., 1988; G- USDA, 1992.

respectively. Holmberg et al. (1983) found that for a given screen, such as the 30 mesh screen, increase of the flow rate from 37.5 to 150 L/min increased the total solids separation from 20.7% to 51.9%, but also increased the moisture content of the separated solids from 83.8% to 90.5%. Pain et al. (1978) evaluated four types of separators with dairy and swine manure slurries having up to 12% TS. They found that with the TS above 8%, the cattle slurry accumulated on the top of the vibrating separator, coating the screen and resulting no separation. They also found that the separated solids from the low TS manure slurry contained less nutrients than the solids from the high TS slurry, due to the fact that the additional water washed more nutrients from the solids on the screens. Therefore, there is a tradeoff between the solids separation efficiency and the quality of the separated solids. Generally speaking, screen separators work better with the manure of low solids content (>5%). Clogging or blinding of screen openings by slimy manure solids are the major problems associated with the operation of screen separators and frequent cleaning of the screens is recommended. Sometimes, it is necessary to brush the screen with a liquid disinfectant to mechanically break the biological film formed on the screen and also kill the organisms which helped form the film (Shutt et al., 1975).

Belt presses and centrifuges are found to have higher separation efficiencies and produce drier solids than the screen separators as shown in table 2, but their structures and operation are more complicated and costs are higher. The performance data for the screw presses and roller presses are lacking in the literature.

A liquid cyclone was tested by Shutt et al. (1975) with swine manure slurries. The cyclone was a 7.6 cm diameter and 6° apex cone made of polyvinyl chloride (PVC). The testing program included three underflow nozzle openings (0.64, 0.47, and 0.32 cm) and four pressure drops (1.4, 2.8, 4.2 and 5.6 kg/cm^2). The manure slurry was first screened with a 1 mm opening sloping stationary screen before being pumped into the liquid cyclone, to remove the coarse solids and avoid plugging small underflow nozzles. It was found that the liquid cyclone worked better with the manure of higher total suspended solids (TSS) contents. The maximum TS separation efficiency of this cyclone was 27% and the minimum moisture content of the separated solids was 91%.

The performance data of mechanical separators included in table 2 may be used only as reference data when evaluating different types of separators. The testing and reporting procedures used by different researchers varied greatly, not to mention the large differences in the manure used. Close attention needs to be paid to the actual conditions under which the separators were tested and the performance data were obtained. Field tests are always recommended for obtaining accurate information about a particular separator for a specific application.

Chemical Treatment

Use of chemicals as separation aids is a relatively new approach for treating animal manure, even though it has been widely accepted for treating municipal and industrial wastewaters. The type and dosage of the chemicals to be used are largely determined by the initial total solids content, particle size, pH, and temperature of the wastewater to be treated. Some research work has been done to explore the application of various chemicals for animal manure treatment.

Hanna et al. (1985) treated flushed swine manure with nine chemicals which include magnesium chloride ($MgCl_2$), aluminum sulfate ($Al_2 (SO_4)_3$), ferrous sulfate ($FeSO_4$), lignosulfonate, calcium hydroxide (Ca(OH)2), ferric chloride ($FeCl_3$), Chitosan, and an organic polymer. The specifications of the organic polymer were not given by the authors. The tests were conducted in both laboratory and field. Their laboratory-scale test protocol included the use of 400 mL liquid supernatant obtained from swine manure of 1% TS after removing settleable solids by 20 min mixing and 100 min settling, and one hour settling after chemical treatment of the supernatant before the settled solids and the liquid were separated and characterized. Their results showed that the VS removal efficiency increased by 8 to 13% with the use of different chemicals as compared with no use of the chemicals (from 76% without chemicals to 84 to 89% with chemicals). Piccinini and Cortellini (1989) treated fresh and digested swine and beef cattle manure slurries with a cationic polymer prior to processing them with a horizontal centrifuge. The specifications of the polymer were not given by the authors. The TS of the manure slurry was 1.0 to 7.3% for fresh swine slurry, 5.6% for fresh beef cattle slurry, and 1.4 to 6.2% for the digested slurry. Their results showed that use of the polymer increased the TS removal efficiency by 10 to 23% for the slurries of low TS (<1.5%) but not much for the slurries with high TS. Powers et al. (1995) tested four chemicals [$Fe_2(SO_4)$, $CaCO_3$, CaO, a polymer] on dairy manure slurries with 0.5%, 1.0%, 1.5% TS, respectively, in the laboratory. Their test protocol

included one hour settling of 1 L liquid manure in a graduated cylinder (360 mm or 14.1 in. tall and 65 mm or 2.5 in. diameter) before the settled solids and the liquid were separated and characterized. After a combination of chemical treatments for the slurry with 1.5% TS, as compared with no use of the chemicals, the TS removal efficiency increased by 18 to 30% (from 65% without chemicals to 83 to 95% with chemicals); the TKN removal efficiency increased by 21 to 44% (from 30% without chemicals to 51-74% with chemicals); and P removal efficiency increased by 28 to 78% (from 12% without chemicals to 40-90% with chemicals).

A recent laboratory study carried out by Zhang and Lei (1996) investigated the use of metal salts (ferric chloride and aluminum sulfate) and cationic polymers with swine and dairy manure of different TS levels (0.5 to 2.0%) for the purpose of improving the performance of sedimentation basins and screen separators. For chemical treatment and sedimentation, ferric chloride ($FeCl_3$) was tested at the dosage of 100 to 1500 mg/L for swine manure and 250 to 1750 mg/L for dairy manure, using a cylindrical column of 1 m (3 ft.) in depth and 13 cm (5 in.) in diameter as the settling column. For each treatment, 5 min mixing and 1 h settling were used before the supernatant liquid and settled solids were separated and characterized. The settling rate measured during 1 h settling period, volumes of separated solids and liquid, and solids content of the separated liquid were determined as the parameters to evaluate the effectiveness of each treatment. Ferric chloride was found to be effective in enhancing the settling of suspended solids. Based on the highest settling rate, an optimum dosage of $FeCl_3$ was determined for each TS level and was higher for a higher TS level (swine manure: 100, 250, 500, and 750 mg/L for 0.5%, 1.0%, 1.5%, and 2.0% TS, respectively; dairy manure: 250, 750, 1000, and 1000 mg/L for 0.4%, 0.8%, 1.2%, and 1.6% TS, respectively). Excess use of $FeCl_3$, however, deteriorated the treatment.

Aluminum sulfate was found to be equivalent to ferric chloride. To achieve a reasonable settling rate, it was recommended that the total solids content of the manure is limited to less than 1% if chemical treatment and sedimentation are used as the only separation processes. For chemical treatment and screening, five cationic polyacrylamide polymers and two metal salts (ferric chloride and aluminum sulfate) were tested with pre-screened swine and dairy manure. These polymers were highly charged (>30% molar basis), high-molecular (5-7 million), cationic water-in-oil emulsions. The polymers were tested alone as a single chemical and in combination with a metal salt. Chemical treatment was performed using 1 L beakers and the cylindrical settling columns as described above. A 20 mesh screen with 0.8 mm openings was used to separate the flocculated solids from the liquid in each treatment. The five polymers tested performed about equally well. The use of a single polymer at a dosage level of 0.015% for screened swine manure of 1% TS and 0.075% for screened dairy manure of 1% TS yielded 71 to 76% TS removal and 77 to 83% VS removal from the swine manure and 67 to 78% TS removal and 76 to 86% VS removal from the dairy manure. The dosage of the polymer was expressed as the percentage of concentrated polymer (as purchased) added to the manure on a volume basis. As a comparison, without polymers, the TS and VS removals were 15% and 17% for the swine manure, respectively, and were 9% and 16% for the dairy manure, respectively. The optimum dosage of the polymer was determined as a linear function of the TS in the manure.

Ferric chloride or aluminum sulfate alone was found not effective for improving the solids removal by screening. However, its use together with a polymer considerably improved the phosphorus removal from the manure and lowered the required polymer dosage. For screened dairy manure of 0.5% TS, combined use of 700 mg/L $FeCl_3$ and 0.005% polymer yielded 99% total phosphorus removal from the manure as compared to 53% total phosphorus removal with the use of 0.04% polymer alone.

The purpose of solid-liquid separation and the intended use of the separated solids are the major factors to be considered when selecting a separation unit for a particular manure management system. If the primary purpose is to remove coarse particles for easier manure handling, the screens alone may be sufficient. If odor control and nutrient removal from the manure are the primary purpose, the separators that are capable of removing fine particles as well as coarse particles will be needed. If necessary, chemical treatment should be considered.

Economics of Solid-liquid Separation

Solid-liquid separation, like other operations on animal farms, require initial capital investment for the separator system and installation, labor for the system's operation, maintenance and repair. The retail price of a mechanical separator varies from $10,000 to $50,000+, depending on the type of the separator and its throughput capacity (amount of wastewater processed per unit time in m^3/min or gal/min). The throughput capacity of a typical mechanical separator varies from 0.38 to 2.27 m^3/min (100 to 600 gal/min). With the same capacity, screens are usually less expensive than presses and centrifuges. But the characteristics of the manure to be treated also affects the type of separators to be used. Screens, especially stationary and rotating screens, generally work better with the manure of a low TS level (<5.0%), while presses and centrifuge work better with the manure of a high TS level. Generally speaking, the economics of using solid-liquid separation on animal farms is determined by the amount of manure to be processed, the extent of solids removal from the manure, and the potential for solids reuse and value recovery.

Sneath (1988) evaluated the economic aspects of five different combinations of solid-liquid separation and aerobic treatment of swine manure on odor control for 5 days or 30 days of storage. The manure under the examination was assumed to have 1.5 to 8.0% TS initially, and two farm sizes (2,000 and 8,000 pigs) were used for this economic analysis. The five manure treatment combinations were: (1) aeration of raw slurry; (2) solid-liquid separation with a brush screen/roller press, then aeration; (3) solid-liquid separation with a centrifuge, then aeration; (4) aeration of raw slurry, then solid-liquid separation with centrifuge; and (5) solid-liquid separation with a brush screen/roller press, then aeration, then removal of more solids with a centrifuge. The costs of the separators used in this study were $11,900 for the brush screen/roller press and $51,000 for the centrifuge (assuming US $1.70/Br £). It was concluded that for small farms (2,000 pigs), if the manure slurry contained less than 4.5% TS, aerobic treatment of raw slurry is of the lowest cost

for odor control, but if the manure slurry contained over 4.5% TS, using a brush screen/roller press to remove solids before aeration produced the least expensive odor control; for large farms (8,000 pigs), solid-liquid separation with either separator before aeration is less expensive than aerating the raw slurry to control odors for 5 to 30-day storage.

Impact of Solid-liquid Separation on Odor Reduction

The solid-liquid separation divides raw manure into two fractions, solids and liquids. As indicated earlier, newly separated solids with either sedimentation basins or mechanical separators are still quite wet with the moisture content at least above 70%. If left alone in the field, the solids will naturally undergo anaerobic decomposition and become odorous. Therefore, special care must be provided to preclude the odor generation if the solids are to be stored for an extended period of time. Composting or drying immediately after separation will help keep the odors of manure solids at a minimum level. The odor generation in the liquid fraction largely depends on the amount of odor-producing organic substances remaining in the liquid and management of the liquid in the subsequent storage and/or treatment units. Theoretically speaking, we can expect a reduced odor generation rate in the liquid which has reduced BOD as compared to raw manure, if the same storage and/or treatment practices are applied to both liquid and raw manure. The quantitative information about this reduction, however, is lacking. Pain et al. (1990) evaluated the effects of solid-liquid separation and aerobic treatment of swine manure on the reduction of odor emissions after land application. A brush screen/roller-press separator was used. Compared to unseparated and untreated pig slurry, solid separation reduced odor emissions by about 20 to 30% and aerobic treatment (4-day retention time at 35°C) of the manure liquid after solid separation resulted in 55% reduction of odor emissions in the first 52 h after application to the grassland.

Summary

The impact of solid-liquid separation on odor and nutrient reduction in liquid or slurry manure is largely determined by the amount of biodegradable organic solids and nutrient elements removed from the manure. Analysis of the distribution of particle sizes and chemical constituents in the manure suggests that removal of fine particles from the manure as well as coarse particles is important for effecting odor control and nutrient reduction. Quantitative measurement and analysis are needed to develop a clear understanding of the impact of solid-liquid separation at different separation levels on odor reduction in the subsequent liquid manure storage and/or treatment units, and the economics of different separations. There are various types of separation techniques and equipment currently available for processing animal manure. Due to relatively low separation efficiencies of these equipment, however, the effectiveness of their application on odor control and nutrient reduction in the liquid manure are not definite. Chemical treatment of manure prior to separation may become an effective approach to improve the performance of sedimentation basins or mechanical separators. Cost effective and reliable chemical application equipment need to be developed and integrated into the manure management system and more field-scale studies are needed to develop correct procedures for chemical handling and application to ensure the safe and effective use of the chemicals on the farms. The economics for application of solid-liquid separation in animal manure management systems are determined by the needs for easily manure handling, odor control and/or nutrient management, and value recovery through manure solids utilization.

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