Mechanical Solid-Liquid Separation of Livestock Manure Literature Review

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R I D G E T O W N • O N T A R I O

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1.00 Introduction

Solid-liquid separation of livestock manure involves the partial removal of organic and inorganic solids from liquid manure. Effective solid-liquid separation can remove a substantial amount of the organic solids from fresh liquid (or slurry) manure and offers the benefits of the production of nutrient-rich solids. Other advantages include:

a) Ease of handling and transport - The effluent from a solid-liquid separator has a lower potential to plug transfer pipes, due to the reduced particle size of the solids. Also, less power will then be required to pump the same volume of material because the percentage of solids in the liquid manure is decreased. Solid-liquid separation can make it easier to use irrigation systems where manure must be pumped long distances. It allows for lower pressures at the pump, thus minimizing the risk of ruptured seals, leading to manure spills.

b) Odour reduction in liquid manure solids - Odour generation largely depends on the amount of odour-producing organic substances remaining in the liquid. The organic loading in treatment lagoons of the separated liquid fraction tends to be reduced following solid-liquid separation as the solids become more concentrated with organic material.

c) Reduced threat to water quality - The separated liquid has a lower potential to pollute the surface water and groundwater it may enter. It contains less nitrogen, phosphorous, and other constituents and it is commonly applied to farmland.

The separation of solids from the liquid portion is usually achieved by using the effects of gravity or by using a mechanical device. Mechanical separation typically may involve a screen, press, or centrifuge. Drawbacks of mechanical separation include:

a) High cost - Along with the expense of the separating device, some mechanical separating systems have high energy operating costs. Also, two separate manure handling systems are needed - one to handle the liquid fraction and the other for the solids stream.

b) Increased management requirements - An operator must ensure the system is functioning properly. Regular maintenance may be required to avoid breakdowns, depending on the type of separator.

The separated solids may be used for composting, soil amendments, animal feed supplements, or for generating biogas (methane). Composted material may be used as bedding in free stall barns. The separated liquid fraction could be recycled as flush water or stored and land-applied.

2.00 Classification of Mechanical Separators

Most mechanical separation includes at least one of three physical separation processes: screen separation, centrifugation, and filtration/pressing. Some exceptions to this are discussed in a later section.

2.10 Screen Separation
Screen separators include stationary inclined, vibrating, rotating, and in-channel flighted conveyor screens. All separators of this type involve a screen of a specified pore size that allows only solid particles smaller in size than the openings to pass through. This type of separator generally works best with manure having a solids content of less than 5 % (Bicudo, 2001).

2.11 Stationary Inclined Screen
Liquid manure is pumped to the top edge of the inclined screen (see Figure 1). Liquids pass through the screen while the solids accumulate on the screen and eventually move downward due to gravity forces and fluid pressure. This system has no moving parts or power requirements with the exception of a pump needed to move the liquid manure to the top of the screen. The drawback of the stationary inclined screen separator is that a biological slime builds up and clogs the openings. Frequent brushing is necessary to ensure the holes remain unplugged (Fleming, 1986).
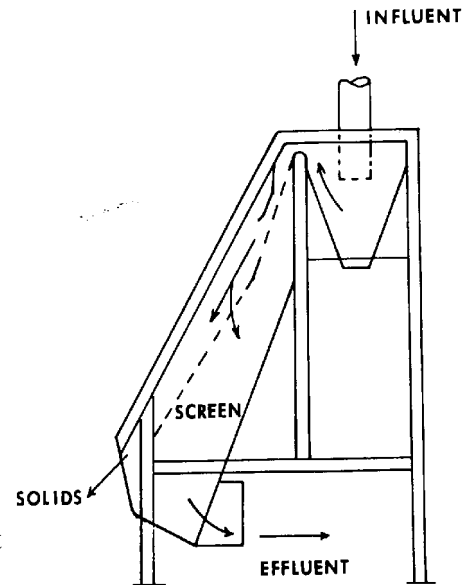
Figure 1. Stationary Inclined Screen (Shutt et al., 1975)

2.12 Vibrating Screen
Liquid manure is pumped onto the flat vibrating screen at a controlled rate (see Figure 2). The liquid flushes through the screen while the short, rapid reciprocating motion employed moves the solids to the screen edge where they are collected. The vibration reduces clogging of the screen. The power requirement is higher with this system than with the stationary inclined screen.
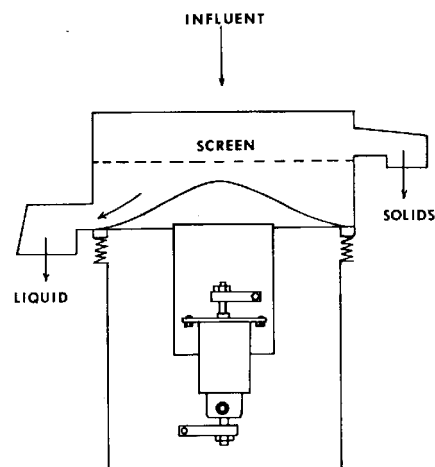
Figure 2. Vibrating Screen (Shutt et al., 1975)

2.13 Rotating Screen

A continuously turning or rotating screen receives liquid manure at a controlled rate (see Figure 3). The liquid passing through the screen is collected in a tank while the retained solids are scraped from the surface into a collection area.
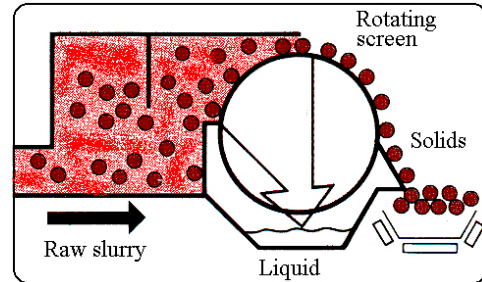
Figure 3. Rotating Screen (Bicudo, 2001)

2.14 In-channel Flighted Conveyor Screen

This screen separator system consists of an inclined screen and a series of horizontal bars called flighted conveyors (see Figure 4). The separator can be placed directly in an open manure channel, which eliminates the need for a sump or a pit and a lift pump. Liquid passes through the screen and drains into the channel on the downstream side of the separator, while the separated solids are deposited on a collection pad. Uses are similar to those of the stationary inclined screen separators, but the in-channel flighted conveyor screen separator requires more mechanical maintenance because it's moving parts are exposed to corrosive and abrasive materials.
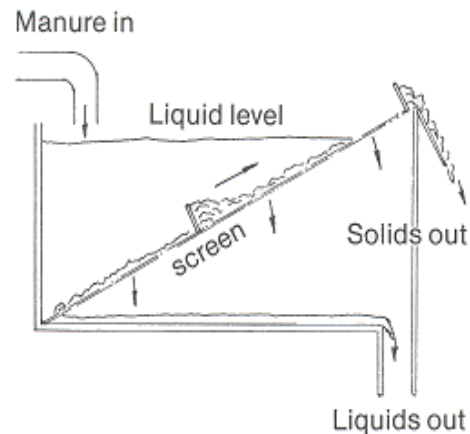
Figure 4. In-channel flighted conveyor screen (Fleming, 1986)

2.20 Centrifugation

Centrifugation involves solid-liquid separation using centrifugal forces to increase the settling velocity of suspended particles using either centrifuges or hydrocylcones. These separators function best with liquid slurries of 5 to 8 % solids, and are not as efficient when the solids content is lower (Sheffield, 2000).

2.21 Centrifuge

Typically centrifuges consist of a horizontal or vertical cylinder which is continuously turned at high velocities. Centrifugal forces separate the liquid and solids onto the inside wall of the cylinder into two layers. An auger, which turns slightly faster than the cylinder, moves the solids to the conic part of the unit where they are discharged. The two types of centrifuge separators are centrisieves and decanters. Centrisieves (Figure 5) consist of a an inclined revolving drum that is lined with a filter cloth. The slurry to be separated is pumped into the drum centre. The liquid leaves the drum through the filter cloth and the solids move by centrifugal force to the edge of the drum where they are removed separately. In the case of decanter centrifuges (see Figure 6), an auger, turning at a slightly higher speed than the cylinder in which it
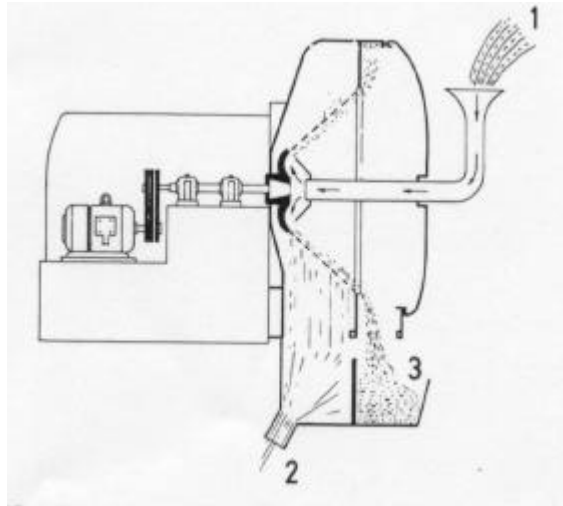
Figure 5. Centrisieve (1 slurry, 2 liquids, 3 solids) (Glerum et al., 1975)

is contained, moves the slurry to the conic part, where it is discharged. Centrifuges are very effective at solids separation and can achieve relatively low moisture levels. The initial cost is high, however, and the energy requirement is also quite high in comparison to other systems (Fleming, 1986).
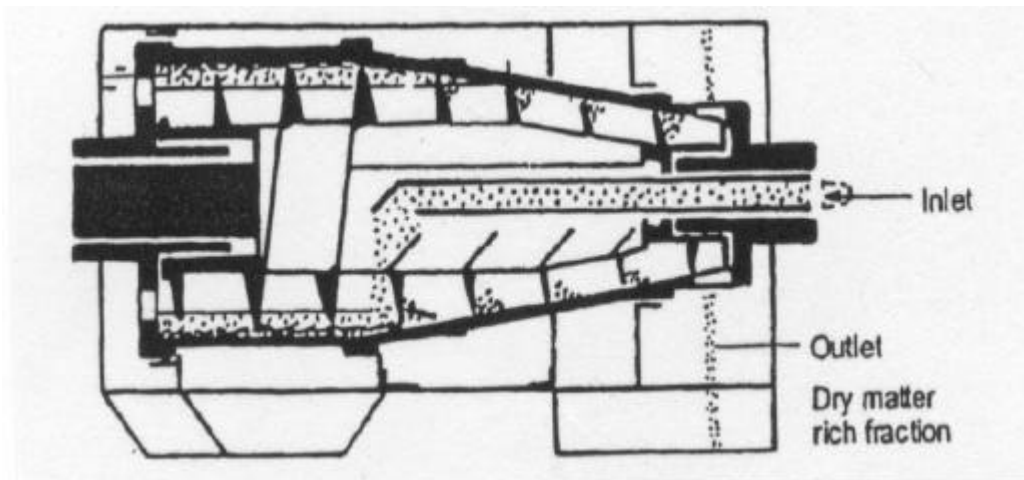
Figure 6. Decanting Centrifuge (Møller et al., 2000)

2.22   Hydrocyclone
Hydrocyclones are cone-shaped separators that
have no moving parts and the necessary vortex motion is
performed by the liquid itself (see Figure 7). They are
configured so that when manure is pumped at an angle into
the cylinder (near the top), it swirls at a high speed. The
strong swirling motion accelerates the gravity settling of
solid particles to the bottom of the cone while the liquid is
discharged through a cylindrical tube fixed in the centre of
the top.
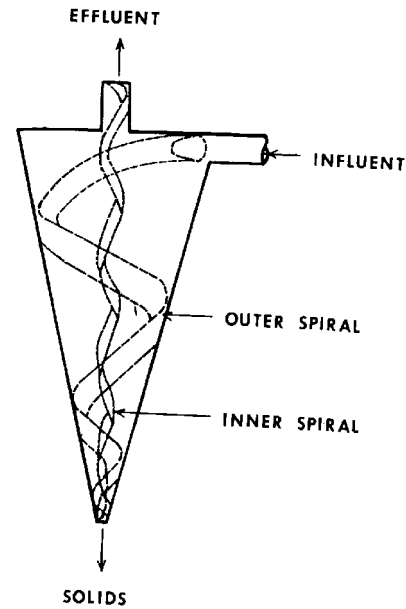
Figure 7. Hydrocyclone (Shutt
et al., 1975)

2.30   Filtration/Pressing
Presses act as continuously-fed dewatering devices that involve the application of
mechanical pressure to provide additional separation of the manure slurry. They are often used to
remove additional water from the separated solids portion produced following screening or
centrifugation. This physical separation process typically achieves a high level of dewatering and
the pressed solid cake can be composted or used for refeeding. The three main types of
mechanical filtration devices are roller, belt, and screw presses. A fourth type is the filter press.

2.31   Roller Press
This type of press has two concave screens and a series of brushes or rollers. The manure
slurry is initially deposited onto the first screen and then moved across the two screens with
brushes and squeezed by the rollers. The liquids are squeezed through and the solids remain on
the screen. The following two separators use these principles in their operation.

a) The **Brushed Screen with Press-Rolls**, also referred to as a Brushed Screen/Roller
Press, separates manure using a screen in the first stage (see Figure 8). The screen is kept
clean by a rotating brush which moves the solids on to the next stage. Here, a roller
presses more liquid out of the solids. The concentrated solids are then brushed out of the
separator and transferred to storage.
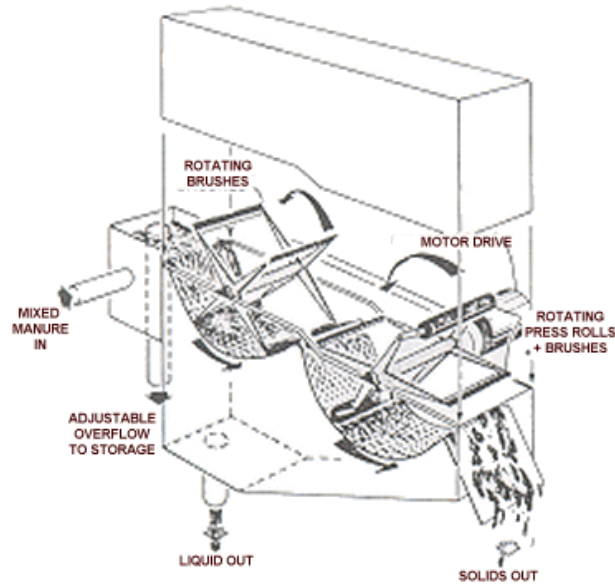
Figure 8. Brushed Screen with Press-Rolls
(Farrow Irrigation, 1978)

b) The **Perforated Pressure Roller Separator** is a two-stage double roller compression separator (see Figure 9). Liquid slurry is force-fed into the first set of perforated separator rollers. Separated liquid is removed at this point for storage. Separated solids from the first stage are conveyed to the second set of separator rollers where the fibre solids are removed by a mechanical conveyor to the storage area. The liquid fraction is drained off at this point and returned to the initial liquid slurry tank.
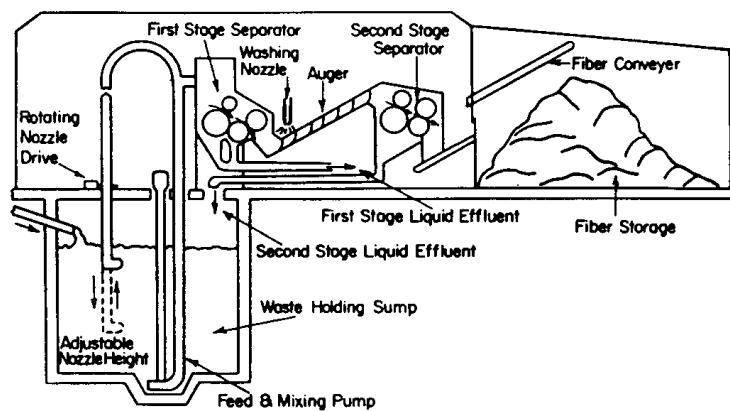
Figure 9. Perforated Pressure Roller (Rorick et al., 1980)

2.32   Belt Press

The belt press consists of a flat, woven, fabric belt that runs horizontally between rollers (see Figure 10). The liquid is forced through the belt by the rollers and the solids are carried along on the belt and dropped into a solids collection chamber.
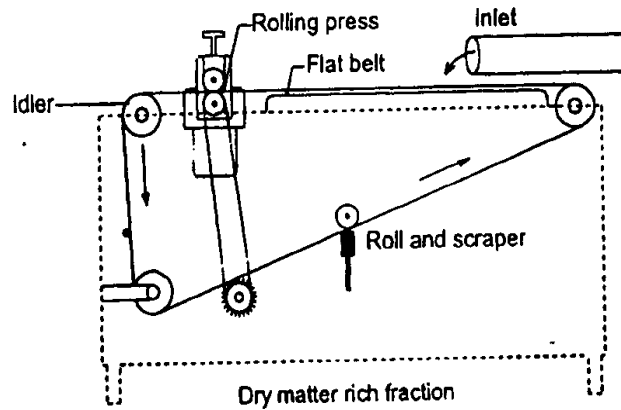
Figure 10. Belt Press (Møller et al., 2000)

2.33   Screw Press

The screw press (Figure 11) is composed of a screw-type conveyor, in the centre, that forces the slurry through a tube and past a cylindrical screen. The screw conveys the solids retained on the screen to the end where the solids are discharged.
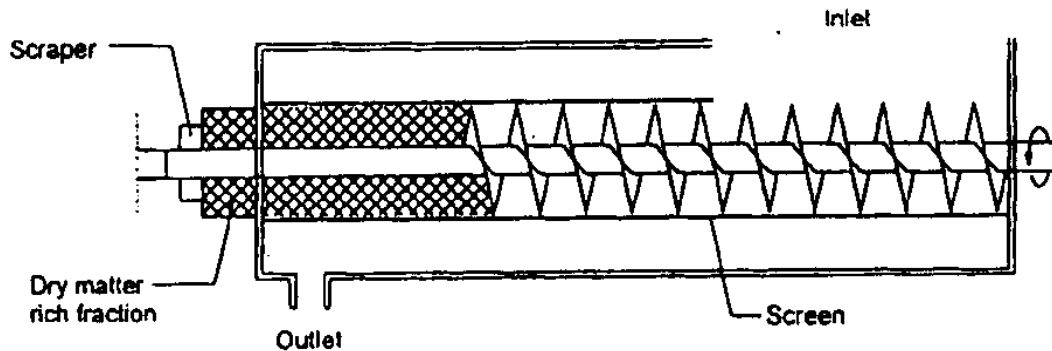
Figure 11. Screw Press (Møller et al., 2000)

2.34   Filter Press

This category of presses includes vacuum filters and chamber filter presses. The use of a filter cloth is incorporated into these designs for further solids removal.

a) The **Vacuum Filter** consists of a slow-revolving drum which is divided into a number of sections. It moves partly through the liquid to be treated. A filter cloth is fitted over the drum and one or more rollers. A vacuum is established in the sections moving through the liquid and the liquid is forced through the cloth. Solids are deposited on the cloth and removed by means of a scraper.

b) **Chamber Filter Press** separators may also be termed "pressure filters". The manure to be separated is introduced into the filtration chambers. These chambers are configured as plates which are forced against one another to de-water the manure. The number of chambers or plates may vary and they are equipped with a filtering cloth.

3.00 Livestock Manure Characteristics

This section outlines some common manure constituents for swine, dairy, and beef in Ontario based on typical feeding regimes. Odour generation and storage of manure are also discussed.

3.10 Typical Ontario Livestock Manure Constituents

Livestock manure contains a mixture of feces and urine, and may also include wasted feed, bedding and water (including: spilled water, flush water, wash water, and precipitation). Manure characteristics are generally affected by diet, species and the growth stage of the animals, and the manure collection method used, including the amount of water added to dilute the waste (Zhang and Westerman, 1997).

The following table provides typical concentrations, on an 'as is' basis, of liquid manure samples submitted to Ontario laboratories and reported using NMAN2000, a computer database (OMAFRA 2000).

Table 1. Average concentrations of Dry Matter (DM), Nitrogen (N), Phosphorous (P), and Potassium (K) in liquid manure samples submitted to Ontario laboratories (OMAFRA, 2000)

	Average Concentration (%)				
	DM	N	P	K	Number of Samples
Poultry	8.3	0.78	0.27	0.31	37
Beef	5.5	0.25	0.08	0.18	32
Swine	3.5	0.37	0.11	0.16	359
Dairy	6.7	0.29	0.08	0.26	254

Total solids (TS), also referred to as dry matter (DM), is the amount of solids expressed as a percentage of the overall mass of manure. TS is also the sum of suspended solids (SS) and dissolved solids (DS). Each solids fraction (TS, SS, and DS) is further comprised of a fixed solids (FS) portion and a volatile solids portion (VS). Fixed solids is a measure of the amount of inorganic matter present, while the volatile solids fraction is a measure of the amount of organic matter present.

Chemical oxygen demand (COD) is another parameter that can be used to quantify the amount of organic material present in the manure. In particular, it is defined as the amount of oxygen required to chemically oxidize the organic material in the manure slurry. The biochemical oxygen demand (BOD) is defined as the amount of oxygen necessary to biochemically oxidize the organic matter in the manure. Since not all the organic matter in the manure is biodegradable, the biochemical oxygen demand is necessary to measure this component of the organic matter. Five-day biochemical oxygen demand (BOD_5), a wastewater treatment parameter, is defined as the

quantity of oxygen required to biochemically oxidize the organic matter in the manure in a five-day period.

Table 2 gives mean fresh manure production and characteristics per 1 000 kg of live animal mass per day. This includes only the production of feces and urine and does not include spilled feed or any dilution water.

Table 2. Fresh dairy, beef, and swine manure production and characteristics per 1 000 kg of live animal mass per day (ASAE, 1998)

Parameter (kg)	Dairy	Beef	Swine
Total Manure	86	58	84
Total Solids	12	8.5	11
Volatile Solids	10	7.2	8.5
BOD_5	1.6	1.6	3.1
COD	11	7.8	8.4
TKN	0.45	0.34	0.52
Ammonia Nitrogen	0.079	0.086	0.29
Total Phosphorous	0.094	0.092	0.18
Potassium	0.29	0.21	0.29

Other parameters commonly measured when evaluating a separator's performance include total nitrogen (TN), total Kjeldahl nitrogen (TKN), organic nitrogen (organic-N), ammonium nitrogen (NH_4-N) [note: this is often reported as ammonia-N (NH_3-N)], total phosphorous (TP), and potassium (K). Nitrogen is present in several forms, including organic nitrogen, ammonium nitrogen, nitrite, and nitrate. Total Kjeldahl nitrogen includes organic nitrogen and ammonia nitrogen, while total nitrogen represents all forms (including nitrate and nitrite). Nitrate and nitrite are present in raw manure in only small quantities and subsequently TN and TKN are almost the same quantities when considering livestock slurries. Phosphorous exists in both the organic and inorganic form. We are often interested in the Total Phosphorous. This nutrient occurs in wastewater and biological sludges as phosphates, both as precipitated inorganic forms and incorporated into organic compounds. Potassium, another nutrient, is found in livestock manure in significant quantities.

3.20   Storage of Manure

On most farms in Ontario, manure is stored for long periods of time and spread onto fields at times when the greatest amounts of nutrients can be used by the crop. Types of liquid manure storages include: a) concrete tanks directly under barns, b) uncovered clay-lined earthen storages, c) circular uncovered concrete or steel tanks, and d) covered concrete storages.

Several factors should be considered in determining when manure should undergo solid-liquid separation. The effect of storage time on manure constituents was evaluated by Pos et al. (1984) using swine, beef, and dairy slurries. They found the dry matter content in the influent for all types of manure decreased with length of storage time. For example, the dry matter of the beef manure decreased from 7.26 % at 57 days of storage to 3.29 % at 102 days and 2.53 % at 129 days. This decrease was attributed to the biological degradation of organic matter which increases with length of storage time. These researchers also found that N, P, and K values varied directly with length of storage time. As the organic matter breaks down during storage, an increasing proportion of these elements are transferred from the solid fraction to the liquid fraction.

Zhu et al. (2000) conducted a laboratory study that revealed the dynamic changes of solids in swine manure during storage, in order to determine the best time for efficient solid-liquid separation. Fresh swine feces were collected from the floor of a swine finishing barn and diluted to approximately 8% solids content. Data revealed that separation should be conducted within 10 days after manure excretion for particle sizes equal to or greater than 0.5 mm and within five days for particle sizes smaller than 0.5 mm. After the first 10 days of storage, the total suspended solids (TSS) tended to be decomposed at a faster rate, thus reducing the separation efficiency (% TS removal). During the first 20 days of storage, particles equal to or smaller than 0.25 mm were biologically decomposed at the same rate, regardless of the particle size. The authors recommended additional research be done to confirm their findings.

3.30   Odour generation

Over time, liquid manure storages typically become anaerobic - little or no oxygen is present. This leads to odour production, and siting formulas are often used to maintain enough distances to non-compatible land uses to minimize odour conflicts. In the case of separation, odour generation is linked to the quantity of organic substances remaining in the liquid portion following separation. The higher the separation efficiency of a mechanical separator, or the more organic material is removed in the solids, the lower the odour generation potential of the liquid fraction.

4.00 Measures of Performance and Economics for Mechanical Separators

Various parameters to compare the performance and economics of mechanical separation systems are outlined in this section. The physical or chemical concentrations of constituents, energy requirements, rate of energy consumption, separator throughput, cost, odour observations and particle size distribution have been used by different researchers as measures of the performance of separators. Analysis of the various measures used in the studies considered in the literature review was for sections 6.00-6.30 inclusive. Sections 6.40, 6.50, and 6.60 were not considered in the analysis.

4.10 Components of Raw Manure and the Separated Fractions

The constituents of the raw and separated manure was often analyzed to determine the portion of solids or nutrients the separator was capable of removing. Researchers would consider physical constituents, chemical and physical constituents, and/or particle size distribution of the separated and raw manures. Often a separation efficiency would be reported by researchers to account for the composition of the liquid and solid phases.

4.11 Physical Constituents

The concentration of physical parameters of the influent, effluent, and/or separated solids were considered by some researchers. These constituents include, but may not be limited to TS, SS, DS, FS, and VS.

4.12 Physical and Chemical Constituents

The physical and chemical constituents of the raw, effluent liquid, and/or the separated solids fraction would often be measured. The concentrations of some parameters considered most frequently in these phases include TS, DS, FS, VS, SS, TKN, TN, TP, TK, Organic-N, and NH_3. Various conclusions could be drawn concerning the portion of these constituents removed from the raw manure based on their change in concentration between the influent and liquid effluent.

4.13 Particle-Size Distribution

Particle-size distribution has been studied by a few researchers to determine the profile of screened manures. Gilbertson and Nienaber (1978) measured the 'fineness modulus' and a 'uniformity index' in the raw beef manure, the screen effluent, and the separated solids fraction. These parameters represent the relative fineness, and the distribution of coarse, medium, and fine particles in the particular sample. The fineness modulus calculated for the raw manure solids was 0.8 and the uniformity index was 1-1-8 (i.e. coarse, medium, and fine). The fineness moduli for solids separated from the raw manure were 3.2, 2.4, 2.0, respectively, for the 10, 20, and 30 mesh screens. The uniformity indices were 4-3-3, 2-4-4, and 0-5-5 for the respective screens. These researchers used the particle-size distribution for diluted beef cattle manure to show that the screens were efficiently removing the coarse particles. Gilbertson et al. (1987) determined particle size distribution by wet sieve analyses. These authors used a water-sawdust mixture to determine the effect of geometric screen opening on flow capacity and solids removal capacity.

Fineness modulus, uniformity modulus and geometric mean particle size were calculated using the sieve analysis results.

Fernandes et al. (1988) analysed raw swine manure and the separated liquid for particle-size distribution according to a wet method of sieve analysis. These researchers measured a solid removal efficiency based on the range of particle sizes in the liquid effluent as a percentage of the original mass of raw manure solids. These efficiencies of solids removal ranged from 47 to 59 % for influent slurries having between 3 and 8 % dry matter contents

Hegg et al. (1981) measured the particle size distribution of solids retained on the screen for beef, dairy, and swine manure. The analysis was conducted using samples of the wet separated solids on top of a set of 12 stacked soil screens of decreasing mesh sizes. Water was slowly poured over the manure sample until all the particles that would pass through the top screen had flowed through. This screen was then removed and the procedure was repeated for each successive screen. The cumulative average of dry matter retained from the manure was nearly the same for beef and swine manure for all 12 screens. The screen mesh sizes in the test were: 1.05, 4, 8, 10, 20, 40, 60, 80, 100, 120, 140 and 200. Of these, the researchers found that the 20 and 40 screen mesh sizes retained the highest percentage of dry matter for the three manure types (see glossary for ASTM screen mesh size conversion to metric).

4.20   Operational Considerations and Odour Observations

Parameters such as the flow rate and observations related to the relative offensiveness of odour were conducted by different researchers during the testing period.

4.21   Separator Capacity

The capacity or throughput of a mechanical separator was often reported by researchers as a measure of a separator's performance. At different flow rates of influent manure into a separator, a particular unit may function differently in terms of solids removal.

4.22   Odour Observations

When odour was assessed in the various research studies it was often qualitative in nature. For example, a researcher would comment about the odour from the stacked separated solids. Certain authors have hypothesized about odour-generating parameters such as TS or VS. They have then measured these parameters to determine if some relationship existed between odour generation and the concentration of these parameters.

4.30   Labour and Energy Requirements

These requirements include the physical man-power and the energy requirements needed to operate various separators.

4.31   Maintenance Requirements

Management and maintenance requirements were often provided in research studies to give an indication of the amount of labour required to operate a certain separator. Normally these requirements were reported as observations by the researchers. For example, those who evaluated a mechanical screen separating device may have found the screen to clog frequently and

require brushing.

4.32   Energy Requirements

Many researchers would give the power or energy necessary for the operation of the separator expressed in units of kilowatts (kW). Many separators require pumps or motors for their operation. Separation units with lower energy requirements tend to be more simple mechanically.

4.33   Rate of Energy Consumption

The rate of energy consumption was used to give a measure of a separator's performance often in units of kWh/m^3 for a particular separator.

4.40   Economic Feasibility

4.41   Cost

The cost was considered by various authors to determine the economic feasibility of a particular separator. Very often, researchers would include the capital, power, and maintenance costs associated with a particular separator.

Figure 12. Various measures used in the 27 studies considered to evaluate the performance
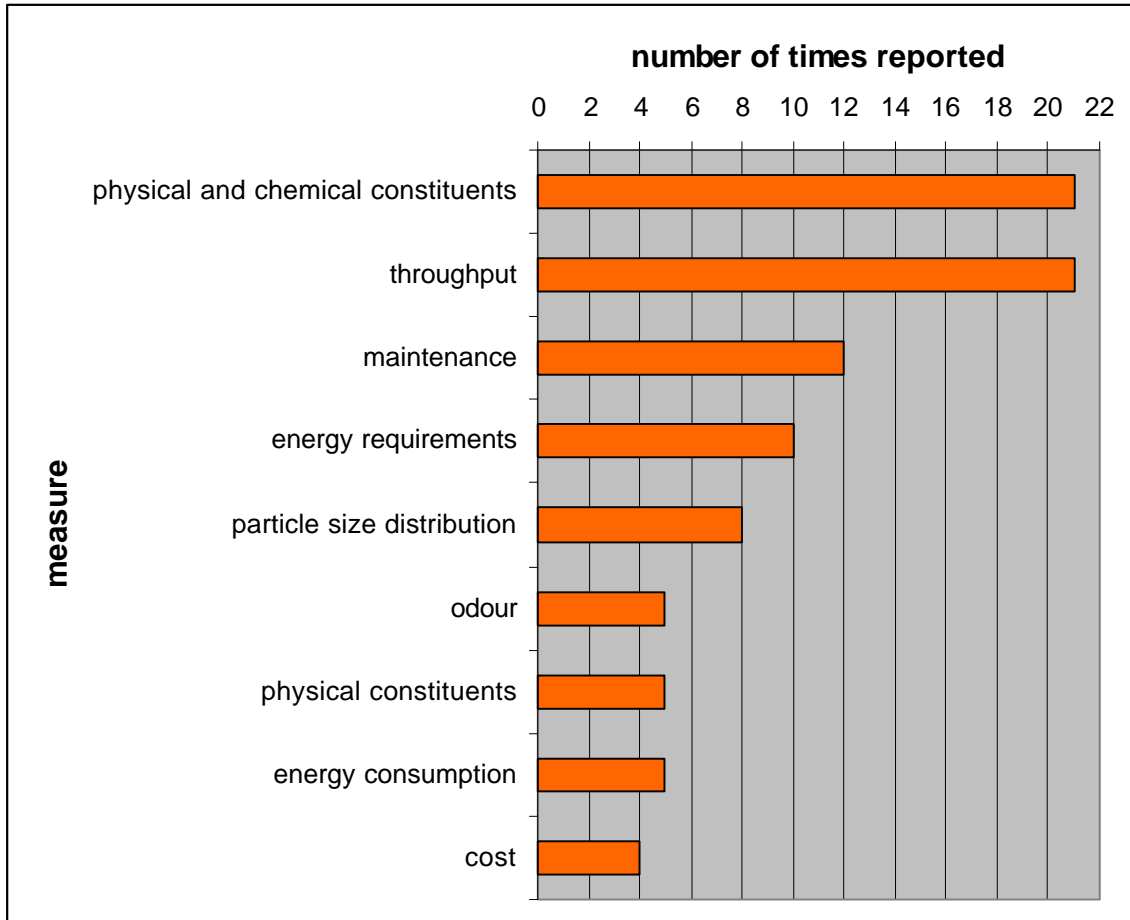
Figure 12. Various measures used in the 27 considered studies to evaluate the performance of a mechanical solid-liquid manure separator

The performance of the separators described later in this literature review (sections 6.00 to 6.30 inclusive) were evaluated using a variety of measures. The 27 studies considered used one or a variety of the discussed measures to reach certain conclusions about the separator's operation. As Figure 12 illustrates, reporting the physical and chemical constituents of the influent and effluent streams, and reporting the throughput of the separator were the two most commonly used measures.

5.00 Separation Efficiency

Separation efficiency in terms of solids or nutrient removal is often used as a measure of a separator's performance. This measure is based on the change in chemical or physical constituents in the raw and separated portions of manure. They are four ways separation efficiency can be defined. In section 6.0 of this report, the separation efficiency used by the particular author(s) will be noted so it is clear how the author(s) evaluated the mechanical unit's efficiency. To demonstrate the various calculations, consider the following:

```
example situation:
        A screw press separator operating with dairy manure
        DM of influent        = 4.89 %
        DM of effluent        = 3.27 %
        DM of fibre           = 28.90 %
        Flow rate of influent = 323 kg/min (i.e. wet)
        Flow rate of effluent = 302 kg/min (i.e. wet)
        Flow rate of fibre    = 21 kg/min (i.e. wet)
```

5.10   % removal
This is a common measure of a separator's performance, based on the change in concentration of a particular constituent (e.g. dry matter, N, P). The particular constituent must be measured both prior to and following separation in the influent and separated liquid fraction (or effluent).

% removal = influent solids concentration (%) - effluent solids concentration (%)   x 100
                        influent solids concentration (%)

Using the above example, the % removal of dry matter = 100 x (4.89 - 3.27) / 4.89 = 33.1
So, the liquid effluent dry matter content is 33.1 % lower than the influent dry matter.

5.20   Concentration of constituents in the separated solids fraction
This is the most common measure of a separator's efficiency. Various parameters such as the DM, TN, or TP are given for the separated solids portion to determine what concentrations were achieved by a certain separation process. Commonly the TS concentration of the solids stream is reported to show the degree of dryness obtained using a certain separation unit.

Using the above example, the solids (or fibre) stream had a TS content of 28.90 %

5.30   % of solids removed into the separated solids stream
Although the reporting of this separation efficiency parameter is not as common, it gives an indication of the percentage of solids separated into the fibre or solids stream based on the flow

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rate of the raw manure and the solids fraction. Other parameters such as nitrogen and phosphorus can be considered to determine the influent proportion of these nutrients in the fibre fraction. This efficiency rating is more sensitive than that given in 5.10 to differences in relative flow rates between the influent and liquid effluent streams.

% solids removed into the fibre stream = <u>fibre solids (kg/min - dry)</u>   x   100
                                                              influent solids (kg/min - dry)

Using the above example:
fibre solids (dry) = flow rate of fibre x DM of fibre = 21 x 28.90/100 = 6.07 kg/min dry
influent solids (dry) = 323 x 4.89/100 = 15.8 kg/min dry
∴ % solids removed in the fibre stream = (6.07 / 15.8) x 100 = 38.4
So, 38.4 % of the influent solids were removed into the solid (or fibre) fraction.

5.40   Reduced Separation Efficiency Index
    This index was developed by Møller et al.(2000) to give an indication of the increase in concentration of nutrients in the solid fraction. An index value of 0 indicates that nutrients are distributed equally between the solid and liquid fraction and a value of 1 indicates the nutrients are concentrated in the solid fraction. The authors found that the index is a fairly reliable measure when calculating DM separation but not as accurate when used to determine the degree of separation of TP and TN.

First - to define the simple separation efficiency, E_t

E_t = <u>quantity of solid fraction (kg) x concentration of component in the solid fraction (g/kg)</u>
        amount of slurry treated (kg) x concentration of component in the slurry (g/kg)

The reduced efficiency index, $E_t^{'}$

$$\mathbf{E_t^{'} = \frac{E_t - R_f}{1 - R_f}}$$ where R_f = (quantity of the solid fraction) / (amount of slurry treated)

Using the above example situation, we can calculate the reduced efficiency index for the degree of separation of DM:
quantity of solid fraction = 21 kg
concentration of component in the solid fraction = 289.0 g/kg
amount of slurry treated = 323 kg
concentration of component in the slurry = 48.9 g/kg
∴ simple separation efficiency, E_t = (21 x 289.0) / (323 x 48.9) = 0.38
quantity of the solid fraction = 21 kg
amount of slurry treated = 323 kg
R_f = 21 / 323 = 0.065
∴ the reduced efficiency index, $E_t^{'}$ = (0.38 - 0.065) / (1 - 0.065) = 0.34
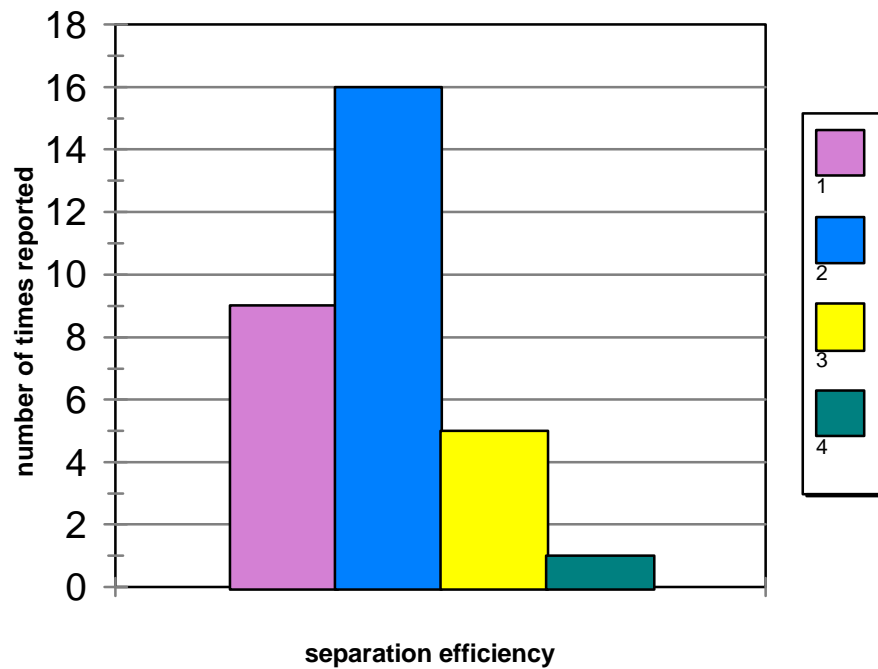
Figure 13. Various types of separation efficiency used for the 17 studies that reported some form of this measure

The above graph presents the most frequent ways separation efficiency was reported for the 17 out of the total 27 that used this as a measure of performance. These papers measured and reported one or a combination of the four listed measures of separation efficiency. Note that the number in the legend corresponds the measure of separation efficiency used (eg., #1 indicates that removal efficiency was reported). The second form of separation efficiency (see section 5.20) occurs most frequently. It was included in 16 of the 17 studies that reported a separation efficiency as a measure of a separator's performance. Measures 3 and 4 were reported in five studies and one study, respectively as illustrated in Figure 13.

6.00 Review of Research on Mechanical Solid-Liquid Separation

This section outlines relevant research on each type of mechanical separator. Most of the research on separators has been carried out using a range of test conditions. Sources of variability include:
- different types of manure,
- different time periods,
- different dilutions of liquid manure, and
- varied flow rates of influent slurries,

In addition, the measured performance of the separators has been expressed in different ways (as discussed earlier). Included in this section are some operational parameters that have been determined for certain separator models.

The various 27 studies considered in this section up to and including 6.30 of this report can be classified under the following six divisions according to their subject matter.

A.   Evaluation of one separator to determine its performance based on measures of separation efficiency. The optimal functioning of a particular separator may have been found by altering screen size, flow rate, or influent manure dry matter contents. Factors such as power requirements and cost may also have been taken into consideration to reach any optimal performance ratings. The primary objective was usually "solids removal".

B.   Evaluation of a group of separators to determine which one performs better under a given set of experimental conditions. A particular separator may be found superior to another based on testing that alters screen size, flow rate, or influent manure dry matter contents. Factors such as power requirements and cost may have been taken into account before any conclusions were reached on which separator outperforms the others evaluated. Again, the aim of this division of studies was most frequently "solids removal".

C.   Evaluation of one separator that involves considering design criteria or operational parameters of the separator. Altering certain parameters during testing may have been found to produce better results in terms of solids removal, for example.

D.   Evaluation of one separator or a group of separators with a particular goal in mind or for a certain area of investigation. For example, a researcher may have evaluated screening as a general method of solid-liquid separation for odour control.

E.   Evaluation of a mechanical separator compared either in series with or against sedimentation methods of separation.

F.   Design of a separator for optimal solids removal or the investigation of the feasibility of a separator design developed by a researcher.
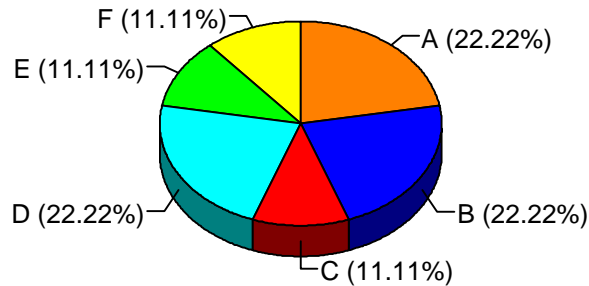
Figure 14. Proportions of the 27 research papers in the designated classed A through F.

As the pie graph (Figure 14) illustrates nearly one quarter of the 27 studies considered in the literature review were conducted with a particular goal in mind or in a specific area of research. Approximately 45 % of the papers, from sections 6.10 to 6.30 inclusive of the this report, were studies that evaluated either one or a group of separators with the primary objective of solids removal.

6.10 Screen Separation

Screen separators for solid-liquid separation of livestock manure have been reviewed extensively. Various authors have indicated the potential of these separators to reduce odour, have found optimal configurations of the screens, have compared geometries of the screen holes, and have determined ideal screen materials.

Ndegwa et al. (2000) found that solid-liquid separation may not be effective in reducing odour problems from swine facilities unless particles smaller than 0.075 mm can be separated from the liquid portion. These authors concluded that screening would be unsuitable as a swine manure separation technique if odour control was the objective, due to the difficulty of screening beyond the 0.075 mm level.

Hill and Baier (2000) compared the percent TS, VS, FS, TKN, organic N, COD, TP, and total ammonia nitrogen retained on the screen when a 0.160 mm screen was used singly and when six screens ranging in size from 4.000 mm to 0.160 mm were used in series. The influent raw manure consisted of swine manure having a 1.86 % TS content. Comparison of the two sets of data revealed that for every parameter tested, the retention was greater when the 0.160 mm screen was used alone. The accumulation of solids on the 0.160 mm screen increased further solids retention and increased the percentage of material retained on the screen when it was used singly. This 'blinding effect' made the single screen more effective than the multiple screens in series at separating the parameters tested.

The effects of geometric screen opening on flow capacity and solids removal capacity was determined by Gilbertson et al. (1987) using a water-sawdust mixture to simulate swine manure particles. Slots 3 mm wide and up to 180 mm long were found superior to 6 mm diameter holes for maintaining inflow rate capacity and for removing settleable solids from the water-sawdust mixture. A follow-up study by these authors showed that polyethylene slotted screens removed 74 % more swine manure solids than comparable steel slotted screens. These polyethylene screens were also found to be more resilient, corrosion resistant, and easier to maintain than slotted screens with zinc, polyurethane, epoxy, or conventional rust resistant paint.

6.11   Stationary Inclined Screen

This emphasis in studies concerning this screen type has been to determine the optimum: a) screen mesh size, and b) flow rate. The primary goal has been to optimize the retention of solids and other constituents by the screen.

Shutt et al. (1975) found that a stationary inclined screen with openings of 1.0 mm, as opposed to 1.5 mm, consistently gave better performance at a loading rate of 123 L/min for the separation of swine manure. The percentage of TS and COD removed by the screen are given in Table 3. At a higher flow rate of 313 L/min, the BOD and TS removal was found to be several times less than that achieved with lower inflow rates. A major problem encountered was the clogging of the openings with a film of biomass between flushes. Daily brushing of the screen increased its effectiveness.

The performance of a sloping screen was also investigated by Hegg et al. (1981). These researchers used the separator for two hours per day over a 90 day period. The manure was from an oxidation ditch for yearling beef steers fed a high-concentrate ration. As reported in Table 3, the dry matter removed by the screen ranged from 1 to 13 % and the dry matter content of the solids fraction ranged from 13.3 to 22.5 %.

Table 3. Results of three studies evaluating stationary inclined screen separators

Study	Model	Screen Size (mm)	Manure Type	% DM of influent	flow rate (L/min)	TS	COD	Solids Stream (% TS)
						% Removal		
Shutt et al., 1975	–	1.0	Swine	0.2 - 0.7	123	35.2	69.1	9.1
Hegg et al., 1981	C.E. Bauer Model 522-17	0.5	Beef	0.97 - 4.41	–	1-13	–	13.3-22.5
Chastain et al., 2001	AgPro	1.5	Dairy	3.83	–	60.9	66.5	20.3

An inclined stationary screen separator preceded a gravity settling basin to separate flushed dairy manure in a study by Burcham et al. (1997). The removal percentages of various parameters found were the same as those later arrived at by Chastain et al. (2001) when the same separator model and dry matter content of manure was used. The research facility where the study by Burcham et al. was conducted incorporated a standard-alley flush type waste removal system and free stalls bedded with sand. The authors presumed the inclined stationary screen would be better suited to a dairy farm operation where organic bedding such as sawdust or shavings are used, since these materials are more readily removed by a screen separator. Although the screen evaluated by Burcham et al. (1997) did experience early failures (generally caused by lodged debris), overall it was reliable.

Chastain et al. (2001) incorporated a stationary inclined screen into a manure treatment system. A two-chambered settling basin and a lagoon followed the screen separation. The influent raw dairy manure had a solids content of 3.83 %. The screen removed 62.6 % of the TSS, 62.8 % of the VS, 45.7 % of the Ammonium-N, 52.2 % of the Organic-N, and 49.2 % of the TKN. The results of the screen's performance are shown in Table 3. The authors found an unexpectedly high removal of ammonium-N. They had reasoned that since ammonium is in solution, it would not be removed by screening. They concluded that the lifting and spreading of manure onto the screen enhanced the volatilization of ammonia, explaining the large removal of ammonium-N.

6.12   Vibrating Screen

Vibrating separators have been evaluated to determine similar parameters to inclined stationary screens, including optimal screen size opening and flow rate through the separator. Again, the aim of most studies has been the removal of solids from the liquid manure. The vibration motion is provided by offset weights mounted on the motor shaft. The vibrations are transferred to the screen, causing the desired vertical and horizontal action. By altering the ratio of the weight above the motor to the weight below the motor (W_t/W_b) or adjusting the lead angle, the performance of the vibrating screen separator may be altered. The lead angle is simply the angle between the top and bottom counterweight.

Glerum et al. (1971) reported that the vibrating separator did not meet expectations. Using a screen with 0.085 mm openings, the separated material was too wet and the separator capacity did not reach more than 3.3 L/min.

Some researchers evaluated a separator's performance based on both the percent removal of certain constituents and on the dry matter content of the solid separate. Shutt et al. (1975) evaluated the performance of a vibrating screen in this manner using swine manure. The screen was 460 mm in diameter and had a surface area of 164 200 mm^2. The following sizes of screen openings were used: 0.12, 0.17, 0.21, and 0.39 mm. The screen with the largest opening of 0.39 mm produced the most desirable results. Table 4 shows the results of testing using a screen of this largest pore size at a flow rate of 67 L/min. These researchers found the screen with the 0.39 mm pore size was able to remove 22.2 % of the TS, 16.1 % of the COD, and 28.1 % of the TVS.

Gilbertson and Nienaber (1978) tested the performance of a vibrating separator using dilute beef manure of approximately 6 % TS. They determined that three counterweights (on the top and bottom) at an eccentric lead angle of 60° was the most efficient configuration of this 610

mm diameter screen. Lead angles greater than 60º resulted in eventual screen overflow and lead angles less than 60º lead to insufficient residence time for fluid flow through the screen. These authors reported a screen efficiency based on the percentage of influent solids separated into the fibre stream (see section 5.30). For 10, 20, and 30 mesh screens (1910 μm, 860 μm, and 520 μm) at 118 L/min, 71.2 L/min and 42.0 L/min, screen efficiencies of 3.6, 26.4, and 72.5 %, respectively, were obtained. Table 4 provides the separation efficiencies based on the percent removal of different parameters and the solids content of the fibre stream for this study.

Hegg et al. (1981) used dairy, beef, and swine manure to evaluate the efficiency of a vibrating separator. The weight ratio of the motor counterweights used in this study was 2.68 (W_{top}/W_{bottom}) and a 30º lead angle was used. These authors noted that flow rate appeared to make little difference in the percent dry matter of the separated solids as long as the flow rate in each particular trial was below the maximum capacity. The separated beef fraction had a slightly higher percentage of dry matter in the screened solids than did the dairy slurries. The dry matter content of the screened solids of the swine slurry was higher than for dairy or beef. Table 4 contains other results of this study, including the percent removal of the parameters and dryness of the solid fraction.

Table 4. Separation efficiencies of vibrating screen separators expressed in two ways

Study	Model	Screen Size (mm)	Manure Type	%DM of influent	flow rate (L/min)	% Removal		Solids Stream (% TS)
						TS	COD	
Shutt et al., 1975	–	0.39	Swine	0.2 - 0.7	67	22.2	16.1	16.4
Gilbertson and Nienaber, 1978	Kason Corp.	0.52-1.91	Beef	5.5-7.4	42.0-118.0	4-44	–	14.7-21.6
Hegg et al., 1981	Sweco	0.635-1.574	Beef	1.55-3.19	–	6-16	0-7	14.8-16.4
			Dairy	0.95-1.90	–	8-16	3-12	5.7-14.8
			Swine	1.55-2.88	–	3-27	1-24	16.9-20.9
Holmberg et al., 1983	Sweco	0.104-2.449	Swine	1.5-5.4	37.5-150	11-67	2-59	2.4-18.1

Holmberg et al. (1983) evaluated the performance of a vibrating separator by using various combinations of flow rate and screen size with flushed swine manure. These researchers determined that the percent removal efficiency of TC, COD, TKN, NH_3-N, ON, TP, and OP increased as flow rate increased and screen size decreased. The same was not true for TS. They determined that an optimal tradeoff of "organic material retained" to "inorganic material passed in the liquid effluent" occurs using a screen size of 0.234 mm and a flow rate of either 37.5 L/min or 75 L/min. The optimal tradeoff depends on the desired application for the liquid or solid separate. This study targeted a separated liquid portion having 5 to 10 % TS which is optimal for anaerobic digestion of this fraction. Table 4 provides the fraction of dry matter and COD removed by the screen over the range of flow rates and screen sizes used.

Regression equations and operational parameters were developed for a vibrating separator by Roszkowski (1988). The parameters for which the separation process would run most favourably included: a frequency of 33 Hz, a vibration amplitude index of 3.2, and shifting the vibrator masses by ð /6 radians. The vibration amplitude index characterizes the value of fluctuations. It is a ratio of the vertical amplitude of an arbitrary point on the screen circumference to its horizontal amplitude. The separator model used in this study allowed the angle of the lower-upper mass arrangement to be altered in such a way that the upper mass preceded or lagged behind the lower mass. By shifting the vibrator masses by ð /6 radians, the lower mass would be retarded in relation to the upper mass. Roszkowski also developed regression equations making it possible to determine the dry matter content in the effluent and the separation process efficiency depending on the operational parameters of the separator.

Powers et al. (1995) conducted a laboratory scale experiment using 500 to 600 g dairy manure samples. These samples were subjected to a wet sieving process using five vibrating separators. Results indicated that an average of 24 % of the total sample dry matter was collected on the 3.35 mm and 2.00 mm standard sieves. The use of smaller screens having opening sizes of 1.40 mm, 1.00 mm, and 0.50 mm was found to be impractical. These screens became clogged due to the large volume of manure passing through the screen.

The vibrating screen was evaluated as a pre-treatment method for the membrane filtration of sow slurry by Pieters et al. (1999). The swine manure used for testing had a dry matter content of between 1.5 and 2 %. Tests were conducted on a CRETEL model separator using a single batch of 4 000 L and at a flow rate of 16.7 L/min. These authors used the third method of measuring separation efficiency (see section 5.30) to determine the percentage of the original quantities that were separated in the solid fraction. Pieters et al. determined that 17 % of the DM, 41 % of the SS, 4 % of the NH_3-N, 5 % of the TN, and 3 % of the TP from the influent was removed into the concentrated solid separate.

6.13   Rotating Screen

The rotating screen has not been tested as extensively as the stationary inclined or vibrating screen separators. Hegg et al. (1981) evaluated a rotating screen separator for its performance separating beef, dairy, and swine manures. These authors found the dry matter removal rates were generally quite low, with the exception of the 2.95 % dry matter dairy slurry. Dairy manure had a slightly higher solids removal, as Table 5 indicates, which was attributed to the higher roughage content of the manure.

Table 5. Results of the performance of a rotating screen separator .

Study	Model	Screen Size (mm)	Manure Type	% DM of influent	flow rate (L/min)	% Removal		Solids Stream (% TS)
						TS	COD	
Hegg et al., 1981	Roto-Strainer	0.75	Beef	1.56-3.68	163-946	4-6	11-16	9.5-12.4
			Dairy	0.52-2.95	80-908	0-14	3-5	6.4-11.0
			Swine	2.54-4.12	80-307	4-8	9-16	15.6-16.6

The authors concluded that the solids separated by the 22 mesh (0.75 mm) screen for beef, dairy, and swine manure would have very similar particle-size distributions, based on their similar removal efficiencies.

Swine manure and slaughterhouse waste were evaluated with a Roto-Sieve drum screen (type 1031-51) separator by Mátyás and Mászáros (1988). The slurry used had a dry matter content of 0.3 to 3.0 %. Screen openings were 0.6 mm diameter and the drum speed was 27 rpm. The resulting capacity of the separator was 1 167 L/min. As far as operational parameters, these researchers reported that the efficiency of the screening could be improved if the working angle of the drum was increased from $2°$ to $6°$. This allows the solids to move more slowly towards the outlet chute, resulting in a higher dry matter percentage. During the 50 days of testing, no mechanical breakdowns were reported. A cleaning unit, consisting of a rotating brush and spray nozzles, prevented a biological slime from accumulating over the perforations.

A rotating conical screen was developed for the separation of larger particles, including spent grain and hair from liquid beef slurries (Shirley and Butchbaker, 1975). The objective was to increase the protein content in the slurry for any future refeeding investigations. The screen was shaped into a cone, unlike other rotating screen separators which are typically cylindrical, to give an uplift force to the particles on the screen thus making the system self-cleaning. The optimum peripheral speed at the outside diameter of the screen was between 50.3 and 51.8 m/min for a $45°$ angle screen. A specific influent rate of 9.8 to 24.4 $kg/s\text{-}m^2$ was found to give optimal separation efficiency. The dry matter content of the separated solids increased as input solids concentration decreased, decreased as influent flow rate increased, and increased as the peripheral diameter increased for the same specific flow rate. The power requirements were extremely low, due to the slow speed of rotation. Thus, only the power necessary to overcome any friction losses due to bearing and belt losses need to be considered in the design.

6.14   In-Channel Flighted Conveyor Screen

An in-channel flighted conveyor screen was evaluated by Møller et al. (2000) using both swine and dairy slurry. These authors developed a different measure of separation efficiency - the reduced separation efficiency (see section 5.40) which gives an index of the distribution of nutrients between the liquid and solid portions. The separator evaluated was a SWEA model

having a 3 mm screen pore diameter. Influent manures had dry matter contents of 5.66 and 7.1 %
for the swine and dairy manure, respectively. This separator removed part of the dry matter and
had some success in removing TP and TN. Based on the percent removal of dry matter, the
separation efficiency was 4.22 % for the dairy manure and 25.8 % for the swine manure tested.
The reduced separation indices and the concentrations of various parameters in the separated
solids are given in Table 6.

Table 6. Dry matter percent removals, solid fraction concentrations, and reduction separation
efficiency indices for an in-channel flighted conveyor screen (Møller et al., 2000)

		Solid Fraction (%)			Reduced Separation Efficiency Index		
Manure type	DM % removal	DM	TN	TP	DM	TN	TP
Dairy	4.22	9.2	0.43	0.09	0.07	0.02	0.00
Swine	25.8	11.7	0.46	0.18	0.41	0.08	0.17

6.20   Centrifugal Separation

As previously mentioned, centrifuges may be classified as centrisieves or decanters,
although often no distinction is made. Hydrocyclones are also termed "liquid cyclones".

6.21   Centrifuge

Glerum et al. (1971) evaluated the performance of a centrisieve using swine manure. The
separator was a conic drum 560 mm in diameter and was lined with a filter cloth. It also had
screen openings of 0.031 mm in size. Using this centrifuge separator, between 30 and 40 % of
the dry matter could be removed, and a separated material with a dry matter content of 14 to 19
% was achieved. The authors found the capacity of the centrisieve was dependent on the dry
matter content of the slurry, and averaged 150 L/min. A reasonable degree of separation was
found to depend both on the homogeneity of the slurry and on the capacity of the separator. The
centrisieve tested was not capable of reducing the BOD_5 content although it did reduce the COD
content by 28%.

The Alfa Laval LISEP centrifuge separator was tested by Chiumenti et al. (1987) using a
beef slurry of 7.5 % TS. This separator required 3.2 kW of power and consumed energy at a rate
of 1.30 kWh/m^3. The separator removed 25 % of the TS and yielded a separated solid material
with a TS content of 18.4 %. This separator had a capacity of 40.8 L/min and removed 35 and 21
% of the COD and TSS, respectively.

Decanters have been tested by Chiumenti et al. (1987). The performance of two different
models was evaluated using beef manure. The NX 309 model had a horizontally rotated axis
activated by an installed 11 kW motor while the Decanter Oribiter DS 550-35 model had a
vertically rotated axis driven by a 7.5 kW motor. The NX 309 model achieved a high level of
separation even in the absence of flocculation. The DS 550-35 achieved a 48 % removal of TS
while the NX 309 achieved 75 % with a similar dairy slurry influent and rate of energy
consumption.

A decanter was also evaluated by Glerum et al. (1971). This separator consisted of a closed cylinder, 320 mm in diameter, with a drum speed of 3500 to 5000 rpm. The dry matter content was considerably reduced and the material separated was quite dry, as indicated in Table 7. The capacity of 10 L/min was low in spite of the high energy consumption. These authors found the tested decanter capable of reducing the influent BOD_5 and COD by 18 % and 52 %, respectively.

Chiumenti et al. (1987) studied solid-liquid separation of livestock manure using a centrifuge and two decanters. They concluded that centrifugal separators permit optimum separation results. These researchers speculated that the use of these separators might be more widespread if they had been introduced to the market in a form that was simpler to operate and less complex mechanically.

Table 7. Results of studies involving the performance of decanter centrifuges

Study	Model	Manure Type	% DM of influent	flow rate (L/min)	% Removal		Solids Stream (% TS)
					TS	COD	
Glerum et al., 1971	–	Swine	7.58	10	66	52	37.4
Chiumenti et al., 1987	Alfa Laval NX 309	Beef	6.9	13.2	64	72	22.1
Chiumenti et al., 1987	Orbiter DS 550-35	Beef	6.0	30	45	56	26.1
Sneath et al., 1988	Alfa Laval NX 314	Swine Swine	1.9 8.0	– –	47.4 56.2	– –	29.0-31.0 25.9

Sneath et al. (1988) also evaluated a decanting centrifuge. Using swine manure, these researchers tried to determine the minimum solids content that could be achieved in the centrifuged liquid portion. The centrifuge tested was driven by a 15 kW motor. Samples of the raw slurry and centrifuged liquid were analyzed for dry matter and suspended solids only. A full analysis of the particle size distribution was conducted for both the raw slurry and the centrifuged liquid. This analysis revealed that only 2 % of the particles in the centrifuged liquid were greater than 2.00 mm in size, compared with 53 % of the particles in the raw manure. Thus, the centrifuge evaluated removed almost all of the particles greater than 2.00 mm in size. These authors used the third measure of separation efficiency (see section 5.30). The centrifuge was able to remove up to 47 % of the TS contained in the raw slurry of 1.9 % DM and 55 % of the TS from the raw slurry at 8 % DM. These researchers found that the fibre dry matter increased as the raw slurry dry matter decreased. Table 7 gives the calculated percent removal efficiencies of the solids and the dryness of the fibre fraction for influent manures of 1.9 and 8 % DM.

Møller et al. (2000) who measured the reduced separation efficiency (see section 5.40) tested the decanting centrifuge. This measured index was high for both dry matter and phosphorous, indicating a large fraction was conveyed by separation into the solid phase. Decanting centrifuges were not, however, efficient in transferring nitrogen to the solid phase, for the dairy and swine manure tested. Møller et al. (2000) also evaluated the economics of separating slurry for a farm having annual production of 4 000 tonnes of manure - corresponding to the yearly production of manure by about 8 000 pigs. The treatment of slurry with a decanting centrifuge was found to be five times more expensive than treatment with a screw press. Both types of equipment, however, have much higher capacities than 4 000 tonnes/year and increasing the volume of manure to be separated would decrease the annual cost per tonne of manure treated.

A rotating flighted cylinder was tested by Miner and Verley (1975). This separator is an inclined tube with a helically wound fin attached to the interior surface. As dilute slurry flows down the open space of the tube, settleable solids are trapped between the wraps of the fin. If the tube is slowly rotated, the solids are carried to the upper end and discharged. The solids concentration of the upper end effluent was determined by these authors to be a function of the design of the wraps of the fin, the rotational speed, and the solids content of the influent slurry. The separator having a 610 mm diameter drum was mounted at an angle of 17.5^o and had a screen with openings of 1.19 mm. When dilute dairy manure (0.05 to 1.2 % TS) was passed through the rotating cylinder, solids removed ranged from 20 to 80 %, depending primarily upon the flow rate. Flow rates varied from 4 to 50 L/min for the flushed dairy manure. When swine manure was tested, flow rates ranged from 17.8 to 26.5 L/min and the separated solids had a dry matter content as high as 4.3 %. The main advantage of this separator, that operated on the same principles of a centrifuge, was its mechanical simplicity. The centrifuges previously discussed, however, achieved much drier separated solid fractions.

6.22   Hydrocyclone

The performance of hydrocyclones, or liquid cyclones, has not been reviewed as extensively as centrifuges. Shutt et al. (1975) tested a hydrocyclone having a diameter of 76 mm and a 6° apex cone. Swine manure was first pumped across a stationary inclined screen with 1.0 mm openings prior to pumping it through the liquid cyclone to remove coarse solids which tended to plug the small underflow nozzles. This separated swine manure used for testing had a TSS concentration ranging from 0.10 to 0.50 %. These researchers found the cyclone's performance was superior at higher influent TSS concentrations. At a flow rate of 88 L/min and using a 3.2 mm underflow nozzle diameter, the separator achieved a maximum removal of solids of 26.5 %. The solids portion under these conditions had a dry matter content of 8.4 %.

The performance of a hydrocyclone was also evaluated by Pieters et al. (1999). These researchers also used swine manure of from 1.5 to 2.0 % DM, however no pre-treatment of the slurry took place in this study. Also these authors used the third method outlined in section 5.30 to measure the separation efficiency. At a flow rate of 250 L/min, the hydrocyclone was capable of transferring only 8 % of the DM and 30 % of the SS from the influent into the fibre fraction. The performance of the SRC liquid cyclone was deemed poor and the authors concluded that the liquid cyclone was not suitable for separating swine slurry.

6.30   Filtration / Pressing

6.31   Roller Press

As previously mentioned, brushed screen / roller press and perforated pressure roller separators can be classified as roller presses since this type of press is incorporated into their design.

Pos et al. (1984) evaluated a brushed screen / roller press manure separator. Swine, beef, and dairy manure having differing lengths of storage time were used. The separator was equipped with two large semi-circular punched steel plates - one having screen openings of 1.6 mm and the other with openings of 3.2 mm. In general, the throughput of the brushed screen / roller press was not influenced by the length of storage time. There was, however, a noticeable difference between types of manure. Average capacities were 50, 105, and 200 L/min for beef, dairy, and swine manure, respectively. These differences were not related to the dry matter content, but instead to the characteristic of the dry matter. For example, the cattle rations had higher percentages of roughage, which accounted for the coarser solids in the slurry and subsequent lower capacities achieved with the separator.

The effect of flow rate was also studied by these authors. As the flow rate increased, the dry matter removed with the solid fraction decreased. With an influent solids concentration of 5.2 %, 17.3 % of the dry matter was removed yielding a solids stream having 18.7 % DM. Recycling of the liquid fraction from the initial separation only removed an additional 1.6 % dry matter at a flow rate of 242 L/min for swine manure. These researchers concluded that recycling the initial effluent from a brushed screen / roller press was not justified.

Sneath (1988) investigated manure treatment to reduce odours in swine manure that was stored for more than five days after treatment. For manure with an initial dry matter content of more than 4.5 % from a 2 000 pig herd, a brushed screen / roller press separator used before aeration produced the lowest running costs. For higher contents of dry matter in manure, separation using the brushed screen / roller press remained the most economical option. Sneath (1988) found that using a separator in the treatment system was more expensive for swine manure of less than 3.0 % dry matter.

A perforated pressure roller was studied by Rorick et al. (1980) using dairy manure of varying solids contents. These contents were 4.5, 6.7, and 9.9 % DM and corresponded to flow rates of 364, 324, and 254 L/min. Increased solid levels in the influent was associated with decreasing loading rates on a volume basis, but an increased TS loading. Increasing the percent TS in the influent slurry from 4.5 to 9.9 increased the percentage of TS removed from 9.5 to 25 %. In addition, the dry matter of the solids stream rose from 26 to 30 %. The combined increase of percent TS and percentage of applied TS removed in the fibre fraction resulted in a significantly greater production of fibre.

The fibre solids were 'washed' to produce a cleaner end product. 'Washing' had the potential to clean the fibre by flushing more of the dissolved solid fraction into the liquid effluent. The drop in VS concentration of the fibre from 93 to 81 % TS as the slurry percent increased was not anticipated by the researchers, and may have been due to the more complete washing of the fibre at higher dilutions of slurry. 'Washing' of the fibre solids produced solids having a slightly greater moisture content. The observations of Rorick et al. (1980) suggest that it would not be

possible to operate the perforated pressure roller with both a high flow and a slurry content that is high in solids. The operation at higher slurry solids levels could, however, be achieved with lower loading rates.

A reciprocating press was designed and built for replacement of a perforated roller press by Koegel et al. (1990). The perforated roller press was deemed unsatisfactory from the standpoint of reliability and repair costs. The pairs of rollers with associated bearings and drive components led to a great number of moving parts that functioned in a highly corrosive environment. Other disadvantages of the perforated roller press included its tendency to plug and its relatively low throughput. The primary goal for the new design was to minimize the number of moving parts while keeping fabrication costs relatively low. The design consisted of a slotted tube with a reciprocating piston inside. Manure entered when the piston was fully retracted. As the piston advanced, the slurry in the tube was trapped between it and a plug of compressed solids remaining from the previous stroke. Liquid was expelled through the slots in the tube wall as the piston advanced. Near the end of the stroke, the plug of solids from the previous stroke was ejected.

6.32   Belt Press

Belt presses have not been as extensively tested as the other types of presses. Møller et al. (2000) evaluated a belt press separator manufactured by SCS having a screen pore diameter from 1 to 2 mm. The influent dairy slurry was 7.1 % TS and the influent swine slurry was 5.66 % TS. Separation efficiencies based on the percent removal of solids was 32.4 and 22.3 % for the dairy and swine manure, respectively. These researchers developed the reduced separation efficiency index. Reduced separation efficiency indices for dairy manure were 0.29, 0.10, and 0.15 for DM, TN, and TP. Treatment of swine manure yielded indices of 0.50, 0.10, and 0.20 for DM, TN, and TP respectively. The belt press transferred a substantial portion of dry matter to the solid fraction and was reasonably successful in removing TN and TP from the influent. DM concentrations of the solid portion were 15.3 and 19.2 % for the dairy and swine manure, respectively.

6.33   Screw Press

Zhang and Westerman (1997) reported that there was a lack of performance data for screw presses in the area of solid-liquid manure separation. Since 1997, various models of these presses have been evaluated using livestock manure. Certain operational parameters have been tested, including the orientation of counterweights applied to the pressure plate arms, and influent and effluent pressures.

Chastain et al. (1998) evaluated a FAN screw press separator, having a stainless steel screen 521 mm long with 0.5 mm openings. The stainless steel screw was turned at 36 rpm. For this study, a 40 kg counterweight was used on each of the pressure plate arms. The capacity varied from 180 to 662 L/min depending on the solids content of the influent swine slurry. The screw press removed 34.9 % of the COD from the manure regardless of the slurry dry matter content. Prediction equations were developed from the data to describe the removal of TS, VS, TKN, NH_4-N, organic-N, and TP. The removal of plant nutrients ranged from zero with an influent TS concentration of 1.11 % to a maximum removal at a TS concentration of 7 %. The total solids content of the separated solids ranged from 22.6 % to 34.4 %. The authors concluded

that swine manure systems that maintained a TS in the manure of 5 % or more would benefit most from the use of a screw press. If maintained at a solids concentration of 5 %, it is possible to remove 15.8 % of the TS, 20 % of the VS, 12 % of the TKN, 15.8% of the organic-N, and 15.8 % of the TP using this screw press. These authors also reported that the proper application of this press should remove a large portion of the slow-to-degrade VS and FS that contribute to sludge build-up in lagoons.

Pieters et al. (1999) used a screw press separator to pre-treat sow slurry ranging from 1.5 to 2.0 % TS. The test to evaluated the FAN screw press in this study was conducted using a single batch of about 4 m^3. The separated solids contained the following fractions of influent parameters: 26 % of the DM, 65 % of the SS, 11 % of the TN, 7 % of the TP, and 12 % of the ammonia-N.

Converse et al. conducted two different studies involving the performance of screw press separators (1999, 2000). Converse et al. (1999) used dairy and swine manure to study two comparable screw presses. Dairy manure was used to evaluate a KP-10 Vincent Screw Press separator. This separator had a 2.4 mm perforated screen and was operated with both 180 and 360 kg of outlet resistance and no inlet pressure. This screw press also had 90 kg and 170 kg weights hanging on the fibre back-pressure plate arm. The second screw press in this study was tested using swine manure. This was a similar press, but had a 0.5 mm gap profile bar screen and was operated under 0, 28, and 62 kPa inlet pressure, and 113 to 160 kg of outlet resistance with and without a barrel extender. For the dairy slurry, the Vincent press throughput decreased with increasing solids concentrations. The dairy fibre solids output ranged from 26.3 to 33.9 % dry matter. The 360 kg outlet resistance produced a significantly drier fibre stream. The solids removal efficiency ranged from 15.8 to 47.0 %, based on the percent change in solids between the influent and effluent dairy manure stream. Based on the percent of influent solids removed into the fibre stream (see section 5.30), the efficiency ranged from 29.6 to 68.8 %. Phosphorous

Table 8. Results of studies involving the evaluation of screw press separators

Study	Model	Manure Type	% DM of influent	flow rate (L/min)	% Removal TS	Solids Stream (% TS)
Chastain et al., 1998	FAN	Swine	5	180-662	15.8	22.6-34.4
Converse et al., 1999	KP-10 Vincent	Dairy	1.0-10.1	–	15.8-47.0	26.3-33.9
	KP-10 Vincent	Swine	1.5-5.3	–	15.0-29.7	23.5-34.5
Converse et al., 2000	FAN	Dairy	2.64	1 456	23.79	26.0
	Vincent	Dairy	4.89	323	33.41	28.9

removal in the fibre ranged from 8.6 % of the influent P at about a 2 % solids content to 28.9 % at a 10 % solids content.

For the swine manure used with the similar press, there was no pronounced trend of flow with influent solids concentration. The fibre output ranged from 23.5 to 34.5 % solids. The solids removal ranged from 15.0 to 29.7 % based on the percent solids change between the influent and effluent streams. The efficiency of the screw press based on the mass rate of solids entering and the mass of solids in the fibre stream/min (see section 5.30) ranged from 17.6 to 28.7 %. Phosphorous removal ranged from about 3.0 % of the influent P at about 1 % solids to about 4.8 % at 5 % solids. The other nutrient removal rates were under 8 %.

Converse et al. (1999) determined optimal operational parameters for this Vincent screw press separator. The press could be operated to meet the particular needs of the operator.

a) To maximize flow rate:
- operate the press under pressure with low influent solids, at least for dairy (probably also for swine manure)

b) To maximize the fibre output rate (e.g. in kg/min)
- operate the unit with as high an influent DM concentration as possible with lower outlet resistance

c) To achieve the driest solids
- operate the unit with the most outlet resistance and a high influent solids content.

d) To remove as many nutrients as possible
- keep the influent solids as high as possible, with minimal dilution

The second study conducted by Converse et al. (2000) involved the evaluation of a FAN and Vincent Screw Press for dairy manure. The FAN press processed flushed manure with a low solids content and the Vincent press processed scraped manure with a higher solids content. The FAN screw press had an average separation efficiency of 23.79 % while the Vincent press had an average separation efficiency of 33.41 % based on the percent removal of solids from the influent stream. The separation efficiency based on the influent solids removed in the fibre portion (the third measure of separation efficiency), was 25.78 and 37.71 % for the FAN and Vincent screw presses, respectively. If solid dryness is the goal then both of these screw presses performed very well. Table 8 provides the discussed results of this study.

6.34   Filter Press

Vacuum filters and chamber filter presses were previously classified as filter presses due to the incorporation of a filtering cloth into their design. Glerum et al. (1971) studied the performance of a rotary vacuum filter having 0.29 mm screen openings. Swine manure with a dry matter of 7.54 % was used in this study and had a throughput of 4.2 L/min. This separator removed 51 % of the dry matter from the slurry inflow and the separated fibre had was 21.5 % TS. The vacuum filter had both a low capacity and a low energy consumption.

A pressure filter was evaluated by Chiumenti et al. (1984) for its efficiency separating beef manure with 7.1 % TS content. This separator functioned similarly to the chamber filter press described in Section 2.34. The pressure filter was capable of removing 76 % of the TS, resulting in a separated fibre portion having a solids content of 26 %.

The performance of a continuous belt micro-screening unit was analysed by Fernandes et

al. (1988) using swine manure. It consisted of a continuous conveyor belt of woven filter with 0.1 mm pore sizes that is moved horizontally by an electric motor. This separator is not classified as a belt press since rollers do not force the liquid through the belt filter. The solids removed on the belt can be removed in one of two ways. Large particles may fall into a lower pan by themselves as the finer particles are blown off by an air knife. This air knife blows through the bottom of the belt above the solids pan. It acts to continuously clean the filter belt and a high rate of manure separation is expected. The operative variables tested in this study were the influent solids concentration (2 to 8 %), flow rate (10 to 35 L/min), and linear velocity of the filter belt (1.2 to 5.2 m/min). The dry matter of the screened solids was found to range from 14 to 18 %. These authors found a direct relationship between solids concentration in the slurry and that in the separated solids. The increased height and weight of the slurry solids on the belt was found to cause a self-pressing effect which increased the dryness of the solids. This relatively small machine was found to efficiently handle a total hydraulic loading of 35 L/min. The unit operated for about 300 hours in total, during which time there were no mechanical problems. In terms of solids removal, this unit was capable of removing in the range of 40 to 60 % of the influent solids. This study revealed that the hydraulic loading had no significant effect on solids removal. As much as 40 % of the COD, 35 %of the TKN, and 21 % of the TP were removed by separation.

Finally, Pieters et al. (1999) tested a chamber filter press using swine manure from 1.5 to 2.0 % DM. The maximum capacity varied from 3.3 to 5.8 L/min. The separation efficiency was expressed as the percent of the original mass of the respective substances in the concentrated solid fraction. The solid fraction consisted of the following percentages of the influent: 51 % of the TS, 77 % of the SS, 31 % of the TN, 42 % of the TP, and 31 % of the potassium. The chamber filter press performed much more efficiently than a hydrocyclone, vibrating screen, and screw press under similar influent conditions.

6.40   Summary of Reported Parameters

Sections 4 and 5 discussed the measures of performance and types of separation efficiency reported, respectively. This section will outline that various parameters that were reported for the first and second measure of separation efficiency (see sections 5.10 and 5.20). For the first measure of separation efficiency or the percent removal efficiency, Figure 15 illustrates parameters that were reported at least twice. The second measure of separation efficiency measured the concentrations of parameters in the separated solids fraction. The concentrations of parameters reported at least twice for this second measure by various researchers are included in Figure 16.
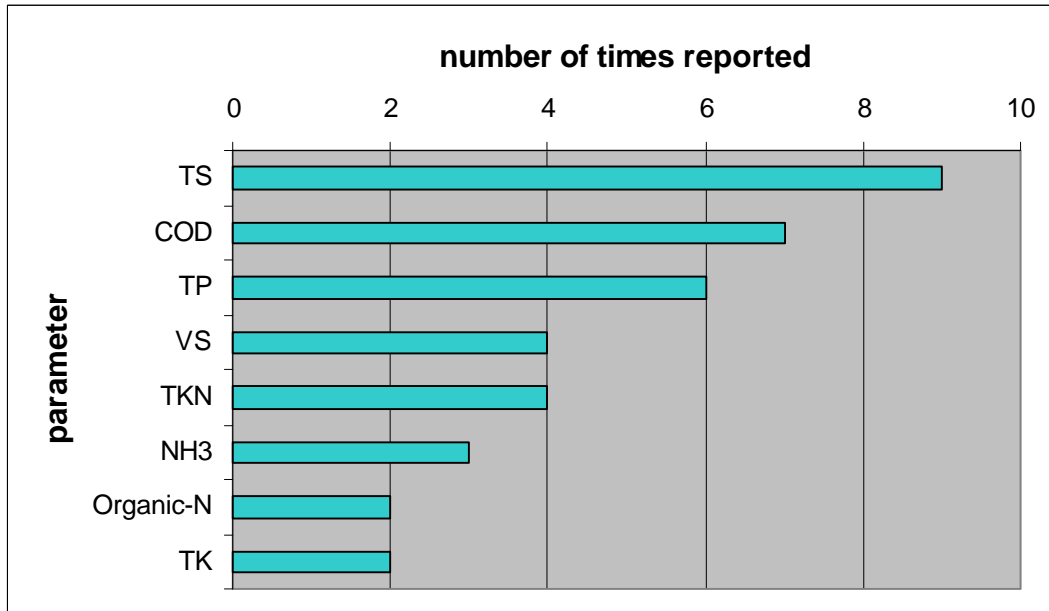
Figure 15. Parameters reported at least twice in the 9 studies that reported the percent removal efficiency form of separation efficiency

Nine studies out of a total of 17 reported removal efficiency as a measure of separation efficiency, as opposed to the three other forms. Parameters reported only once included: SVS, BOD, BOD_5, BOD_{20}, Ortho-Phosphorus (OP), TC (Total Carbon), Ca (Calcium), Mg (Magnesium), S (Sulphur), Zn (Zinc), Cu (Copper), Na (Sodium), and Mn (Manganese). These parameters were not included in Figure 15. The reported NH_3 parameter includes both ammonia and ammonium. TS or DM was the only parameter expressed in terms of percent removal from the influent reported for all nine studies. The top five parameters reported for the first measure of separation efficiency as indicated in Figure 15 are TS, COD, TP, VS, and TKN.
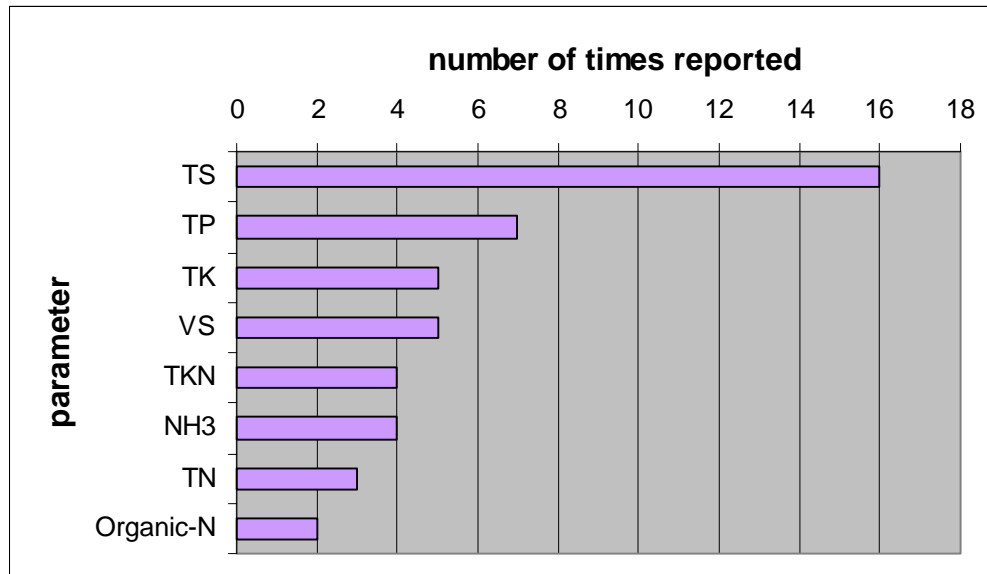
Figure 16. The concentration of various parameters reported in at least two of the 16 studies that used the second measure of separation efficiency

16 studies out of a total of 17 reported the concentration of parameters in the solid fraction as a measure of separation efficiency. Parameters reported only once include COD, TSS, FS, Non VS, TC, and OP (Ortho-Phosphourus). The reported NH_3 parameter includes both ammonia and ammonium. The solids content of the separated fibre fraction was measured in all the studies that used the second measure of separation efficiency. The top four concentrations measured for this measure of separation efficiency include TS, TP, TK, and VS.

6.50   Combinations of Separator Designs

Various combinations of separator designs have been incorporated to improve the overall performance of the separator. Huijsmans and Lindley (1984) compared four combinations of separators using dairy manure. The systems included:

a)   sloping (vibrating at a frequency of 60 Hz) screen (3.05 mm openings) that could be adjusted between angles of 45 and 60° in combination with a screw press (Model 1)

b)   the same as system (a) with the addition of spray nozzles at the top of the sloping screen that expelled recycled liquid for approximately half of the length of each test

c)   perforated pressure roller (cylinders 610 mm in length and 200 mm in diameter) placed between the sloping (vibrating) screen (3.05 mm openings) and the screw press (Model 1) of system (a)

d)   coarser sloping screen (4.06 mm openings and vibrating at 60 Hz) that could be adjusted between angles of 45 and 60° in combination with a modified screw press (Model 2)

In the Model 1 screw press, the pressure was increased by a reverse flight screw beyond the cylinder. By changing the distance between the cylinder and reverse screw, the pressure could be regulated. In the Model 2 screw press, a rubber cone replaced the reverse screw. The back

pressure, however, could be altered by changing the length of the rubber cone. Screen angle was not found to cause a significant effect in the TS concentration of the liquid fraction of systems (a), (b), or (d). The driest solid fraction for system (d) resulted from a screen angle of 47° and 51° for both systems (a) and (b). For system (c), however, altering the screen angle had a significant effect on both the liquid and solid fractions. At lower angles, the inflow filled the screen uniformly but the effluent solids entered the perforated pressure roller as large cakes. This caused the pressure roller to be heavily loaded. With higher angles, the inflow began rolling as small clumps and the pressure roller was only lightly and continuously loaded. Comparisons of systems (a) and (b) revealed that the use of a spray nozzle did not improve performance. Both systems removed 25 % of the solids and produced a solid fraction of about 23 % TS. The addition of a pressure roller in system (c) produced only a slightly drier solids fraction as indicated in Table 9. System (d) consisting of a modified screw press and a sloping screen having 4.06 mm screen openings produced the driest solids.

Table 9. Separation efficiency based on the dryness of the separated solids (Huijsmans and Lindley, 1984)

System	Inflow % TS	Separated Solids % TS
a	11.3	23.2
b	11.3	23.1
c	11.1	24.3
d	11.1	31.3

Chiumenti et al. (1987) evaluated the performance of a rotating cylinder with press rolls (see Figure 17). This design combined principles of both screen separation and filtration by
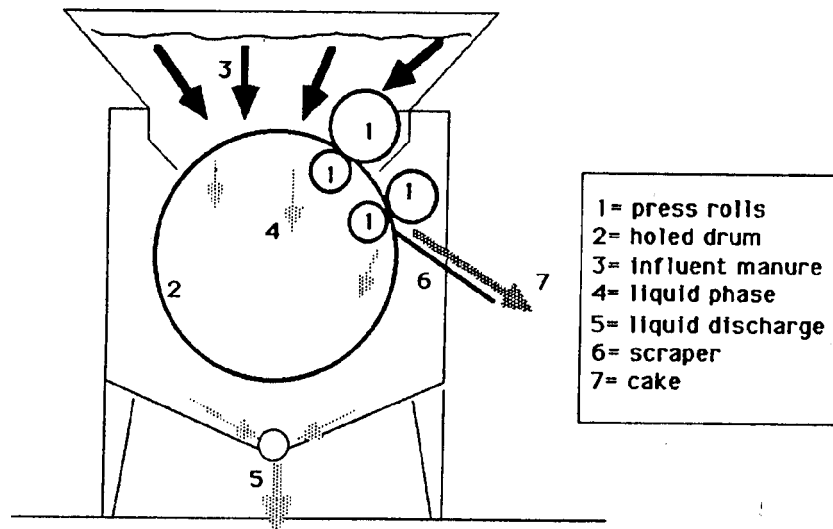

1= press rolls
2= holed drum
3= influent manure
4= liquid phase
5= liquid discharge
6= scraper
7= cake

Figure 17. Rotorpress design (Chiumenti et al., 1987)

pressing. The separator had a perforated horizontal steel cylinder rotating at low speed. Two series of oppositely pressing rollers were inserted on the external and internal part of the cylinder. A cake of manure attached to the external part of the cylinder was formed by the pressing action of the rollers. This cake was expelled by a plastic scraper. The rotating cylinder with press rolls was evaluated using beef cattle manure having 9.3 % TS. This separator removed 24.7 % of the TS achieving a solid phase with a dry matter content of 21.0 %.

Jamieson et al. (2001) tested the TR separator (see Figure 18). A paddle conveyor moved the raw manure onto the inclined screen. A flight of rubber paddles moving over the screen transported the solids to the top of the screen. Here a screw auger provided further moisture removal from the solids fraction. A weighted cantilevered door provided pressure to squeeze the liquids. Swine manure from sow, feeder, and weaner barns having TS concentrations of 3.4, 5.4, and 6.6 % respectively was used. The TR separator was capable of removing TN, TP, TK, TS, BOD_5, and TSS, although the reductions were low to modest at best. The concentration of BOD_5 remaining in the liquid fraction was usually greater than 5 000 mg/L. Concentration reductions of TN were minimal. Total N concentrations in the liquid fraction typically exceeded 2 000 mg/L and was primarily in the NH_4-N form. The TR system usually removed greater than 20 % of the TS and TP from the influent manure. The solid fraction represented 15 % of the original volume of manure. Jamieson et al.(2001) concluded that continuous agitation of the raw manure as it was being pumped to the separator and the use of fresher manure may have enhanced separation efficiencies.
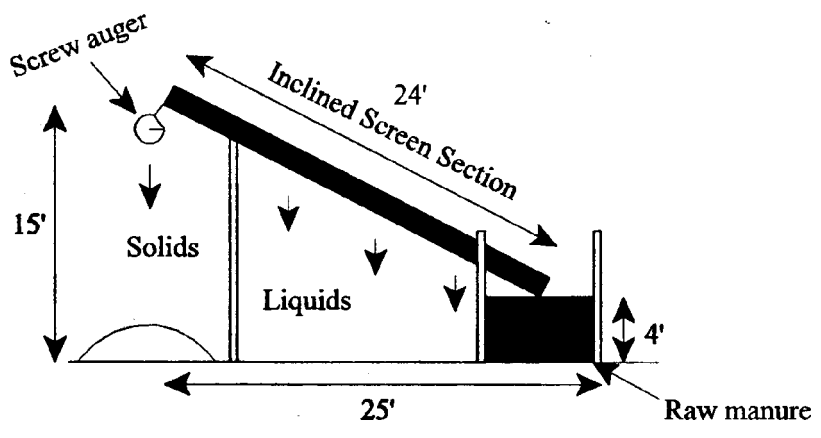
Figure 18. TR separator design (Jamieson et al., 2001)

6.60 Emerging Technologies Related to Solid-Liquid Separation

Two new technologies related to solid-liquid separation of livestock manure include the use of porous materials as filter media, and membrane filtration. Laboratory research has been conducted using five crop residues as filters to separate solids from liquid swine manure by Zhang and Lorimor (2000). Solids removal efficiencies and plugging characteristics were examined. A 250 mm diameter, 580 mm tall PVC cylinder was used in the study to hold the biofilter material. A bottom drain allowed collection of the filtered liquid. Prior to filtration, the selected biomaterial was packed into the separation cylinder with specific orientation, depth, and density.

For filtration, 3.78 L of swine manure was applied on top of the filter. As expected by these authors, the solids removal efficiencies were greater for manure with 6.0 % solids initially than for manure with 1.4 % solids, although plugging occurred sooner. These removal efficiencies also generally increased with increasing initial filter densities. Oat, straw, soybean stubble, and corn stover were found to be effective filter materials. Corncobs and ground cobs were not effective biofilters. In the best case, 180 L of 3.9 % TS swine manure was filtered/kg of oat straw.

Membrane filtration is another emerging solids-liquid separation technique. Pieters et al. (1999) developed a separation technique involving natural settling to separate the swine solids from the slurry, followed by sieving, micro-filtration, and reverse osmosis. The liquid fraction obtained by means of natural settling was processed through a 0.1 mm bag filter to prevent sand and other particles from damaging the membranes used in the following membrane filtration process. Micro-filtration was carried out using ceramic membranes that offered high chemical resistance, thus making them simple to clean. Reverse osmosis was chosen by these researchers because it resulted in a high-quality liquid fraction. The reverse osmosis led to the complete removal of dry matter, while the levels of the most important minerals were highly reduced. The micro-filtration unit utilized in this study was capable of processing 5 500 m^3 of raw sow slurry (the yearly production of about 1 100 sows). This separation technique produced a relatively clean liquid fraction which could be land-spread or possibly discharged to the public sewer system. These authors perceived that the economic feasibility of the system was highly dependent on the value of the concentrated fraction.

7.00 Alternatives to Mechanical Separation

Two alternatives to mechanical separation are sedimentation and chemical treatment of the livestock manure.

7.10 Sedimentation

Gravity settling, or sedimentation, involves a settling basin or pond. The inflow of manure to the basin is restricted to allow some of the solids to settle out. The larger, heavier solids settle out first. Floating or suspended solids, however will not settle out. The liquids and some of the solids gradually drain to a holding pond, treatment lagoon, or some other storage. The settled portion has a high moisture content and is handled as a thick slurry.

Pieters et al. (1999) found that natural settlement is a more economical and efficient separation technique for swine manure slurries with a dry matter content below 5 %. Sedimentation has been identified as effective for treating highly diluted manure or feedlot runoff consisting of less then 3 % TS. The separation efficiency (% removal of TS) of settling basins has been reported as high as 64 % for a concrete swine feedlot, and 39 to 75 % for an earthen beef feed lot (Mukhtar et al., 1999).

Settling basins were found superior on the basis of TSS and COD removal when tested against a liquid cyclone (hydrocylcone), vibrating screen, and a stationary inclined screen (Shutt et al., 1975). However, the final TS concentration was found to be less than the other devices and therefore not as effective in concentrating the solids. In comparison, Powers et al. (1995) found sedimentation had the potential to capture more of the solids from flushed manures than screening

(65 % of TS versus 24%). Burcham et al. (1997) evaluated an inclined stationary screen both in series with and against a gravity settling basin. Dairy manure from a research facility having a standard alley-flush type waste removal system and free stalls bedded with sand was used for testing. The gravity settling basin was capable of effectively removing sand from the waste stream. It proved to be more practical than the inclined stationary screen from a management and maintenance standpoint.

7.20   Chemical Treatment

Chemical treatment involves the addition of chemicals to alter the physical state of dissolved or suspended solids (DS or SS) and to facilitate their removal by physical separation processes. This form of treatment includes chemical precipitation, particle coagulation, and particle flocculation.

Chemical precipitation is the formation of an insoluble precipitate through the chemical reactions between the dissolved ions in wastewater, such as phosphate, and the metal ions added commonly: calcium (Ca^{+2}), iron (Fe^{2+} or Fe^{3+}), or aluminum (Al^{3+}). This process is most commonly used for the removal of dissolved phosphorous in the wastewater. Coagulation involves combining suspended (colloidal or dispersed) particles to form settleable flocs through the addition of electrolytes or organic polymers. Finally, flocculation combines coagulated particles into large rapidly settling particles, or flocs.

Some work has been done on the use of chemicals as separation aids although no standard method exits for testing in the field (Mukhtar et al., 1999). Treatment with polyacrylamide (PAM) polymers prior to mechanical removal or gravity settling has the potential for enhancing solid-liquid separation and increasing the capture and removal of fine suspended solids. PAM flocculants are high molecular weight, long chain, water soluble polymers capable of destabilizing suspended charged particles by adsorbing them and building bridges between several suspended particles resulting in flocs that settle out of the liquid. Vanotti and Hunt (1999) found TSS removal efficiencies greater than 90 % were obtained with PAM rates of 26 and 79 mg/L applied to samples containing 1.5 and 4.1 g/L TSS respectively.

The addition of alum (Aluminum Sulfate) was found effective at removing a significant portion of solids from liquid manure in a settling basin. The basin removed approximately 60 % of the solids present in the effluent and when amended with alum at 0.5 % volume, the separation efficiency increased to approximately 70% (Worley and Das, 2000). Zhang and Lei (1998) reported that the use of a metal salt together with a polymer considerably enhanced the phosphorous removal from manure and would potentially reduce the requirement of the polymer, thus lowering the cost of chemicals.

8.00 Conclusions

        The papers considered in this review of research on mechanical separation of livestock manure can be classified into six categories (as done in section 6.00). Nearly half of the papers (from sections 6.10 to 6.30 inclusive) were studies that evaluated either one or a group of separators with the primary objective of solids removal.

        In the appendix, a summary table (Table A1) provides the percent removal efficiencies of different chemical and physical parameters, the solids content of the fibre fraction, influent flow rates, manure types, and influent manure solids contents for the separators considered, grouped according to their generic type. Figure 19 shows the range of dry matter contents for the separated solids fraction achieved using the different mechanical separators. The ranges of values are given and take into account variations in flow rate, manure type, influent manure dilution, and screen pore size.
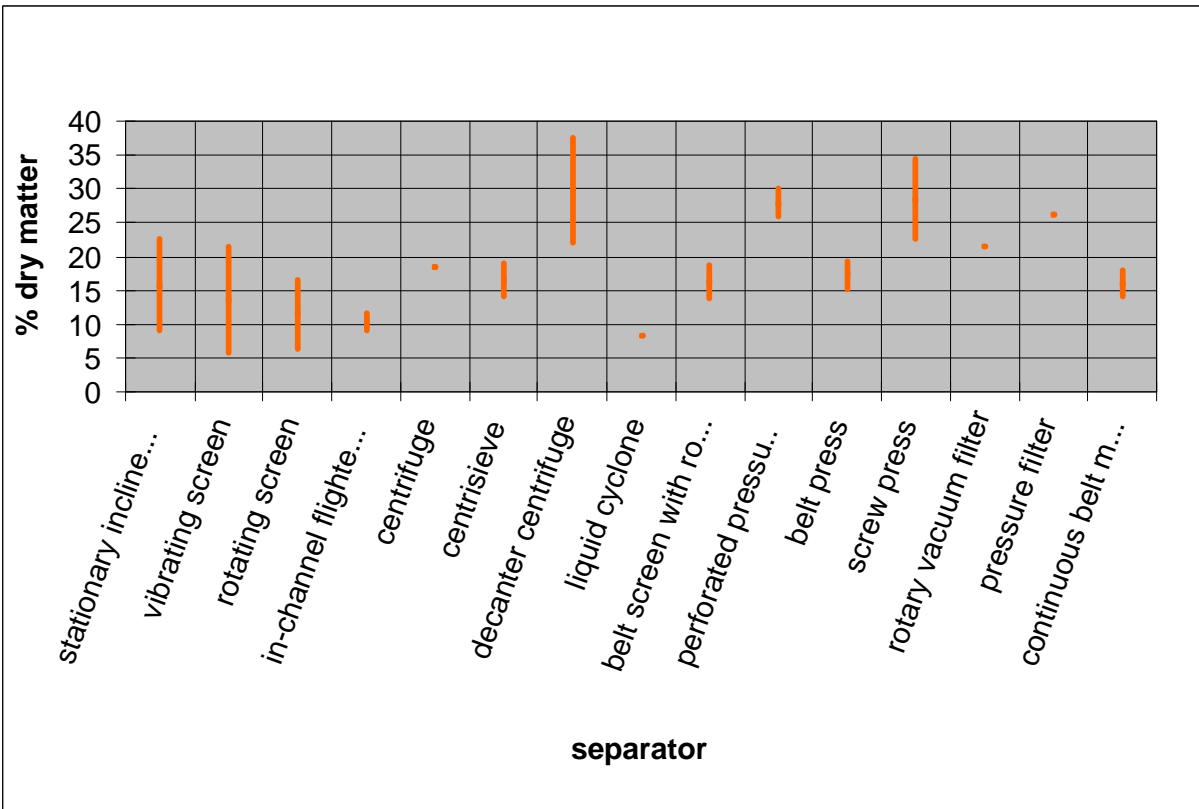

Figure 19. Dry matter contents of the separated solids fraction for the different separators considered in the various studies (over a range of different test conditions)

Specific findings of this review:

- Mechanical solid-liquid manure separators generally fall into three categories: screens, centrifuges, and presses and may include combinations of these.

- The most commonly used measures to evaluate a separator's performance in the past have been the separator throughput and the physical and chemical constituents of the separated fractions in relation to the raw manure.

- The shortfall of many studies has been their limited focus on certain constituents. Some parameters which should be considered more often by researchers evaluating a particular separator's performance include: particle size distribution, maintenance requirements, odour observations, energy consumption, and cost.

- The greatest single improvement to most separator test protocols would be the analysis of the particle size distribution of the raw manure and the separated liquid effluent. The profile of solids in the raw manure would allow for the selection of the most appropriate screen size. Comparison of the separated liquid and the unseparated manure would reveal the efficiency of a particular separator at removing solid particles within a specific range.

- It is important that researchers clearly state or derive how they calculated the separation efficiency. If a reader has difficulty understanding how a value was obtained for the separation efficiency, it would be impossible to reproduce these calculations in a future study.

- The measure of separation efficiency referred to as the "percent removal efficiency", is a commonly used indicator of separator performance and is simple to calculate. It provides useful information to a researcher testing a separator or to an individual determining the feasibility of a certain unit in their manure handling system. The second measure of separation efficiency which considers the concentrations of parameters in the separated solids fraction should also be used, regardless of the goal of the testing.

- Many studies have not reported or measured enough parameters to conduct a mass balance. The flow rate of the influent and liquid effluent streams should be reported, to make mass balance calculations possible.

- Chemical and physical analysis of constituents in the different separated streams and the raw manure have been highly variable. The top three reported parameters for the percent removal efficiency (the first form of separation efficiency) were TS, COD, and TP, respectively. The concentrations of these three constituents were measured both in the separated liquid and the raw manure. The top four reported concentrations of parameters in the separated solids fraction included TS, TP, TK, and VS, respectively.

- Great variability in the test conditions existed among the manure type and dilution, influent flow rate, operational parameters, and the length of testing. Because of this variability, it is very difficult to draw general conclusions about the performance of generic separator types.

- Sand bedding in free stall barns presents a challenge to the dairy industry since sand is very abrasive to mechanical manure system components, including separation units. Manure from free stall barns with sand bedding has been used in the testing of a stationary inclined screen. Other separator types, however, have not been tested with manure containing sand bedding.

- There is a misconception that phosphorus can be easily concentrated in the separated solids portion. In all but one of the studies reviewed, less than 30 % of the TP was removed into the solids fraction for swine and dairy manure of varying dilutions and influent flow rates.

Acknowledgments

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Glossary

aerobic / anaerobic conditions:
Aerobic conditions implies the presence of oxygen while anaerobic conditions implies little or no oxygen is present which may result in odour production.

ASTM screen mesh sizes:
The following table reports the specified ASTM [American Society for Testing and Materials] mesh screen size as an equivalent metric opening size. The mesh size value is a measure of the screen openings per inch.

Mesh size	Equivalent screen opening (μm)
5	4 000
10	2 000
20	841
60	250
100	149
120	125
200	74

"blinding" of a screen:
This phrase is used to describe the accumulation of solid particles on a screen used to separate the manure liquid and solids. The accumulation of these solids acts to help the screen retain additional solids.

coagulation:
A process of gathering solids that are suspended in a liquid into a mass to form particles that can settle.

dry matter (DM) content:
The amount of solids as a percentage of the overall mass of diluted manure. In this report, the term is used interchangeably with the total solids content.

effluent:
The separated or treated liquid stream exiting a manure handling system. Also referred to as the separated liquid stream or liquid fraction.

fineness modulus:
A parameter that represents the relative fineness of particles in screened or unscreened manure profiles.

flocculation:
A process that converts coagulated particles into large, rapidly settling masses, also called flocs.

gravity settling basin:
A tank or pit that relies on gravity to physically separate solids from the liquid manure.

influent:
The diluted raw manure entering a manure handling system prior to any treatment or separation.

membrane filtration:
Includes nanofiltration, ultrafiltration, and microfiltration. It has gained popularity in the wastewater treatment field and is now being used to remove solid particles from livestock manure.

microfiltration:
This process is used primarily for particle removal as a stand alone treatment or as a pre-treatment to advanced processes such as reverse osmosis. It has been demonstrated to be capable of removing protozoan cysts to below detection limits as well as meeting turbidity requirements of surface water treatment regulations.

moisture content:
The amount of liquid present as a percentage of the overall mass of diluted manure (opposite to the dry matter content).

nitrogen:
Ammonia-N exits in the gas phase while ammonium-N exists in the aqueous phase, although ammonium nitrogen (NH_4-N) is often reported as ammonia-N (NH_3-N).

operational parameters:
The addition or arrangement of a physical aspect on a separator such as a counterweight on a vibrating screen separator which will alter the performance of the separator.

organic / inorganic matter:
Organic matter refers to living material that eventually decomposes while inorganic matter refers to non-living matter.

regression equations:
Equations developed by applying statistical analysis to experimental data to generate linear relationships among variables.

reverse osmosis:
In this process which very often follows membrane filtration, water is the only material passing through the membrane. Essentially all dissolved and suspended material is rejected.

separation efficiency:
A measure of a mechanical separator's performance usually indicated as a percent where a 100 % rating indicates an optimal efficiency. This measure can be reported or calculated in one of four ways as discussed in section 5.00.

solid fraction:
The fibre or concentrated portion also referred to as the separated solids.

uniformity index:
An index that indicates the distribution of coarse, medium, and fine particles in a particular manure sample. For example, a uniformity index of 2-4-4 reflects the distribution of coarse, medium and fine particle in a profile of screened or unscreened manures.

Appendix

Table A1. Summary table of calculated and reported parameters for the separators included in the literature review

Sources: (not including sources from sections 6.50 or 6.60)

A: (Shutt et al., 1975), B: (Hegg et al., 1981), C: (Chastain et al., 2001), D: (Gilbertson and Nienaber, 1978), E: (Holmberg et al., 1983), F: (Møller et al., 2000), G: (Chiumenti et al., 1987), H: (Glerum et al., 1971), I: (Sneath et al., 1988), J: (Pos et al., 1984), K: (Rorick et al., 1984), L: (Chastain et al., 1988), M: (Converse et al., 1999), N: (Converse et al., 2000) and O: (Fernandes et al., 1988)

Separator Type	Manure Type	Screen size (mm)	Influent % DM	flow rate (L/min)	TS	TSS	VS	NH_3-N	Organic-N	TKN	TN	TP	BOD_5	COD	Solids Fraction % DM	Ref.
Stationary Inclined Screen	Swine	1.0	0.2-0.7	123	35.2									69.1	9.1	A
	Beef	0.5	0.97-4.41	–	1-13									–	13.3-22.5	B
	Dairy	1.5	3.83	–	60.9	62.6	62.8	45.7	52.2	49.2				66.5	20.3	C
Vibrating Screen	Swine	0.39	0.2-0.7	67	22.2		28.1							16.1	16.4	A
	Beef	0.52-1.91	5.5-7.4	42-118	4-44									0-7	14.7-21.6	D
	Beef	0.635-1.574	1.55-3.19	–	6-16									3-12	14.8-16.4	B
	Dairy	0.635-1.574	0.95-1.90	–	8-16									1-24	5.7-14.8	B
	Swine	0.635-1.574	1.55-2.88	–	3-27									–	16.9-20.9	B
	Swine	0.104-2.449	1.5-5.4	37.5-150	11-67		14-70	3-47		2-51		2-59		2-59	2.4-18.1	E
Rotating Screen	Beef	0.750	1.56-3.68	163-946	4-6									11-16	9.5-12.4	B
	Dairy	0.750	0.52-2.95	80-908	0-14									3-5	6.4-11.0	B
	Swine	0.750	2.54-4.12	80-307	4-8									9-16	15.6-16.6	B

Separation Efficiency reported as a Percent Removal Efficiency (%)

					Separation Efficiency reported as a Percent Removal Efficiency (%)											
Separator Type	Manure Type	Screen size (mm)	Influent % DM	flow rate (L/min)	TS	TSS	VS	NH$_3$-N	Organic c-N	TKN	TN	TP	BOD$_5$	COD	Solids Fraction % DM	Ref.
In-Channel Flighted Conveyor Screen	Dairy	3	7.10	–	4.22										9.2	F
	Swine	3	5.66	–	25.8										11.7	F
Centrifuge	Beef	–	7.5	40.8	25									35	18.4	H
Centrisieve	Swine	–	5-8	133-150	30-40								0	28	14-19	H
Decanter Centrifuges	Beef	–	6.9	13.2	64									72	22.1	G
	Beef	–	6.0	30	45									56	26.1	G
	Swine	–	7.58	10	66								18	52	37.4	H
	Swine	–	1.9	–	47.4										29.0-31.0	I
		–	8.0	–	56.2										25.9	I
Liquid Cyclone*	Swine	–	–	88	26.5	38.8	5.8								8.4	A
Brushed Screen / Roller Press	Swine	–	5.2	–	17.3										18.7	J
	Dairy	–	4.8	–	25.0										13.9	J
	Beef	–	4.5	–	13.3										17.1	J
Perforated Pressure Roller	Dairy	–	4.5	364											26	K
			6.7	324											27	K
			9.9	254											30	K
Belt Press	Dairy	1-2	7.1	–	32.4										15.3	F
	Swine	1-2	5.66	–	22.3										19.2	F

					Separation Efficiency reported as a Percent Removal Efficiency (%)											
Separator Type	Manure Type	Screen size (mm)	Influent % DM	flow rate (L/min)	TS	TSS	VS	NH$_3$-N	Organic-N	TKN	TN	TP	BOD$_5$	COD	Solids Fraction % DM	Ref.
Screw Press	Swine	–	5	180-662	15.8		20		15.8	12		15.8			22.6-34.4	L
	Swine	–	1.0-5.0	–	15-29.7							3.0-4.8			23.5-34.5	M
	Dairy	–	1.0-10.1	–	15.8-47							8.6-28.9			26.3-33.9	M
	Dairy	–	2.64	1 456	23.79						4.2				26.0	N
	Dairy	–	4.89	323	33.41						0.4				28.9	N
Rotary Vacuum Filter	Swine	–	7.54	4.2	51										21.5	H
Pressure Filter	Beef	–	7.1	35	76.0										26.1	G
Continuous Belt Micro-screening unit	Swine	–	2-8	10-35	40-60					<35		<21		<40	14-18	O

* manure was pumped over a stationary inclined screen with 1.0 mm openings prior to separation with the liquid cyclone