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Review article

Solid–liquid separation of animal slurry in theory and practice. A review

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Abstract – Animal slurry contains plant nutrients that are essential for crop production. However, intensive livestock production may lead to a surplus of plant nutrients on farms and, as a consequence, discharge or emission to the environment. In order to ensure that the slurry applied to fields matches the nutrient requirements of the crops, techniques have been developed to reduce the nutrient content of slurry by means of separation. This review discusses the separation technologies used for animal slurry treatment and the physical and chemical processes involved in separation. These processes need to be understood before efficient, reliable and cheap separation technologies that take into account the actual properties of slurry and the likely end-use of the separation products can be developed. A simple separation efficiency expression can be used to assess the efficiency of slurry separation. It is indeed important to measure the amount and composition of the slurry before treatment, the dry-matter-rich fraction and the liquid fraction. The separation efficiency of mechanical separators for the removal of dry matter and phosphorus (P) is ranked as follows: centrifugation > sedimentation > non-pressurized filtration > pressurized filtration. In general, the separation of total N and NH_4^+ follows the same pattern, but the separation efficiency is lower than for dry matter and P. Treatment with a flocculant before separation improves separation efficiency significantly. Of the polyacrylamide polymers tested, high-molecular-weight, linear cationic polymers with a medium charge density (20–40 mol%) were found to be the most efficient flocculants. The best mechanical separation techniques for flocculated slurry are screens or filter belts. The separation efficiency of polyacrylamide-treated slurry can be improved by adding a multivalent ion to coagulate particles and for precipitation of phosphorus. Aluminium sulfate ($Al_2(SO_4)_3$) or ferric chloride ($FeCl_3$) seem to be very efficient for improving the mechanical separators. Alternatively, the mineral struvite ($MgNH_4PO_4$) may be formed by changing the slurry characteristics, such as by the addition of magnesium (Mg) or by increasing the pH to 9. The struvite crystals are removed during solid–liquid separation. The products of the solid–liquid separation may be further treated by evaporation, membrane filtration or ammonia stripping in order to obtain the desired end-products; however, low-maintenance and/or cost-efficient operation of these post-treatments has not yet been demonstrated. The separation should be developed as a whole-system approach, paying attention to parameters such as the value of end-products, environmental consequences and economy.

Key words: manure / phosphorus / nitrogen / sedimentation / centrifugation / filtration / coagulation / flocculation / struvite

Contents

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1. INTRODUCTION

Livestock production increased towards the end of the 20th century and, due to increasing demand in developing countries, production is expected to increase further in Asia and South America (FAOSTAT, 2006). Globally, the intensification of agricultural systems increases the environmental impact of food production, as high concentrations of livestock increase the risk that organic waste nutrients are used for crop production in excess of crop requirements.

This section briefly discusses current problems related to discharge and the unsustainable use of slurry, with a focus on how to optimize separation as a sustainable and cost-effective treatment option for animal slurry.

Livestock slurry contains phosphorus (P) and potassium (K), which have fertilizer values equivalent to those of mineral fertilizers, while its nitrogen (N) content has a lower and more variable fertilizer value than that of commercial fertilizers. If applied at a rate higher than plant uptake, there is a great risk of nutrient leaching and runoff that will pollute surface- and groundwater (Burton and Turner, 2003). This leads to an increased need for water purification to provide safe drinking water supplies. Slurry is also harmful to the environment when discharged directly into receiving waters (Rattanarajcharkul et al., 2001; Steinfeld et al., 2006; Petersen et al., 2007; Vu et al., 2007). Negative effects from heavy applications of slurry may include salinization in semi-arid regions, toxic concentrations of heavy metals, and decreased soil aeration (Bernal et al., 1992, 1993). Larger production units may result in higher local emissions of odor and ammonia gas from housing and stores. Intensive livestock production may also lead to higher energy use for the transport of livestock wastes to be recycled in crop production elsewhere (Sørensen et al., 2003; Sørensen and Møller, 2006), and the risk of spreading disease among livestock will increase.

Until recently, European farmers have tried to minimize the environmental problems caused by slurry management through recycling on farm. It has been recognized that livestock slurry represents a valuable resource that, if used appropriately with minimal loss, can replace significant amounts of mineral fertilizers (Bouwman and Booij, 1998; Le, 1998). However, an increasing number of large, intensive livestock production units with insufficient area for the sustainable recycling of slurry nutrients have emerged in recent years. This specialization in livestock production tends to weaken the link between livestock and plant production and increases the farm's impact on the environment. To facilitate the recycling of slurry produced on these farms, there is a need to transport the slurry to farms specializing in crop cultivation. The cost of transporting slurry may be reduced, and its fertilizer value increased, by separating the slurry into (1) a liquid fraction intended for on-farm use, and (2) a dry-matter- and nutrient-rich fraction that can be exported to farms with few or no animals (Møller et al., 2000; Sørensen et al., 2003). Separation may also contribute to a reduction in odor emission (Zhang and Westerman, 1997) and assist in producing energy-rich biomass that can be used for incineration or biogas production (Møller et al., 2007a; Hjorth et al., 2009).

In Asia, slurry from pig farms is often separated in-house on small- to medium-sized farms by manual scraping, while on large farms the solid fraction is separated from the liquid fraction by filter separators or decanter centrifuges (Ong, 2002; Vu et al., 2007). The liquid fraction is transferred to fish ponds, where it fertilizes aquatic plants that are eaten by herbivorous fish (Vu et al., 2007). The solid slurry produced by pigs and cattle that is scraped off the floor is composted, and an organic fertilizer is produced that is sold to vegetable and fruit producers as a highly valued product for soil amelioration.

In Europe and North America, the solid fraction is often not considered to have much value and slurry processing is therefore considered as an additional cost of livestock production (Petersen et al., 2007). Thus, the challenge is to reduce the cost and improve the efficiency of the processes while adding value to the separation products – especially the solid fraction, which has a high energy and P content. In this context, it is important to understand that slurry management consists of several interrelated operations carried out from the time the slurry is removed from the animal house until it is used for bioenergy production and to fertilize crops. Therefore, a whole-system approach should be considered when developing the technology for optimizing the recycling of plant nutrients in livestock production and optimizing green energy production using livestock slurry (Petersen et al., 2007).

It should be borne in mind that the separation of animal slurry may create new problems; for example, a change in the ratio of plant nutrients to heavy metals in the biomass. A recent study showed that solid–liquid separation with flocculation as a pre-treatment transferred zinc (Zn), copper (Cu) and cadmium (Cd) to the solid fraction (Møller et al., 2007b). The additives used when optimizing the separation of slurry (e.g. polymers and Al) may also pose an environmental problem (Nahm, 2005; Schechter et al., 1995).

Overall, slurry separation and recycling of organic matter and plant nutrients can mitigate the environmental hazards described above, since it will contribute to the optimization of crop fertilization, thereby reducing the need for external supplies of N, P, K and micronutrients.

An effective separation system can only be designed if the following three points are taken into account:

1. the chemical and physical properties of the slurry;
2. the desired end-products;
3. the potential separation techniques, including pre- and post-treatments and combinations of different techniques.

Knowledge of these variables will provide the information needed to produce separation products that can be used efficiently in crop production. Desirable separation products would, for instance, comprise a liquid fraction containing N, P and K at a ratio equivalent to the plant demand, and a solid fraction with high P, a relatively high N content (including organic N), and a high content of *DM*, which could be used as a carbon source for energy production (Hjorth et al., 2009).

A thorough understanding of the physical and chemical processes involved in the separation of slurry is required in order to develop reliable, efficient and cheap separation technologies, taking into account the actual slurry properties and the end-use of the separation products. This review aims to present a characterization of animal slurry relevant for slurry separation, and to describe concepts of separation optimized to treat slurry with the specified characteristics. The review includes the presentation of separation techniques, including the use of additives as pre-treatments.

2. SLURRY PRODUCTION

The management of slurry will affect its physical and chemical characteristics. Animal housing may be designed so that both solid and liquid slurry are produced. Alternatively, some animal houses are designed that have slatted floors with cellars or channels beneath. Below the slats, a slurry consisting of a mixture of feces and urine, strewing material, and spilt feed and water is collected.

The range of animal housing design and methods of slurry collection, storage and handling reflect the large differences in climate and production objectives throughout the world. Slurry management systems have been developed in order to reduce the manual labor required. The animal slurry in these systems is mainly stored and transported from animal houses via deep pit, pull plug, pit recharge and flushing systems (Menzi, 2002; Arogo et al., 2003). There is little or no seasonal variation in untreated slurry composition (Petersen and Kjellerup 1990; Conn et al., 2007), which reflects the fact that the diets given to the animals and the slurry management normally do not vary significantly throughout the year. With respect to the separation of animal slurry, the slurry removal system and method of storage is important because the physical and chemical characteristics of the slurry will change due to microbial transformation processes during storage (Hindrichsen et al., 2006). Slurry characteristics may also be changed by introducing additives or changes in feed, as these changes will be reflected in slurry composition (Otto et al., 2003). The composition of the slurry also varies significantly with depth in the slurry store due to sedimentation and surface crust formation (Burton and Turner, 2003).

Separation of urine and feces may be carried out in the animal house. In cattle houses with tethered cattle, the manure may be separated into solid and liquid fractions by collecting the solids from the floor behind the animals while the liquid is drained through gutters. In these houses, the collected solid manure mainly contains feces and straw and the liquid slurry contains a mixture of water, urine and soluble fecal components (Sommer and Hutchings, 2001; Sommer et al., 2007). In modern pig houses, the animals move freely on slatted floors, and therefore in-house separation of the slurry needs to be carried out below the slatted floor (Kroodsma, 1986; Lachance et al., 2004). However, farmers are still reluctant to install this technology because of problems related to equipment maintenance; instead, the separation of mixed urine and feces, i.e. slurry, will be the focus of this review.

3. NITROGEN AND PHOSPHORUS TRANSFORMATION DURING STORAGE

The distribution of nitrogen (N) and phosphorus (P) between the solid and liquid slurry fractions is affected by the microbial transformation of organic matter that takes place during storage before slurry separation. As shown in Section 4, the N and P are distributed between a solid phase (particles) and a liquid phase, and this distribution is affected by excretion and storage.

3.1. Nitrogen

In livestock farming, usually not more than 5–45% of the nitrogen (N) in plant protein is transformed into animal protein, depending on the type of animal and livestock management (Oenema et al., 2001). The remaining 55–95% is excreted via urine and dung as organically bound N. Following deposition on the floor of the animal house or in pastures, a major fraction of the organic N is rapidly hydrolyzed into ammonium (NH_4^+) by the enzyme urinase, which is present in the feces (Sommer et al., 2006).

Immobilization of inorganic N into organically bound N is a microbial process, which depends on the C:N ratio in the degradable organic compounds. Slurry mixtures have C:N ratios in a range between 4 for pig slurries and 10 for cattle slurries (Chadwick et al., 2000). In general, there is no immobilization of N in slurry mixtures, because the C:N ratio of the easily degradable compounds is low (<15) (Kirchmann and Witter, 1989; Thomsen, 2000). During in-house storage, most of the digestible compounds containing N are transformed, and about 10% of the organic N is mineralized (Zhang and Day, 1996; Sørensen, 1998). During outdoor storage of slurry, little N is mineralized and it is assumed that about 5% of the organic N is transformed into inorganic N during the course of 6–9 months' storage (Poulsen et al., 2001).

Approximately 70% of the N in slurry is dissolved and most of the dissolved N is present as NH_4^+ (Christensen et al., 2009). The NH_4^+ in slurry, as well as in the liquid and solid separation fractions, may be lost due to volatilization as NH_3 (pKa = 9.25) or after microbial transformation as nitrous oxide or N_2 (Hansen et al., 2006). Thus, the total loss of gaseous N from animal housing and slurry storage ranges from about 10% of the excreted N in dung and urine from dairy cattle to >30% for pigs and poultry in intensive livestock operations (Oenema et al., 2001).

3.2. Phosphorus

Phosphorus is fed to the animals via plants, but also as additives in the form of inorganic phosphate. Cattle are able to utilize P very efficiently and only the plant P that is not mobilized and adsorbed in the digestive system is excreted. Most of this P is excreted in feces and very little in urine (Meyer et al., 2007). Higher amounts of dietary P may lead to higher P excretion in feces (Dou et al., 2003; Chapuis-Lardy et al., 2004).

The digestive system of pigs is not as efficient as that of cattle in absorbing P in feed, and pigs excrete about 50–60% of their P intake in feces and urine. Surplus P intake is excreted in urine. The enzyme phytase is added to pig feed to improve P uptake. Phytase degrades the organic P compound phytate and makes the P more easily available; consequently, the inorganic P supplement can be reduced and P excretion reduced significantly, i.e. by >20% (Pfeiffer, 1995; Han et al., 2001; Sommer et al., 2008). This reduction mostly affects the amount of P in urine (Poulsen, 2000) and is affected by P digestibility, the amount of feed in relation to the requirements of the pig, and the age and category of animal. Production systems will also affect P excretion; for instance, changing the group size of fattening pigs may increase welfare and reduce P excretion. In contrast, group housing of sows and the addition of straw may increase P excretion (Krieter, 2002).

In slurry >80% of the dissolved P is orthophosphate. The orthophosphate fraction may vary during storage, i.e. increase immediately after excretion and reach a maximum, and thereafter it will decrease slightly (Christensen et al., 2009).

4. PHYSICAL AND CHEMICAL CHARACTERIZATION OF SLURRY

Animal slurry from housing is a mixture of feces and urine, bedding material (e.g. straw, wood shavings, sawdust, sphagnum), spilt feed and drinking water, and water used for washing floors. Factors of importance for optimizing the efficiency of slurry separation include particle size, concentration of organic and inorganic components, pH and buffer systems of the slurry. The physical and electrochemical properties of the particles are also important for separation.

Water use will vary due to differences in animal housing systems and management; therefore, due to the amount of dilution, the composition of the animal slurry will vary. In pig slurry, in particular, the concentration of the components varies due to variations in use of water, for instance, because more water is used in sow than in pig houses (Conn et al., 2007), and because a large amount of water is used in Asian pig production to cool the pigs and to clean solid floors (Taiganides, 1992; Sommer et al., 2005). Thus, in slurry from finishing pig houses, the total N, P and K concentrations may be 2.3, 2.5 and 1.7 times greater, respectively, than in sow slurry (Conn et al., 2007). Also, the average *DM* content in slurry from finishing pigs is six times greater in European slurry than in Asian slurry (Sommer et al., 2005).

4.1. Particle size

Particle size distribution in the slurry is important for separation; for example, filtration will only retain particles above a certain size, and during sedimentation particles in the range between 1 nm and 1 μm (i.e. colloids) are subject to Brownian motion and move by diffusion in the liquid, and therefore settle very slowly or not at all.

The amount of *DM* in the particle size fraction below 0.025 mm is greater in pig slurry than in cattle slurry; 66–70% and 50–55% in pig and cattle slurry, respectively (Møller et al., 2002; Sommer et al., 2008). Feed composition may affect particle size distribution; for instance, the proportion of *DM* in the particle size fraction >1 mm was lower in slurry from cows fed only roughage compared with slurry from cows whose diet was supplemented with concentrates (Nørgaard, 2006; Sommer et al., 2008). The effects of diet and category of animal are also reflected in the variation in total solids found in the <0.125 mm category of fresh feces from cattle, being 50%, 41% and 44% (±1.4) for lactating cows, heifers and calves, respectively (Meyer et al., 2007).

Microbial transformation of the organic pool (see Sect. 3) will change the particle size distribution. The amount of organic matter in slurry decreases due to microbial transformation into CH_4 and CO_2 during anaerobic storage. The *DM* content may decrease by 25% during 5 months of storage at 20 °C (Møller et al., 2002). At low storage temperatures, anaerobic transformation of organic material – and therefore *DM* reduction – will be significantly lower (Christensen et al., 2009), i.e. about 10 times lower at 10 °C than the reduction at 20 °C (Sommer et al., 2006).

Anaerobic digestion reduces the *DM* concentration of animal slurry, and changes the particle size distribution. It has been observed that particles <10 μm account for 64% of *DM* in raw slurry, while it increases to 84% of *DM* in anaerobically digested slurry (Massé et al., 2005). In contrast, the concentration of particles <1.6 μm is reduced most during anaerobic storage in slurry stores (Møller et al., 2002). In anaerobic digesters, stirring and high temperatures facilitate microbial degradation of large particles, leaving relatively small particles with slowly degradable material. In a cold unstirred slurry, the slow transformation of particles primarily degrades small particles, transforming only a minor fraction of the large particulate material.

In cattle slurry >80% of N and P is in the particle fraction below 0.125 mm (Meyer et al., 2007), and a very detailed analysis of particle size fractions showed that in slurry more than about 70% of the undissolved N and P was in the particle size fraction 0.45–250 μm (Massé et al., 2005). Because approximately 30% and 80% of N and P, respectively, is contained in particles (see Sect. 3), the small particles contain a large percentage of the total P in slurry. The addition of phytase to the diet of pigs or supplementing the diet of dairy cows with concentrates does not affect the distribution of total P in the different particle size fractions (Sommer et al., 2007).

4.2. Organic components

The composition of the organic components may affect separation, as charge and pH will influence flocculation and also the cation absorption on and charge neutralization of the particles being separated from the liquid. Animal slurry contains short-chain volatile fatty acids (VFA) with 1–5 atoms of carbon, organic lipids, proteins, carbohydrates and lignin, which also contains non-carbohydrate organic components such as phenols (Møller et al., 2004; Massé et al., 2005; Christensen et al., 2009). Carbohydrates comprise the largest fraction of the organic material, followed by proteins, lipids, lignin and VFA. The organic components in slurry include compounds with the functional groups carboxylates, hydroxyls, sulfur hydryls and phenols (Massé et al., 2005) which, at the pH interval in slurry, will contribute to a negative charge of both dissolved and particulate organic matter.

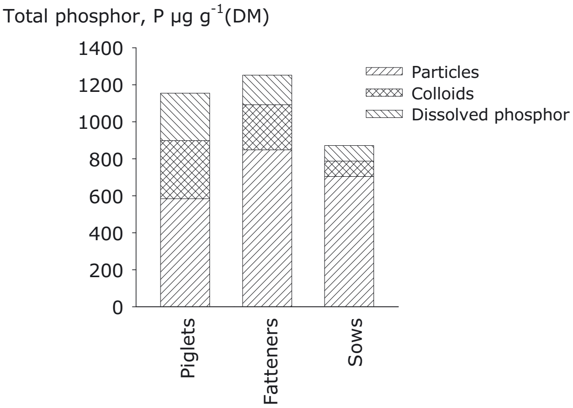

Figure 1. Distribution of phosphorus between the particles, colloids and dissolved fraction of pig slurry (adapted from Christensen et al., 2009).

Most of the P in animal slurry is in the particle fraction of slurry, and >30% is dissolved in the liquid phase (Fig. 1). One study showed that organic P in solution only constitutes about 5% of the P in slurry (Fordham and Schwertmann, 1977a). The remaining P is mainly associated with the particle fraction, where it may be bound inorganically in crystalline form or is adsorbed onto particles.

4.3. Inorganic components

The separation efficiency of different technologies is greatly affected by the slurry composition; for instance, large minerals will end up in the solid fraction. In addition, electrical conductivity will affect flocculation, and the relative concentration of cations will affect crystallization of compounds such as struvite.

The composition of ions in animal slurry varies significantly among slurry from different animals and is affected by the diets fed to the animals and slurry management (Tab. I). Electrical conductivity depends on the concentration and species of ions in solution and varies from 0.008 to 0.026 S cm^{-1} (Sommer and Husted, 1995a; Christensen et al., 2009). Cattle slurry contains more sodium, potassium and calcium than pig slurry (i.e. 2–3 times more) due to an intake of roughage having a high content of these cations (Sommer and Husted, 1995a; Massé et al., 2007a). In cattle slurry, the content of these ions varies twofold due to variation in diets (Chapuis-Lardy et al., 2004).

Table I. Variability in the composition of animal slurries from one site and between slurries from different sites. DM: dry matter. TAN: total ammoniacal nitrogen.

Slurry origin		Component content (g/kg slurry)									Reference
		DM	Total-P	Total-N	TAN	K	Ca	Mg	Cu	Zn	
Sows	Mean	23	0.8	3.2	2.0	2.0	0.7	0.2	0.0		Møller et al., 2007a; Conn et al., 2007
	Standard deviation	(15)	(0.2)	(0.9)	(0.7)	(0.3)	(0.4)	(0.1)			
Finishing pigs	Mean	67	2.1	7.5	4.5	3.3	2.1	0.9	0.0	0.1	Conn et al., 2007; Ye et al., 2005; Massé et al., 2005; Møller et al., 2004, 2007a; Saeys et al., 2005; Sommer and Husted, 1995a; Sommer et al., 2008
	Standard deviation	(26)	(0.8)	(2.5)	(2.1)	(1.1)	(0.9)	0.4	0.0	(0.1)	
Dairy cows	Mean	82	1.0	3.7	5.0	4.3	1.6	0.6	0.0		Amon et al., 2006; Clemens et al., 2006; Møller et al., 2007a; Sommer and Husted, 1995a; Sommer et al., 2008
	Standard deviation	(24)	(0.2)	(1.7)	(9.3)	(1.8)					

The distribution of P between the solid and liquid phases is affected by pH, with more P being dissolved at a decreased pH. The distribution is almost constant down to pH = 6.5, whereas the concentration of dissolved P increases by a factor of 5 when pH is lowered from 6.5 to 5.5; mainly due to dissolution of struvite (Christensen et al., 2009). In slurry, P may be crystallized as struvite ($MgNH_4PO_4 \times 6H_2O$) and different forms of calcium phosphates (Fordham and Schwertmann, 1977b, c), i.e. calcium dihydrogen phosphate $Ca(H_2PO_4)_2$, calcium hydrogen phosphate $CaHPO_4$ and tricalcium phosphate $Ca_3(PO_4)_2$. The forms of phosphate will be affected by the pH of the slurry (Eq. (1)).

$$Ca_3(PO_4)_2 + 2H_2SO_4 + 4H_2O \leftrightarrow 2CaSO_4 \cdot 2H_2O + Ca(H_2PO_4)_2 \cdot 2H_2O \quad (1)$$

Studies suggest that, in slurry, phosphate can crystallize as struvite (Fordham and Schwertmann, 1977b, c; Bril and Salomons, 1990; Sommer and Husted, 1995a; Gungor and Karthikeyan, 2005). Ammonium is present in large excess for struvite formation, thus crystallization is mainly controlled by magnesium concentration and pH.

An increase in the amount of iron (Fe^{3+}) dissolved in the slurry will reduce pH; for example, if the Fe^{3+} precipitates as crystalline iron phosphate.

$$Fe^{3+} + H_3PO_4^{n-3} \leftrightarrow FePO_4(s) + nH^+ \quad (2)$$

Precipitation of calcite ($CaCO_3$) is mainly controlled by the concentration of calcium (Ca^{2+}), because carbonate (CO_3^{2-}) is present in large excess in slurry. Slurry pH is reduced significantly by adding Ca^{2+}, thereby precipitating CO_3^{2-} and producing the crystal calcite (Witter and Kirchmann, 1989; Husted et al., 1991).

$$Ca^{2+} + HCO_3^- + H^+ \rightleftarrows CaCO_3(s) + 2H^+ \quad (3)$$

Part of the inorganic P may precipitate as calcium phosphate, or it may absorb to $CaCO_3$ (Fordham and Schwertmann, 1977a, b).

Most K^+ and NH_4^+ salts are very soluble, and struvite (see Sect. 6.2) is the only crystal that in practice contributes to settling or separation of ammonium (Bril and Salomons, 1990). Thus, most K^+ and NH_4^+ is dissolved in the liquid phase (Masse et al., 2005).

4.4. pH buffer systems

When considering which process or technology is optimal for the separation of slurry, the pH needs to be known, since struvite precipitation is greatly affected by pH, as is the precipitation of P and ammonia stripping. It has been shown that the main buffer components in animal slurry controlling $[H^+]$ are total inorganic carbon ($TIC = CO_2 + HCO_3^- + H_2CO_3$), total ammoniacal nitrogen ($TAN = NH_3 + NH_4^+$) and volatile fatty acids ($VFA = C_2$–C_5 acids) (Angelidaki et al., 1993; Sommer and Husted, 1995a, b; Vavilin et al., 1998). In stored slurry, the concentration of TIC may be larger than those of TAN and VFA; so this component is therefore of major importance in controlling slurry pH (Japenga and Harmsen, 1990; Sommer and Husted, 1995b). In addition to inorganic buffers, negatively charged particles in the slurry will contribute to acid groups with pKa values from 5 to 9 (Christensen et al., 2009).

A number of processes will affect the pH of slurry; the emission of CO_2 and NH_3 is particularly important because emission of CO_2 will increase pH, and emission of NH_3 will reduce pH. Oxic degradation of organic material reduces the content of acids in solution and thereby increases pH. In contrast, anoxic processes will contribute to the formation of organic acids (e.g. $VFA = C_1$–C_5) and thereby reduce pH. In an anoxic environment, the content of organic acids may be reduced by methanogenic microorganisms by transformation into CH_4 and CO_2 which, in contrast, will increase pH.

Diet and feeding practices may affect the concentration of ionic species in the slurry and the pH, because the electric charge of the solution has to be neutral. At present, soya beans in the diet supply most of the crude proteins needed by pigs. As soya contains high concentrations of K^+, this will, when excreted, increase the pH of urine and slurry. Reducing the soya concentration in the diet and supplementing with amino acids will reduce the K^+ concentration and, because of the charge balance, the concentration of H^+ will increase (Sommer and Husted, 1995b). Thus, for pig urine and slurry, and for cattle urine, it has been shown that pH declines when cationic species in the feed are reduced; for pig slurry, a reduction of more than 1 pH unit has been observed within the range of traditional diets with and without the addition of amino acids and the reduction of soya (Canh et al., 1998; Portejoie et al., 2004).

The addition of multivalent ions (e.g. $FeCl_3$ or $Al_2(SO_4)_3$) or cations precipitating carbonate ions ($Ca(OH)_2$) will also affect slurry pH, as indicated in Section 4.3 (Husted et al., 1991; Henze et al., 1997; Estevez Rodríguez et al., 2005).

4.5. Electrochemical properties

Particle charge and ionic strength, which affect the electrical potential around the particles, are of vital importance for the efficient use of flocculants.

Organic particles often have a negative surface charge and the particles will therefore repel each other (Gregory, 1989). It has been shown that, in pig slurry, the particle charge density is –0.18 meq g^{-1} organic solids (Christensen et al., 2009). Furthermore, due to their negative charge, organic particles contribute to the alkalinity of the slurry. The concentration of ions expressed as ionic strength has been shown to be high in most animal slurry studies, i.e. conductivity >10 mS cm^{-1} (Sommer and Husted, 1995b; Christensen et al., 2009). An increasing ionic strength of the liquid will affect processes such as flocculation due to a reduced electrostatic repulsion. Furthermore, at high ionic strength, a linear polymer will change to a more sphere-shaped form, which will lower the efficiency of the polymer (Gregory, 1973, 1989).

The negative charge of organic particles in animal slurry affects the distribution of the ions in solution by adsorbing cations close to the particles (Stern layer), with the remaining counter-ions being distributed in the diffusive layer, which also contains anions. These two layers of ions are referred to as the 'double layer'. It is assumed that the interaction between charged particles is visualized as the overlap of diffusive layers of particles. Therefore, the electrical potential of interest, when considering interactions between two particles, is the potential at the boundary between the Stern and the diffusive layers, which is assumed to be equal to the electrokinetic or zeta potential (ζ, mV; Lyklema, 1977). The effect of the particle charge density will be affected by the extent of the diffusive layer, which decreases with increasing ionic strength. The influence of the particle charge density is therefore expected to be low in slurry with a high ionic strength.

4.6. Physical properties

The density and viscosity of slurry has been correlated to the dry matter (DM) content. Landry et al. (2004) give a thorough review in connection with their own work on concentrated slurry. Their conclusion is that, for a DM between 0 and 50%, the density can be described by the following equations:

Dairy cattle:

$$\rho = 1000 + 14.6 \cdot DM - 2.38 \cdot DM^2 + 0.0367 \cdot DM^3 \tag{4}$$

$$\text{Pig:} \quad \rho = 1000 - 11.2 \cdot DM + 1.19 \cdot DM^2 - 0.0235 \cdot DM^2 \tag{5}$$

where ρ is the density (kg m^{-3}) and DM is dry matter in % (w/w). As seen from the equations, dairy cattle slurry has a lower density and pig slurry a higher density at the same DM content. The flow properties for slurry have, in general, been found to be non-Newtonian at values of DM above 5%, while at lower DM values the slurry behaves as a Newtonian liquid (Landry et al., 2004). In general, animal slurry with a higher DM content shows pseudoplastic behavior, but for simple flow considerations an apparent viscosity will often suffice. Landry et al. (2004) correlated their viscosity data, measured for a DM between 9% and 14% at 20 °C, as follows:

$$\text{Dairy cattle:} \quad \mu_{slurry} = 4.10^{-5} \cdot DM^{4.4671} \tag{6}$$

$$\text{Pig:} \quad \mu_{slurry} = 4.10^{-6} \cdot DM^{4.6432} \tag{7}$$

where μ_{slurry} is the apparent slurry viscosity (Pa s). Although these data should be used with caution, as Landry et al.'s (2004) comparison with other literature data shows, the conclusion is that pig slurry is less viscous than cattle slurry at a comparable DM content.

5. SOLID–LIQUID SEPARATION

Different techniques for separating slurry in a DM-rich and a liquid fraction have been developed and are used on farms. Solid–liquid separation may be carried out in settling tanks, where the solids are removed from the bottom of the tank, or the settling may be forced using centrifuges. Solids may also be removed mechanically by forced filtration using screw presses or drainage through fabric belts or screens. In-house separation can be viewed as an alternative to these solid–liquid separation techniques; however, this technology is not fully developed and is not used in practice. It will therefore not be described further in this review (see Sect. 2). Numerous designs of solid–liquid separators exist for slurry mixed in the animal house, and the majority may be categorized as one of the four standard types of separators mentioned above.

When comparing results from different studies, it is an advantage to use one separation parameter expressing the efficiency of separation. The removal efficiency (R) expresses the efficiency of removal of a specific compound (x) from a slurry to the solid fraction. It is defined as follows:

$$R(x) = 1 - \frac{c(x)_{liquid}}{c(x)_{slurry}} \tag{8}$$

where $c(x)_{slurry}$ and $c(x)_{liquid}$ are the concentrations (g L^{-1}) of the species in consideration (dry matter, P, N) in, respectively, the slurry being treated in the separator and the liquid fraction that is produced. The greater the removal efficiency, the lower the amount of compound x remaining in the liquid fraction. The equation characterizes the efficiency of the separator with respect to the liquid fraction; however, it does not give any indication of the production of the solid fraction.

A separation index (E_t), on the other hand, expresses the distribution of the specific compound between the solid and liquid fractions:

$$E_t(x) = \frac{m_{x,solid}}{m_{x,slurry}} \tag{9}$$

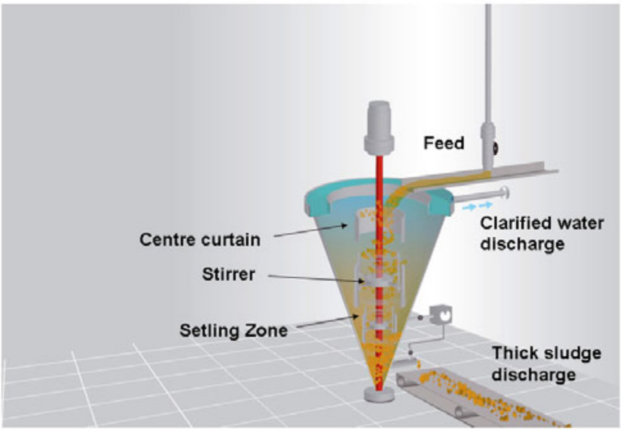

Figure 2. A typical thickener used for sedimentation.

where $m_{x,slurry}$ and $m_{x,solid}$ are the mass (g) of the compound in consideration in, respectively, the slurry being treated by the separator and of the solid fraction being produced. Hence, the values of both the liquid and the solid fraction are indicated. The larger the separation index, the greater the amount of compound x in the solid fraction.

The separation index, however, does not include information on the total amount of solid fraction relative to the total amount of liquid fraction. Thus, the simple separation index will theoretically be 50% if a machine separates the slurry into two equally sized fractions with similar contents of compound x. An improved expression for the separation may be obtained using the reduced separation index (E_t'):

$$E_t'(x) = \frac{E_t(x) - \frac{m_{solid}}{m_{slurry}}}{1 - \frac{m_{soild}}{m_{slurry}}} \tag{10}$$

where m_{slurry} and m_{solid} are the total mass (g) of slurry being treated and the total mass of solids being produced.

As only approximately 25% of the studies presented in the literature on solid–liquid separators contain sufficient data to assess E_t and of these only two-thirds contain sufficient data to assess $E_{t'}$, the separation index (E_t) has been used to compare efficiencies of separations in this review.

5.1. Sedimentation

5.1.1. Technical description

Sedimentation in a thickener is an attractive option for separation, due to the low cost and simple technology. Most thickeners consist of a container that is cylindrical at the top and conical at the bottom. In batch operation, slurry is added to the top of the thickener (Fig. 2) and the solids settle at the bottom of the conical part from whence the solids can be removed (Suzuki et al., 2002; Loughrin et al., 2006). To encourage settling and increase the transfer of solids settled on the upper part of the conical section, small thickeners can be vibrated while, for larger thickeners, this can be achieved by using a rake. Thickeners can also be operated in continuous mode, where slurry is added continuously while solid and liquid phases are removed at the same rate as slurry is added. In this case, the slurry has to be added in the separating zone (Fig. 2). Alternatively, lagoons may be used as settling basins.

5.1.2. Operation and separation efficiency

The time it takes for the solid to separate from the liquid phase can be estimated for dilute slurries from the terminal velocity of a single solid particle. The smallest particles will have the slowest terminal velocity and will therefore determine the final settling time. For small particles, the flow is laminar and the equation for the terminal velocity (v_{tg}) simplifies to (Foust et al., 1980):

$$v_{tg}(d_p) = \frac{\left(\rho_{solid} - \rho_{liquid}\right) \cdot g \cdot d_p^2}{18 \cdot \mu_{slurry}} \tag{11}$$

where μ_{slurry} is the viscosity of the slurry, ρ is the density of solid and liquid (see Sect. 4.5), g is the acceleration of gravity, and d_p is the diameter of the solid particle (all in SI units).

As seen, the settling velocity increases with the solid density compared with liquid density and particle size, but decreases with increasing slurry viscosity. As with solid density, because the viscosity and particle size vary from slurry to slurry, the terminal velocity can seldom be calculated in advance. At the same time, at least in the thickening zone of the thickener, the slurry cannot be assumed to be dilute and hindered settling will take place. Therefore, the terminal velocity as calculated in equation (11) alone cannot be used to determine the thickener size. Instead, the calculations or assessments have to be carried out based on laboratory settling experiments using the Coe–Clevenger method or the Talmadge–Fitch method, as described by Foust et al. (1980). However, the following general findings on slurry can be used as a yardstick.

Increasing the settling time increases the separation efficiency (Ndegwa et al., 2001; Converse and Karthikeyan, 2004). In a laboratory study, the settling of solids in pig slurry was studied for 4 hours. For slurry with an initial *DM* content of between 2% and 4%, the settling was observed to be completed within 1 hour. For pig slurry with a *DM* of 6% the settling time was over 4 hours, as was also observed for diluted slurries with 0.5% and 1% *DM* (Ndegwa et al., 2001). Interestingly, it was observed that the removal of *DM* was highest for 1% and 2% *DM* slurries (60% removal), while the *DM* removal was roughly 30% for the 0.5% and 4% slurries, and only 5% for the 6% *DM* slurry. The indications are that hindered settling and changes in slurry liquid properties slow down the settling velocity for pig slurries above 2% *DM*, while for very dilute slurries (i.e. 0.5% *DM*) the settling also slows down, presumably because at this low concentration fewer of the fine particles are co-precipitated with the larger faster-settling particles. Plant nutrients are not evenly distributed between particles of different density and size (see Sect. 4); in consequence,

Table II. Separation indexes at sedimentation.

Technical specifications	Slurry		Separation index (%)[2]					
Sedimentation time (h)	Origin[1]	Dry matter (%)	Volume	Dry matter	N-total	NH_4-N	P-total	Reference
Mean			22	56	33	28	52	
(standard deviation)			(4)	(10)	(2)	(2)	(21)	
0.2	P	–	–	51	–	–	17	Powers and Flatow, 2002
NA	P	2.0	18	63	–	–	65	Reimann, 1989
0.3	C	1.0	16	72	30	–	69	Sherman et al., 2000
4	C	1.3	25	52	35	27	42	Converse and Karthikeyan, 2004
24	C	2.5	25	42	33	28	46	Converse and Karthikeyan, 2004
1200	C	3.2	25	55	35	30	70	Converse and Karthikeyan, 2004

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

the settling of plant nutrients may not be linearly related to the settling of dry matter.

The mechanisms behind the slower settling velocities at higher *DM* seen in some studies are, for actual livestock slurries, due to a combination of hindered settling and increased density and viscosity of the slurry, as a large content of small particles will cause an increasing viscosity of the slurry liquid and thereby reduce the settling velocity (Henriksen et al., 1998a, b). It must be noted, though, that the effect of *DM* concentration on settling has not been observed in all studies (Gao et al., 1993). Also, the increased weight of the top sediment particles will squeeze water out of the thickening zone, causing turbulence that stirs up the particles; a mechanism that may be more pronounced in batch settling systems compared with technologies where the sediment is removed continuously (Foust et al., 1980). Fermentation and increased buoyancy of the particles due to the trapping of gas bubbles may reduce settling if the process is taking place over a long period of time, e.g. in lagoons; therefore it is recommended that slurry temperature should be kept below 16 °C (Meyer et al., 2007).

Cattle slurry has a higher viscosity than pig slurry at similar *DM* concentrations (see Sect. 4.5; Landry et al., 2004), most probably due to a larger amount of particles, which may contribute to a slower and less efficient settling of *DM* in cattle slurry. As for pig slurry, the *DM* settling of cattle slurry increases when *DM* concentration in the slurry increases; for example, from 0.1% to 1% (Moore et al., 1975). The settling rate of *DM* in cattle slurry decreases exponentially with time, and *DM* settling is almost at maximum after 1.5 hours (Moore et al., 1975). In contrast, because of the large P content in the small, slowly settling particles (Sect. 4.1), P settling may increase significantly over time and increase from about 50% settling after 4 hours to 75% settling after 48 days (Converse and Karthikeyan, 2004). On the other hand, the settling of total N may not increase with increased settling time (Converse and Karthikeyan, 2004). Most K and NH_4^+ is dissolved in the liquid phase (see Sect. 4.3; Massé et al., 2007a); therefore most K and NH_4^+ is recovered in the liquid phase after sedimentation of solids (Tab. II; Massé et al., 2005).

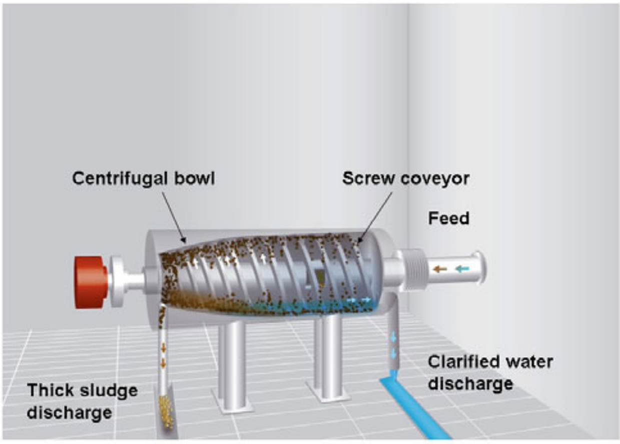

Figure 3. A typical decanter centrifuge.

5.2. Centrifugation

5.2.1. *Technical description*

Increasing the gravitational force can reduce the settling time needed to achieve a given separation efficiency. In practice, this is accomplished in decanter centrifuges, where a centrifugal force is generated to cause the separation.

There are vertical and horizontal types of decanter centrifuges. The horizontal decanter centrifuge (Fig. 3) uses a closed cylinder with a continuous turning motion. The centrifugal force separates solids and liquids at the wall into an inner layer with a high *DM* concentration and an outer layer consisting of a liquid containing a suspension of colloids, organic components and salts. The solid and liquid phases are transported to either end of the centrifuge by rotating the entire centrifuge at high speed and by simultaneously rotating the conveyor at a speed that differs slightly from the speed of the bowl (outer conical shell). The solid particles are conveyed towards the conical end and let out through the solid-discharge openings, whereas the supernatant flows towards the larger end of the cylinder formed by the bowl and the flights of the conveyor. During the transport of the slurry, the particles

Table III. Separation indexes at centrifugation.

Technical specifications		Slurry		Separation index (%)[2]					
Centrifugation velocity (g)	Centrifugation time (s)	Origin[1]	Dry matter (%)	Volume	Dry matter	N-total	NH_4-N	P-total	Reference
Mean (standard deviation)				14 (7)	61 (16)	28 (10)	16 (8)	71 (14)	
1500	600	P	6.3	–	95	–	–	90	Vadas, 2006
2050	30	P	8.9	22	69	34	22	87	Møller et al., 2007a
2050	8	P	7.0	15	57	–	–	–	Sneath et al., 1988
2050	8	P	4.2	8	52	–	–	–	Sneath et al., 1988
2050	8	P	2.0	3	47	–	–	–	Sneath et al., 1988
2200	30	P	5.1	9	51	17	10	71	Møller et al., 2007a
2200	30	P	4.0	7	52	17	7	70	Møller et al., 2007a
2200	30	P	6.8	26	70	36	26	82	Møller et al., 2007a
4100	600	P	5.3	13	60	29	–	62	Møller et al., 2002
4100	600	P	2.6	5	33	13	–	66	Møller et al., 2002
–	–	P	7.0	16	70	32	–	52	Reimann, 1989
1500	600	C	8.0		86	–	–	83	Vadas, 2006
2200	30	C	7.0	23	63	29	16	55	Møller et al., 2007a
4100	600	C	6.4	21	65	49	–	82	Møller et al., 2002
4100	600	C	4.5	12	55	27	–	79	Møller et al., 2002
–	–	C	6.0	13	44	23	–	48	Reimann, 1989

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

are separated from the liquid and the liquid phase is discharged through liquid-discharge openings at the wide end of the decanter centrifuge.

5.2.2. Operation and separation efficiency

For small particles in laminar flow, the terminal velocity (v_{tc}) can be calculated as (Foust et al., 1980):

$$v_{tc}(d_p) = \frac{\left(\rho_{solid} - \rho_{liquid}\right) \cdot \omega^2 \cdot r \cdot d_p^2}{18 \cdot \mu_{slurry}} \tag{12}$$

where r is the distance of the particles from the centrifuge's axis of rotation and ω is the angular velocity, all in SI units.

The only difference between the terminal velocity in a sedimentation tank and a centrifuge is the applied force; gravity versus centrifugal force. For simple laboratory centrifuges, the centrifuge efficiency can thus be related to the improvement in gravitational force, the G force (unit: g):

$$G = \frac{\omega^2 \cdot r}{g} \tag{13}$$

The efficiency of full-scale decanter centrifuges, however, cannot be described as simply as that. This is partly because the distance that the particles travel in a radial direction is large; thus the distance the particles have to travel from the center of the centrifuge, and therefore the settling velocity, vary during the sedimentation process; and partly because the geometry of decanter centrifuges is quite complicated.

The performance of a decanter centrifuge is often described by its feed handling capacity (Q), which can be calculated as (Foust et al., 1980):

$$Q = \frac{\left(\rho_{solid} - \rho_{liquid}\right) \cdot g \cdot d_{pc}^2}{18 \cdot \mu_{slurry}} \cdot 2 \cdot \Sigma = v_{t,g} \cdot 2 \cdot \Sigma \tag{14}$$

where Q is the volumetric feed rate, d_{pc} is the diameter of the smallest particle separated from the slurry in the centrifuge, and Σ is the sigma factor (m^2), all in SI units.

The sigma factor, Σ, is a property of the specific centrifuge geometry and G force and can only be calculated in advance for simple laboratory centrifuges. For full-scale centrifuges, Σ has to be obtained from experiments. As v_{tg} is a function of the slurry alone, and Σ a function of the centrifuge alone, the sigma factor can be used to compare the efficiency of different decanter centrifuges.

The dewatering volume of a decanter is considered to be the total volume (V) of the liquid zone in the cylindrical part of the drum. This volume may be changed by level regulators and the retention time (Rt) in seconds can be calculated as:

$$Rt = \frac{V}{Q} \tag{15}$$

where V is the dewatering volume of the decanter bowl (m^3).

From equations (14, 15), it is obvious that the volumetric feed rate, and therefore the retention time, depends on the chosen value of d_{pc} (the smallest particle to be separated). Reducing the feed rate and thereby increasing the retention time automatically leads to better separation but less economical performance of the centrifuge.

Increasing the retention time by reducing the volumetric feed rate has been observed to increase the efficiency of the separation of slurry (Tab. III; Sneath et al., 1988; Møller et al., 2007a). In consequence, the separation of *DM* and P was found to be high in the laboratory study of Vadas (2006) (see Tab. III) using the relatively long retention time of 600 s.

Increasing the dewatering volume within the centrifuge increases the retention time (Eq. (15)) but reduces the thickening zone (conical water-free part). Therefore, increasing the dewatering zone will increase the removal of *DM* from the liquid fraction. However, it will also reduce the drainage of water from the solid fraction (Reimann, 1989); hence the *DM* concentration in the *DM*-rich fraction will decrease.

Increasing the angular velocity of the decanter centrifuge will increase the *DM* concentration of the solid fraction (Eq. (15)). Thus, using a velocity as high as 2560 g, the decanter centrifuge produced a solid fraction with a *DM* of 40% (Møller et al., 2007a). However, increasing the angular velocity had no effect on the separation of the P, K and N (Møller et al., 2007a).

The separation efficiency of *DM* increases at increasing *DM* content of the slurry (Tab. III). The opposite result may have been expected, as seen in the sedimentation studies, because a higher viscosity of the slurry may reduce the settling velocity of the small particles (Reimann, 1989). It was hypothesized by Sneath et al. (1988) that vigorous stirring of the slurry may enhance the attachment of small particles to larger particles, and thereby improve settling of the small particles. This effect declines with dilution of the slurry; it has been observed that in the liquid from separation of a low-*DM* slurry, 70% of the particles in the liquid were <4 μm, while 50% of the particles were <4 μm in liquid from separation of a high-*DM* slurry. As a consequence of a higher *DM* content of cattle slurry compared with pig slurry, the *DM* separation index is higher for cattle slurry separation than for pig slurry separation (Tab. III). For assessment of the retention of slurry, it is reasonable to assume that decanter centrifuges can retain particles >20–25 μm in the *DM*-rich fraction (Sneath et al., 1988; Reimann, 1989; Møller et al., 2002).

Organic nitrogen and dissolved or adsorbed ammonium is related to the *DM* content of the solid fraction (see Sect. 3.1); therefore, total N separation is related to the *DM* content of the slurry being treated (Møller et al., 2002, 2007a; Sørensen and Møller, 2006). One should bear in mind that the relation between separation efficiencies and *DM* of treated slurry differs between centrifuges (Sneath et al., 1988; Møller et al., 2007a, b), and therefore an algorithm developed in one study cannot easily be applied to another. As decanter centrifuges do not retain the smallest particles, it is not surprising that no relation between separation of P and *DM* of treated slurry was observed (Møller et al., 2007a).

5.3. Drainage

5.3.1. *Technical description*

Many different kinds of slurry separation equipment that filter out solids from liquids are commercially available (Fig. 4). These use screens and filter belts to retain the solid fractions. With simple screens and belt separators, the liquid is drained by gravity from solids in the separator. With a belt separator, the filter cake is continuously removed as the belt rotates, so that the raw-slurry loading area and solid-fraction unloading area change over and are cleaned continuously. Most of the tested filter separators are screens, which may have a variety of designs but often consist of a rotating perforated cylinder with a loading area at the top and a scraper to remove the solids. The liquid flows through the screen and is drained off.

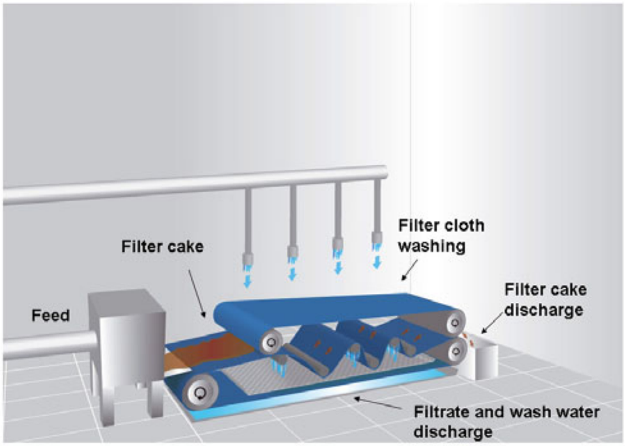

Figure 4. A typical belt separator with pressure rolls.

5.3.2. *Operation and separation efficiency*

The liquid flux through the filter is determined by the hydraulic resistance of the filter medium and the hydraulic resistance of the material deposited on the medium (i.e. the filter cake):

$$J = \frac{P}{\mu_{liquid}\left(R_m + SRF\,\frac{S \cdot V}{A}\right)} \tag{16}$$

where J is the flux (kg/m^2/s), μ_{liquid} is the viscosity of the permeate (Pa·s), R_m is the resistance to flow through the membrane (m^{-1}), S is the particle concentration in feed (kg/m^3), A is the filter area (m^2) and V is the filtrate volume (m^3). SRF is the specific filter cake resistance (m/kg), p is the effective pressure (Pa) and is related to the effective mass of the slurry (i.e. $p = \rho g h$), and h is the height of suspension above the filter cake (m), which decreases during the process.

Particles can adhere to or clog the filter media and thereby increase the resistance of the filter (Massé et al., 2005), and substances such as hair in pig slurry may cause an immediate build-up of a filter cake with a low *SRF* (specific filter cake resistance). Thus, when the filter cake is formed, small particles often clog the filter pores (Severin and Grethlein, 1996). A mixture of particles with a particle size distribution between 1 and 100 μm will produce a cake with a high *SRF*. This will reduce the liquid draining velocity from the filter cake and the effect will be a solid fraction with a low *DM* concentration (Karr and Keinath, 1978). Due to a higher fraction of larger particles (see Sect. 4.1), filter technology is more efficient in separating cattle slurry than pig slurry (Tab. IV).

Table IV. Separation indexes at drainage.

Technical specifications		Slurry		Separation index (%)[2]					Reference
Filter pore size (mm)	Filtration time (min)	Origin[1]	Dry matter (%)	Volume	Dry matter	N-total	NH_4-N	P-total	
Mean (standard deviation)				23 (16)	44 (27)	27 (17)	23 (19)	34 (21)	
0.1	(*x*)	P	1.5–5.4	25	50	33	28	34	Holmberg et al., 1983
0.1	(4**x*)	P	1.5–5.4	45	67	51	47	59	Holmberg et al., 1983
0.11	120	P	6.3	–	87	–	–	53	Vadas, 2006
0.5	–	P	1.8	–	17	5	–	3	Pieters et al., 1999
0.8	–	P	1.5	–	18	–	–	–	Hegg et al., 1981
2.5	(*x*)	P	1.5–5.4	1	11	3	3	2	Holmberg et al., 1983
2.5	(4**x*)	P	1.5–5.4	13	23	16	15	23	Holmberg et al., 1983
3.0	–	P	5.7	30	62	34	–	39	Møller et al., 2000
0.11	120	C	8.0	–	84	–	–	62	Vadas, 2006
0.8	–	C	1.1	–	13	–	–	–	Hegg et al., 1981
0.85	–	C	7.7	4	14	–	–	–	Gilbertson and Nienaber, 1978
3.0	–	C	7.1	44	56	49	–	49	Møller et al., 2000
–	–	C	6	19	54	22	–	20	Pain et al., 1978
–	–	C	12	30	58	29	–	29	Pain et al., 1978

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

x: unspecified constant.

As small particles are caught within the filter cake or adhere to the media, screens and filter will retain not only particles larger than the size of the mesh or the screen openings but also smaller particles. Therefore, one cannot assess filtering efficiency simply from particle size distribution and plant nutrients in different particle fractions and the size of the screen openings.

Increasing the retention time of the filter cake on the screen or the filter fabric will increase the drainage, and hence the *DM* concentration of the solid fraction produced. Retention time is often longer in laboratory studies than in pilot and full-scale tests; therefore, laboratory studies often give the most efficient separation of *DM* and P (Tab. IV) (Vadas, 2006). The best strategy is to determine the *SRF* in the laboratory and use it for the design of pilot or full-scale equipment.

Most P is contained in the small particles or is dissolved in the liquid (Fig. 1), while little N is found on particles larger than 0.125 mm (see Sect. 4.2). Therefore, relatively little P and N is retained on screens or filter fabrics, which only retain large particles (Meyer et al., 2007). Nevertheless, some N, P and K are retained in the filter cake because the cake has a high water content (50–80%-volume is not uncommon) with dissolved N, P and K (Pain et al., 1978; Holmberg et al., 1983; Møller et al., 2000).

5.4. Pressurized filtration

5.4.1. Technical description

The typical equipment used for filtration with applied pressure is a screw press or a press auger. In a press auger separator or a screw press separator, the effluent is transported into a cylindrical screen with a screw (Fig. 5). The liquid will pass through the screen and be collected in a container surrounding the screen. At the end of the axle the *DM*-rich fraction will be pressed against the plate and more liquid pressed out of the solid fraction. The solid phase will drop from the opening between the plate and the opening of the cylindrical mesh.

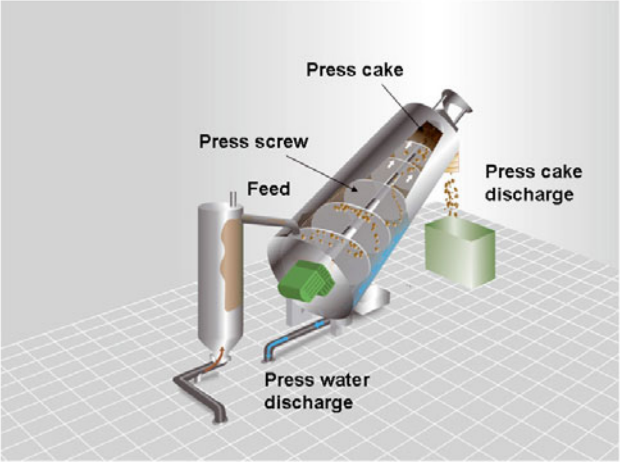

Figure 5. A typical screw press.

5.4.2. Operation and separation efficiency

The liquid flux through the filter medium can be determined from equation (18) by setting *p* equal to the applied pressure. According to filtration theory, *SRF* (specific filter cake resistance) is constant during constant pressure filtration; however, for a complex organic suspension such as slurry, *SRF* often increases during the process. The increasing *SRF* has been ascribed to sedimentation (Christensen and Dick, 1985), small

Table V. Separation indexes at pressurized filtration.

Technical specifications		Slurry		Separation index (%)[2]					
Filter pore size (mm)	Filtration time (min)	Origin[1]	Dry matter (%)	Volume	Dry matter	N-total	NH_4-N	P-total	Reference
Mean (standard deviation)				11 (15)	37 (18)	15 (17)	– (–)	17 (14)	
0.7	–	P	5.7	7	28	7	–	15	Møller et al., 2000
0.75	2	P	6.3		64	–	–	46	Vadas, 2006
0.9	–	P	5.7	5	28	6	–	12	Møller et al., 2000
1.0	–	P	5.3	4	27	7	–	7	Møller et al., 2002
–	–	P	1.8		51	31	–	42	Pieters et al., 1999
–	–	P	1.8		26	11	–	7	Pieters et al., 1999
–	–	P	6.3	7	21	4	–	13	Pos et al., 1984
0.75	2	C	8.0		64	–	–	28	Vadas, 2006
0.9	–	C	7.1	3	14	4	–	7	Møller et al., 2000
1.0	–	C	4.5	2	13	4	–	8	Møller et al., 2002
1	–	C	5.2	10	46	5	–	3	Wu, 2007
1.0	–	C	6.4	5	30	8	–	15	Møller et al., 2002
1.6	–	C	3.8	6	20	–	–	–	Pos et al., 1984
3.0	–	C	7.1	13	40	13	–	21	Møller et al., 2000
3.2	–	C	5.0	13	37	–	–	–	Pos et al., 1984
–	–	C	5.2	13	35	36	–	–	Pos et al., 1984
–	–	C	17.7	60	77	60	–	–	Menear and Smith, 1973

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

particles blocking the pores in the cake (Sørensen et al., 1995), and a time-dependent compression of the cake (Christensen and Keiding, 2007). The slurry filter cake is compressed during pressure filtration; hence the *SRF* is several orders of magnitude higher for pressure filtration than for gravity drainage (Hjorth et al., 2008).

The cake compression ensures that the screw press can produce a solid fraction with a high *DM* content; often being twice as high as for gravity drainage (Møller et al., 2000). Increasing the applied pressure will increase the *DM* content of the solid fraction. Although aggregation of particles on the filter may, to some degree, contribute to the retention of small particles in the screw press, this has no significant effect, as the applied pressure forces small particles through the filter pores. A large proportion of small particles is therefore found in the liquid fraction after separation (Møller et al., 2002). Thus, the filter cake contains little N, P or K, because these are primarily found in the liquid phase and in the small particles which are drained off the filter cake with the permeate. In consequence, the plant nutrient separation efficiency of the screw press is low (Tab. V).

5.5. Concluding remarks about slurry separators

In general, centrifugation is the most efficient technique for the separation of *DM* and P (see Tabs. II–V) and filtration is less efficient for separating *DM*, N and P. To some extent, the separation of NH_4^+ follows the same pattern. The poorest N and P separation is achieved using pressurized filtration. The advantage of pressurized filtration, though, is the production of a solid fraction with a high *DM* concentration of the solid fraction. Therefore, drainage is sometimes followed by pressurized filtration to obtain both high separation efficiency and high *DM* concentration.

The choice of separators will depend on the objective of the separation. The goal may be to reduce *DM* content in the slurry to ease the transport of slurry in pipes or channels, reducing the risk of sedimentation or blockage of the pipes and channels, in which case simple screens or filters may be useful. This simple separation will also produce a liquid fraction that will contribute to a homogeneous spreading of plant nutrients on the field and reduced ammonia and odor emissions (Rubæk et al., 1996; Hansen et al., 2006). If the cost of separation has to be low and retention time is no problem, then sedimentation is a cheap technique that will reduce the plant nutrient composition of the slurry efficiently.

A screw press seems to be a good choice if the objective is to produce biomass with a high *DM* concentration suitable for incineration (Tab. V). The filtration technologies may retain up to about one-quarter of the N and P in the slurry. In some cases this may be sufficient to achieve a harmonious balance between the amount of plant nutrient applied to the field and the plant demand on the livestock farm.

Of the above-mentioned solid–liquid separation techniques, the decanter centrifuge is the most efficient in retaining P and at the same time producing a *DM*-rich fraction low in water. In addition, this technique may produce a liquid fraction with a N:P:K ratio similar to the N:P:K requirements of the crop.

The produced solid and liquid fractions may be treated further to obtain valuable slurry products (see Sect. 7). The

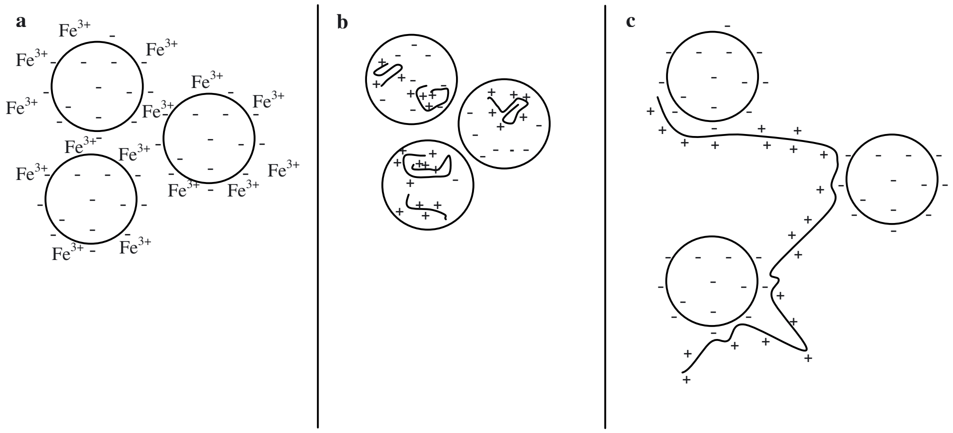

Figure 6. Diagrammatic representations of (a) coagulation, (b) patch flocculation and (c) polymer bridging (adapted from Hjorth et al., 2008).

solid–liquid separation may be improved further by an initial addition of chemicals (see Sect. 6).

The major disadvantages of the above-mentioned solid–liquid separation technologies are that they require investment in expensive equipment, have a limited life span, and require maintenance, process control systems and an external power supply in order to run. These extra costs need to be balanced against the reduction in investment in and cost of slurry transportation between animal houses, slurry storage facilities and fields.

6. PRE-TREATMENT: CHEMICAL ADDITIONS

Solid–liquid separation technologies often have a limited capacity to retain plant nutrients in the solid fraction and thereby produce a liquid fraction with a composition that fulfils the needs of the livestock and plant producer.

Additives such as brown coal, benthonite, zeolite, crystals, chitosan and efficient microorganisms are used by livestock farmers and have been examined in numerous studies (Kayser, 1997; Henriksen et al., 1998a; Sommer et al., 2005; Garcia et al., 2009); however, in this review, these additives will not be considered as a pre-treatment for solid–liquid separation, as reliable information about their efficiency is lacking.

The focus here is on examples of the most commonly used methods that have been developed and used as pre-treatments to sedimentation, centrifugation or filtration. This section concentrates on the theory and use of polymers and multivalent ions, as well as on struvite formation.

6.1. Precipitation, coagulation and flocculation

Flocculation, coagulation and precipitation are chemical pre-treatments that improve the mechanical solid–liquid separation of many suspensions (Gregory, 1973; Smith-Palmer et al., 1994; Ashmore and Hearn, 2000; Nowostawska et al., 2005). In most suspensions, colloidal particles will not aggregate because the particles are negatively charged and repel each other (Gregory, 1989). However, aggregation will be facilitated by adding (1) multivalent cations that cause coagulation and/or (2) polymers, whereby flocculation occurs. The addition of multivalent cations will also enhance the precipitation of P.

6.1.1. *Theory*

Large amounts of phosphate will precipitate following the addition of multivalent cations to the slurry (Hjorth et al., 2008) due to formation of, for instance, $FePO_4$, $Fe_5(PO_4)_2(OH)_9$ and $Ca_3(PO_4)_2$.

At the same time, the multivalent cations cause coagulation of the particles in the slurry (Barrow et al., 1997; Sherman et al., 2000; Hjorth et al., 2008). At coagulation, the multivalent cations neutralize (or partially neutralize) a particle's negative surface charge by adsorbing the oppositely charged ions to the particle surface, creating a double layer (see Sect. 4.5) and thereby removing the electrostatic barrier that prevents aggregation; a process termed 'charge neutralization' (Fig. 6a). An optimum dose exists, and overdosing occurs when the adsorbed ions reverse the surface charge, thus counteracting aggregation (Gregory, 1989).

The addition of polyelectrolyte polymers to slurry induces flocculation. Polymer bridging is the main reaction mechanism, whereas patch flocculation is of limited significance, and charge neutralization is not important (Vanotti and Hunt, 1999; Hjorth et al., 2008). The addition of polymers will cause flocculation of particles and of existing but smaller aggregates that have been produced due to coagulation; for example, induced by the addition of Fe^{3+} to the slurry.

Patch flocculation is the adsorption to particles of oppositely charged polyelectrolytes with a charge density much higher than the charge density of the particles. Thus, local positively and negatively charged areas are formed on the surface of the particles (Fig. 6b; Gregory, 1973). This results in a strong electrical attraction between the particles, especially when the electrical attraction extends far into the solution, i.e. at low conductivity (Gregory, 1973). A greater tendency to patch flocculation is expected for branched polymers compared with linear polymers, and for high-molecular-weight polymers compared with lower-molecular-weight polymers (Bouyer et al., 2001; Bratskaya et al., 2005). However, since the conductivity of slurry is relatively high (see Sect. 4.5) patch flocculation is of minor relevance.

Polymer bridging occurs when long-chain polymers adsorb to the surface of more than one particle, causing the formation of strong aggregates of large flocs (Fig. 6c; Gregory, 1989). At high conductivity of the slurry or at high doses of added polymer (see Sect. 4.5), the polymer coils up and forms loops and tails. Due to steric hindrance between the particles, the loop and tail formation leads to deflocculation (Gregory, 1973). The maximum adsorbed mass of polymers increases with increasing ionic strength (Eriksson et al., 1993). Polymer characteristics of importance to polymer bridging are molecular weight and the molecular structure, as large molecules with long tails are capable of catching by-passing particles relatively easily. Charge density is also important, as this affects the number of loops and tails that are formed and the interaction between polymer and particles (Larsson et al., 1999; Ashmore and Hearn, 2000; Bouyer et al., 2001).

6.1.2. *Technical description*

Multivalent ions and polymers need to be added carefully to the slurry in order to achieve satisfactory particle aggregation. If both additives are used, then the multivalent ion is added first to the slurry, which is then stirred to ensure homogeneous distribution of ions and dry matter (Fig. 7). Several minutes of slow stirring are necessary for the charge neutralization and coagulation to occur. Next, the polymer is slowly added in small doses during vigorous stirring, followed by slow stirring, which is necessary for polymer bridging and patch flocculation to occur. The shear applied (for example, by the impeller, i.e. time and stirring velocity), has a large impact on the formation of the aggregates; too low a shear causes the aggregates to be non-uniform and unstable with low particle catchment, while too large a shear causes the aggregates to be destroyed (Mikkelsen, 1999). After the addition and aggregation, the slurry may be transferred to ordinary solid–liquid separators (see Sect. 5; Fig. 7).

6.1.3. *Operation and separation efficiency*

A broad range of multivalent cations intended to precipitate P and coagulate the slurry have been tested. These tests provide an opportunity to compare the efficiency of additives and to assess which multivalent ions provide the best slurry separation (Tab. VI). If the multivalent cation added to the slurry is calcium, the efficiency is ranked as $CaO > Ca(OH)_2$; if the multivalent ion is iron, the efficiency is ranked as $FeCl_3 > Fe_2(SO_4)_3 > FeSO_4$; while if the multivalent ion is aluminium, the efficiency is ranked as $Al_2(SO_4)_3 > AlCl_3$.

The use of the separation products should also be considered when selecting the multivalent ion. For example, a decrease in pH is observed upon addition of $FeCl_3$ and $Al_2(SO_4)_3$ (Hjorth et al., 2009), which could be an advantage with respect to NH_3 emissions; while CaO causes pH to increase, which may be preferable when a nitrification/denitrification step is to follow the separation (Szögi et al., 2006). The environmental consequences of applying multivalent cations should also be considered (Nahm, 2005).

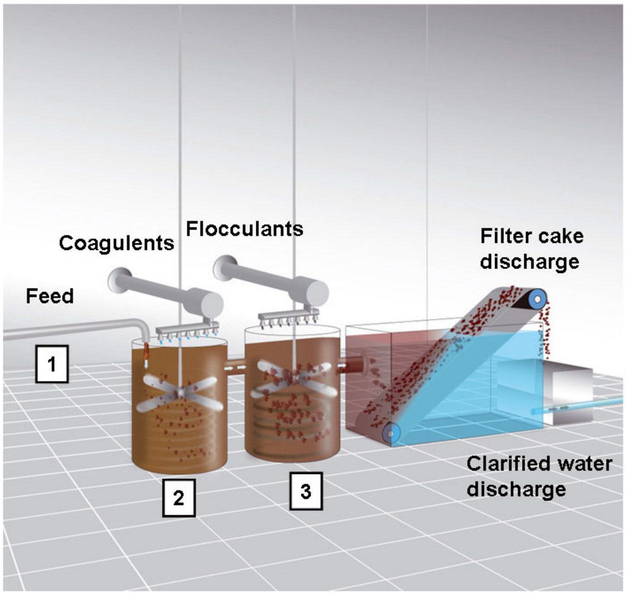

Figure 7. Example of the use of additives and separating the solids from the liquids using a filter bed separator with containers and stirrers for treatment with (1) slurry pumped into the separator, (2) coagulants added to the slurry pumped into the first container, and (3) polymers added to slurry transferred from the first to the second container. The additives may be added into the tubes transferring the slurry to the separator and between containers, or the additives may be added to the slurry in the containers that are equipped with a stirrer: vigorous stirring may break up the flocs.

The literature reports on a wide range of polyacrylamide (PAM) polymers that have been examined, with characteristics that may vary with respect to charge, charge density, molecular size and structure (Tab. VII). These studies therefore provide an opportunity to compare polymers and to give an indication of the polymer characteristics likely to provide the best slurry separation.

Most studies indicate that a cationic polymer is superior to anionic and neutral polymers (Tab. VII), which correlates well with the fact that the particles in animal slurry are mainly negatively charged (see Sect. 4.5). Polymers of medium charge density (20–40 mol%) have been shown to be most efficient in most studies, confirming the hypothesis that polymer bridging is the main mechanism behind flocculation in slurry (Vanotti and Hunt, 1999; Hjorth et al., 2008). The reason is that a polymer of medium charge density has a large number of charged sites and hence would have the ability to catch particles efficiently; however, a polymer of medium charge density also has many non-charged sites and will therefore not neutralize the particles completely, thereby leaving charges available on the particle surface for another polymer. This is supported by the finding that optimal separation has been

Table VI. Comparison of precipitants/coagulants with respect to separation-relevant criteria.

Slurry origin[1]	ID	Precipitant/coagulant	Comparison	Criteria[2]	Reference
P	1 2 3 4	$FeCl_3$ $Fe_2(SO_4)_3$ $AlCl_3$ $Al_2(SO_4)_3$	1>2>3=4	pH reduction	Hjorth et al., 2009
P	1 2	$Fe_2(SO_4)_3$ $Al_2(SO_4)_3$	1>2 2>1	Volume separation *DM*, N, P and NH_4 separation	Møller et al., 2007a
P	1 2	$FeCl_3$ $Fe_2(SO_4)_3$	1>2 1=2	Liquid turbidity, volume separation *DM*, VS, COD and P separation	Estevez Rodríguez et al., 2005
C	1 2 3	$Al_2(SO_4)_3$ $FeCl_3$ CaO	1>2,3 1=2>3	pH reduction *DM*, P, N, NH_4 and TOC separation	Karthikeyan et al., 2005
C	1 2	$AlCl_3$ $FeCl_3$	1>2 2>1 1=2	pH reduction P separation *DM* separation	Krumpelman et al., 2005
P	1 2 3 4 5	$Al_2(SO_4)_3$ $FeCl_3$ CaO $FeSO_4$ $CaCO_3$	1=2=3>4=5 1=2>3>4=5 1=2>3>4>5	*DM* separation Volume separation P separation	Powers and Flatow, 2002
C	1 2	$Al_2(SO_4)_3$ $FeCl_3$	1=2 2>1	*DM* separation pH reduction	Dao and Daniel, 2002
P	1 2	$Al_2(SO_4)_3$ $FeCl_3$	1=2	*DM* separation	Zhang and Lei, 1998
P	1 2	$FeCl_3$ $Al_2(SO_4)_3$	1>2 2>1	*DM* separation P separation	Ndegwa et al., 2001
C	1 2	$FeCl_3$ $Al_2(SO_4)_3$	1>2 2>1	Volume, P and N separation *DM* separation	Sherman et al., 2000
C	1 2 3	$FeCl_3$ $Al_2(SO_4)_3$ $AlCl_3$	1=2=3	*DM*, P separation	DeBusk et al., 2008
P	1 2 3	$FeCl_3$ $Ca(OH)_2$ $Al_2(SO_4)_3$	1>2=3	*DM* separation	Gao et al., 1993
C	1 2 3	CaO $Ca(OH)_2$ $CaSO_4$	1>2>3 1=2>3	*DM* separation pH increase	Barrow et al., 1997
C	1 2	$Fe_2(SO_4)_3$ $FeSO_4$	1>2	*DM*, N and P separation	Barrow et al., 1997
C	1 2	$FeCl_3$ $Fe_2(SO_4)_3$	1>2	*DM*, N and P separation	Barrow et al., 1997

[1] P = pig, C = cattle.

[2] *DM* = dry matter, COD = chemical oxygen demand, TOC = total organic carbon, VS: volatile solids.

observed at approximately 30% neutralization of the particle surface charge (Hjorth et al., 2008). Further indications are that linear polymers are preferable to branched polymers, and polymers of large molecular weight are preferable to those of smaller molecular weight (Tab. VII). The reason seems to be the very efficient capture of smaller particles by the large, loose flocs and/or that the shape of large, loose flocs is an advantage in the solid–liquid separators used to treat the slurry, especially when using separators where liquid is drained off the solids.

The separation products are often destined to be deposited in landfills or applied to cultivated fields; thus the environmental and health consequences of the applied polymer must be considered. The monomers of PAM used in most slurry separation studies (Tab. VII) can be toxic; however, a study on separated slurry products showed the risk to be minimal (Schechter et al., 1995). In the USA, these additives are considered to be ‘generally recognized as safe’ (GRAS) when added to the slurry below a specific application rate related to the end-use (Vanotti et al., 2002). However, there is a need for further studies on the efficiency of alternative polymer types for slurry separation, with the objective of replacing PAM with potentially less toxic polymers. Furthermore, when considering new polymers, one must take into consideration the toxicity of the organic components produced during degradation of the polymers.

The chemical and physical properties of slurry may vary (see Sect. 2) because slurry varies between livestock farms. During a separation run, slurry properties may vary even if the slurry is stirred when treated. Consequently, the optimal application rate of multivalent cations and polymers to slurry varies between farms and during a separation run. Various analytical

Table VII. Comparison of flocculants (all polyacrylamide – PAM) with respect to separation-relevant criteria.

Slurry Origin[1]	Id	Flocculant (polymer)					Comparison	Criteria[2]	Reference
		Trade name	Charge	Charge density (mol%)	Structure	Molecular weight			
P	1	Superfloc c-2260	+	40	Linear	Large	1>2 1=2 1<2	P separation, Liquid turbidity Dewatering at drainage DM separation Dewatering at pressurized filtration	Hjorth et al., 2008
	2	Zetag 7878FS40	+	80	Branched	Medium			
P	1	Superfloc c-2220	+	10	Linear	Large	5>1,2,3,4	Liquid turbidity	Hjorth et al., 2009
	2	Superfloc c-2230	+	15	Linear	Large			
	3	Superfloc c-2240	+	20	Linear	Large			
	4	Superfloc c-2250	+	28	Linear	Large			
	5	Superfloc c-2260	+	40	Linear	Large			
C	1	MCP1	+	Medium	–	–	1>2>4>3	DM, VS and COD separation	Rico et al., 2007
	2	MCP2	+	Medium	–	–			
	3	MAP	–	Medium	–	–			
	4	SCP	+	Large	–	–			
P	1	Magnafloc 90L	–	10	–	–	1=2>3=4	DM separation Dewatering at filtration/pressure	Szögi et al., 2006
	2	Magnafloc 120L	–	34	–	–			
	3	Zetag 7837	+	13	–	–			
	4	Zetag 7867	+	20	–	–			
P	1	NA	+	4	–	–	4=5>1,2,3,6 5>1,2,3,4,6	DM separation Dewatering at filtration/pressure	Vanotti et al., 2005
	2	NA	+	7	–	–			
	3	NA	+	13	–	–			
	4	NA	+	20	–	–			
	5	Magnifloc C-1596	+	40	–	Large			
	6	NA	+	70	–	–			
P	1	Nordfloc CE 169	+	60	Linear	Large	1,2,3>4 1=2=3	Dewatering at filtration/pressure DM, VS, COD and P separation	Estevez Rodríguez et al., 2005
	2	Nordfloc CE 169 WD	+	60	Linear	Large			
	3	Nordfloc CE 129	+	40	Linear	Large			
	4	Nordfloc CE 166 TR	+	60	Branched	Large			

C	1	Superfloc A 1885 RS	–	Large	–	–	5,6,7,8>1,2,3,4 1=2=3=4=5=6 =7=8	DM and P separation Soluble reactive P separation	Timby et al., 2004
	2	Superfloc A 1883	–	Medium	–	–			
	3	Superfloc A 1849 RS	–	Small	–	–			
	4	Superfloc N 1986	0	0	–	–			
	5	Superfloc C 1594	+	Medium	–	–			
	6	Magnifloc 240 G	+	Medium-large	–	–			
	7	Superfloc C 1598	+	Large	–	–			
	8	Magnifloc 255 G	+	Large	–	–			
C	1	C-1596	+	40	–	Large	1=2>3	DM separation	Dao and Daniel, 2002
	2	C-581	+	100	–	Large			
	3	SD-2085	+	55	–	Medium			
P	1	Magnifloc 494 C	+	20	–	–	1>2=3 1=2=3	Volume, DM, COD, organic-N and organic-P separation NH4 and ortho-P separation	Vanotti and Hunt, 1999
	2	Magnifloc 985 N	0	0	–	–			
	3	Magnifloc 844 A	–	33	–	–			
P	1	Magnifloc 494C	+	20	–	–	1>2>3>4 1>2=3>4 1>3>2=4	DM separation COD separation P separation	Garcia et al., 2007
	2	Excel Ultra 5000	+	75	–	–			
	3	Magnafloc 120L	–	34	–	–			
	4	Magnifloc 985N	0	0	–	–			
P	1	Excel 5020	+	20	–	–	1>2>3=4	Volume and DM separation	Vanotti and Hunt, 1999
	2	Excel 5040	+	40	–	–			
	3	Excel 5055	+	55	–	–			
	4	Excel 5000	+	75	–	–			
P and C	1	Magnifloc 240 G	+	Large	–	Large	4>1,2,3,5	DM separation	Zhang and Lei, 1998
	2	Magnifloc 240 GL	+	Large	–	Large			
	3	Magnifloc 240 GSD	+	Large	–	Large			
	4	Magnifloc 255 G	+	Large	–	Large			
	5	Magnifloc 1596 C	+	Large	–	Large			
C	1	P 234 GD	+	–	–	–	1=2	DM, N and P separation	Sherman et al., 2000
	2	P C 494	+	–	–	–			

[1] P = pig, C = cattle.

[2] *DM* = dry matter, COD = chemical oxygen demand.

Table VIII. Slurry characteristics potentially useful for assessing optimal coagulant and polymer dosage to slurry prior to separation.

Slurry characteristics	Flocculated sample	Observed sample Liquid fraction	Solid fraction
DM content		X	X
VS content		X	X
P content		X	X
N content		X	X
NH_4 content		X	X
Metal content		X	X
Dewaterability	X		
Settling	X		
Turbidity		X	
Viscosity		X	
Surface erosion from flocs	X		
Capillary suction time (CST)	X		
Floc size	X		
Particle dispersion ánalysis (PDA)	X		
Streaming current	X		

VS: volatile solids.

methods have proved useful for evaluating the efficiency of different additives (Tab. VIII). Of these, measurement of the *DM* content of the solids, dewatering ability, surface erosion from flocs, turbidity of the liquid fraction, capillary suction time, viscosity of the liquid fraction and floc size have proved to be useful as laboratory tests of slurry separation (Hjorth and Christensen, 2008).

The separation technique affects the separation efficiency of slurry treated with multivalent ions and flocculants. As for the combined solid–liquid separation technique, drainage appears to be superior when considering P and *DM* separation (Tab. IX), as pressure may disintegrate the flocs.

The addition of a coagulant/precipitant (a multivalent cation) increases the P separation (Tab. IX). There is a maximum multivalent ion amount above which no additional P will be retained in the solid fraction. The maximum separation index shows that 99% of the P in treated slurry is retained in the solid fraction (Sherman et al., 2000; Estevez Rodríguez et al., 2005). Due to coagulation, the addition of the multivalent cation may increase the *DM* and N separation (Barrow et al., 1997; Sherman et al., 2000). In theory, the multivalent ion may be overdosed when all dissolved P has been precipitated and all particles have been charge neutralized. Overdosing will cause the separation indexes to decrease, because the particles then become positively charged and repel each other.

Polymer (flocculant) addition improves *DM*, N and P separation (Tab. IX), because floc formation increases the amount of *DM* retained in the solid fraction and also the N- and P-containing organic and inorganic particles. Depending on the polymer, the structure of the flocs varies. The addition of linear polymers of large molecular weight produces large, loose flocs; while the addition of branched polymers of small molecular weight produces small, dense flocs (Hjorth et al., 2008). As sedimentation and centrifugation efficiency depend on particle density, it may be advantageous to produce small, dense flocs using branched small-molecular-weight polymers. Alternatively, when using filtration without applied pressure, draining of the liquid should be eased by producing large, loose flocs, resulting in a filter cake with high porosity. Filtration with applied pressure is favored by non-compressible flocs; and thus small, dense flocs may be the floc structure giving the best separation.

Ammonium and K are dissolved in the liquid (see Sect. 4.3); hence the polymer will not improve the NH_4^+ or K separation. Due to the positive charges of NH_4^+ and K, a multivalent cation will not improve the separation through precipitation or charge neutralization. Adding polymers may increase NH_4^+ and K content in the solid fraction (Hjorth et al., 2009), because liquid with dissolved NH_4^+ and K is retained in the flocs, as floc liquid is difficult to remove by mechanical solid–liquid separation (Vesilind, 1994).

The charge of *DM* particles have to be neutralized. Therefore at increasing charge of the *DM* and increasing concentration of the particles demands increasing addition of multivalent cation and polymer to a successful separation (Zhang and Lei, 1998). In contrast, decreasing amounts of polymer are needed when coagulation is improved by pre-treatment with an increased amount of multivalent cations (Krumpelman et al., 2005; Hjorth et al., 2009).

The separation indexes of untreated slurry (Tabs. II–V) are much lower than the indexes of slurry treated with flocculants and coagulants (Tab. IX), with flocculation having a larger impact on filtration than on centrifugation (Hjorth et al., 2008). Thus, separation is improved by flocculation and further improved when multivalent ions are also added to the slurry.

6.2. Struvite crystallization

Slurry contains struvite or the inorganic components contributing to the formation of struvite crystals. Thus, physical and chemical changes in slurry may initiate struvite formation. This is a problem in biogas plants because struvite will build up on pipe surfaces and reduce the capacity of slurry transport, but struvite formation may also be used to remove P and NH_4^+ from the slurry.

Table IX. Separation indexes following coagulation and flocculation.

Technical description			Slurry		Separation index (%)[2]					
Separation technique	Coagulant/ precipitant	Flocculant	Origin[1]	Dry matter (%)	Volume	Dry matter	N-total	NH_4-N	P-total	Reference
Mean					**22**	**70**	**43**	**20**	**79**	
(standard deviation)					**(16)**	**(13)**	**(24)**	**(14)**	**(21)**	
Sedimentation	$Al_2(SO_4)_3$	(none)	P	–	–	78	–	–	62	Powers and Flatow, 2002
Sedimentation	$FeCl_3$	(none)	P	–	–	82	–	–	64	Powers and Flatow, 2002
Sedimentation	$Fe_2(SO_4)_3$	(none)	P	–	–	58	–	–	38	Powers and Flatow, 2002
Sedimentation	$CaCO_3$	(none)	P	–	–	61	–	–	18	Powers and Flatow, 2002
Sedimentation	CaO	(none)	P	–	–	75	–	–	50	Powers and Flatow, 2002
Centrifugation	$CaCl_2$	(none)	P	3.1	10	34	1	10	59	Poels et al., 1988
Centrifugation	$CaCl_2$	(none)	P	3.3	10	64	28	21	86	Poels et al., 1988
Centrifugation	(none)	Optifloc c-6260	P	1.2	5	55	20	8	72	Møller et al., 2007a
Centrifugation	(none)	Optifloc c-6260	P	2.8	13	84	54	18	85	Møller et al., 2007a
Centrifugation	$Fe_2(SO_4)_3$	Optifloc c-6260	P	1.2	6	56	24	9	75	Møller et al., 2007a
Centrifugation	$Fe_2(SO_4)_3$	Optifloc c-6260	P	2.1	5	54	16	7	73	Møller et al., 2007a
Centrifugation	$Al_2(SO_4)_3$	Optifloc c-6260	P	2.1	10	73	35	15	91	Møller et al., 2007a
Centrifugation	$Al_2(SO_4)_3$	Optifloc c-6260	P	4.2	18	87	45	28	90	Møller et al., 2007a
Drainage	(none)	Superfloc c-2260	P	7.0	35	79	45	36	85	Hjorth et al., 2009
Drainage	$FeCl_3$	Superfloc c-2260	P	7.0	43	88	62	50	97	Hjorth et al., 2009
Drainage	FeCl3	Nordfloc CE 169	P	2.5	–	70	–	–	99	Estevez Rodríguez et al. 2005
Drainage	$FeCl_3$	Nordfloc CE 169WD	P	2.5	–	65	–	–	99	EstevezRodríguez et al. 2005
Drainage	$FeCl_3$	Nordfloc CE 129	P	2.5	–	70	–	–	99	Estevez Rodríguez et al., 2005
Drainage	$Fe_2(SO_4)_3$	Nordfloc CE 169	P	2.5	–	70	–	–	99	Estevez Rodríguez et al., 2005
Drainage	$Fe_2(SO_4)_3$	Nordfloc CE 169WD	P	2.5	–	67	–	–	99	Estevez Rodríguez et al., 2005
Drainage	$Fe_2(SO_4)_3$	Nordfloc CE 129	P	2.5	–	65	–	–	99	Estevez Rodríguez et al., 2005
Sedimentation	$Al_2(SO_4)_3$	(none)	C	1.1	54	92	83	–	99	Sherman et al., 2000
Sedimentation	$FeCl_3$	(none)	C	1.1	47	78	75	–	94	Sherman et al., 2000
Sedimentation	(none)	P-234GD	C	1.1	29	66	35	–	67	Sherman et al., 2000
Sedimentation	(none)	P C-494	C	1.1	29	67	36	–	67	Sherman et al., 2000
Drainage	$AlCl_3$	(none)	C	2.0	–	60	–	–	–	Timby et al., 2004
Drainage	$AlCl_3$	(undefine)	C	2.6	–	97	80	–	–	Worley et al., 2008
Pressurized filtration	CaO	MCP1	C	5.0	24	69	48	–	78	Rico et al., 2007

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

Table X. Separation efficiency of struvite precipitation and sedimentation.

Addition	Slurry		Separation index (%)[2]		Reference
	Origin[1]	Dry matter (%)	N-total	P-total	
Mean			16	63	
(Standard deviation)			(1)	(37)	
Mg, OH^-	P			85	Nelson et al., 2003
Mg, NH_3	P			60	Bowers and Westerman, 2003
Mg, increase pH	P	18		18	Suzuki et al., 2007
Mg, increase pH	P	18		49	Suzuki et al., 2007
Mg, increase pH	P			96	Burns et al., 2003
Mg, increase pH	P			98	Burns et al., 2003
Fe, OH	P		17	98	Laridi et al., 2005
Fe, OH	P		15	99	Laridi et al., 2005
Mg, NH_3	C			8	Sheffield et al., 2005
Mg, NH_3	C			19	Sheffield et al., 2005

[1] P = pig, C = cattle.

[2] Separation index is the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry.

6.2.1. *Theory*

Crystallization of phosphate is used to facilitate the sedimentation of phosphorus as particles. Animal slurry contains P in the form of struvite ($MgNH_4PO_4 \cdot 6H_2O$) and apatite $Ca_5OH(PO_4)_3$ (hydroxyapatite) crystals (see Sect. 4; Bril and Salomons, 1990; Greaves et al., 1999; Suzuki et al., 2002). Struvite has been shown to be the most significant of the solid forms of P in slurry, and struvite crystallization has been widely used as a method for separating P from wastewater and slurry (Ohlinger et al., 2000; Burton and Turner, 2003). Hydroxyapatite is not as attractive as a means of removing P from slurry and wastewater, because much calcium will have crystallized as calcite $CaCO_3$ in slurry.

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \leftrightarrow MgNH_4PO_4 \cdot 6H_2O(s) \tag{17}$$

The formation constant (K_0) of struvite is 1.41×10^{13} and the equilibrium ion-activity product (IAPeq) is 7.08×10^{-14}. In slurry, the product of [Mg^{2+}], [NH_4^+] and [PO_4^{3-}] is generally lower than the conditional formation constant, due to low concentrations of dissolved magnesium (Mg^{2+}) (Sommer and Husted, 1995a; Nelson et al., 2003), so little or no struvite is formed. The dissolved Mg may be lower than that determined with traditional extraction and measuring techniques, because a major fraction of the Mg^{2+} ions may form complexes with dissolved organic matter (Bril and Salomons, 1990; Christensen et al., 2009). The concentration of PO_4^{3-} will also have a major impact on struvite crystallization. HPO_4^{2-} is a weak acid and at pH levels below pH 7 the formation of HPO_4^{2-} and a low concentration of PO_4^{3-} will reduce struvite crystallization (Nelson et al., 2003). In most slurries with a typical pH of 7.5–8.3, the NH_4^+ concentration is higher than the 1:1:1 ratio ([Mg^{2+}]:[NH_4^+]:[PO_4^{3-}]) for the formation of struvite and will not be the limiting factor in the reaction (Nelson et al., 2003). At high pH, the NH_4^+ concentration will decrease, and low NH_4^+ concentration may limit struvite formation (Buchanan et al., 1994). Optimal conditions for the sedimentation of struvite therefore occur at about pH 9 (Buchanan et al., 1994; Nelson et al., 2003).

6.2.2. *Technical description*

In a slurry container, the slurry may be manipulated with the purpose of forming struvite that will precipitate. Afterwards the slurry can be transferred to a thickener or another type of solid–liquid separator (see Sect. 5). In the pilot plant described by Suzuki et al. (2002), the struvite was formed in a thickener, which was also used to remove the struvite. Alternatively, the struvite may be produced in a psychrophilic anaerobic sequencing batch reactor biogas plant, where the P settles as struvite and is removed with the sludge (Massé et al., 2007a), or struvite may settle in anaerobic slurry lagoons and be removed with the sludge (Nelson et al., 2003).

6.2.3. *Operation and separation efficiency*

P removal can be increased by adding Mg to the slurry being treated (Tab. X). The addition of Fe and a base to the slurry will enhance dissolution of Mg and thereby increase P removal (Suzuki et al., 2002; Laridi et al., 2005). On the other hand, P removal may be low even after the addition of Mg and NH_3 if pH is low (Tab. X; Sheffield et al., 2005).

Aeration of slurry or anaerobic digestion of slurry will increase pH and also reduce the organic matter content in the slurry (Suzuki et al., 2002; Massé et al., 2005). Both processes will greatly enhance crystallization of struvite due to an increase in the concentration of dissolved Mg^{2+} and PO_4^{3-}. Thus, aeration may produce a slurry with a mole ratio optimal for struvite crystallization, and increase struvite crystallization by a factor of about 10. In a continuous-flow pilot-scale sedimentation plant, this leads to the removal of 65–99% of P and 15% of total N (Tab. X; Suzuki et al., 2002).

Crystallization is initiated by nuclei, which may be grains of sand, or by contributing energy to the nucleation process by using rakes (Battistoni et al., 2002). In most slurries, the amount of sand is generally high and one would not anticipate any need to enhance the nucleation process.

7. POST-TREATMENT: SEPARATION TECHNIQUES

Post-treatment separation techniques need to be employed when eco-efficient technical solutions to the processing of animal slurry are sought. The objective is to produce clean water, heat and power, fuel, and high-value N, P and K fertilizers from animal slurry – products that may not be obtained when using solid–liquid separation on its own. Some technologies have been tested on the laboratory scale, while a few have reached the farm pilot-production scale. The techniques described in this section have been chosen based on the criterion that sufficient knowledge is currently available to discuss their possible usefulness.

7.1. Evaporation

7.1.1. Technical description, operation and separation efficiency

Water and volatiles can be removed from the slurry or the liquid fraction by evaporation. The liquid is heated to boiling point, which for slurry will be a little over 100 °C at atmospheric pressure. At this temperature, both water and volatile organic compounds, such as free fatty acids and NH_3, will evaporate. This vapor phase has to be condensed in order to retrieve the energy used to evaporate the water and volatiles. The energy consumed in the process is high, as the heat needed for evaporation represents roughly 670 kWh per metric ton of water evaporated. The energy (q) consumed in a single-step evaporator can thus be estimated as:

$$q = \dot{m}_{water} \cdot \Delta H^{vap} \tag{18}$$

where ΔH^{vap} is the heat of evaporation (J kg^{-1}), $\dot{m}_{water}$ is the amount of water removed (kg s^{-1}), and q is the energy consumption (W).

To reduce the energy costs, evaporators can be operated either as single evaporators using recompressed steam, or in series where the vapor generated in the first evaporator is used as heating steam for the next evaporator. In order to transfer energy from the steam to the liquid in each evaporator, the steam temperature has to be higher than the liquid temperature. Therefore, each consecutive evaporator is operated at a lower temperature than the preceding evaporator. Boiling can thus only be achieved in each evaporator by operating each at a slightly lower pressure than the preceding evaporator. As the boiling point for slurry increases with solid content, the liquid slurry should enter the last evaporator and run countercurrent to the vapor. Even though multi-step evaporation increases investment costs, experience from industrial applications shows that between three and six evaporators in series is economically viable (Foust et al., 1980; McCabe et al., 2005). In this way, a 92%-volume reduction can be achieved at an energy consumption of 120–130 kWh per ton slurry treated (Pedersen, 2004). No literature on the effect on N separation has been found.

7.2. Membranes

For small particles, membrane filtration of the liquid fraction could be an attractive supplement to solid–liquid separation (see Sect. 5). Furthermore, membrane separation may be used to separate and concentrate dissolved K, P and N nutrients, producing a nutrient-rich liquid phase and, in principle, pure water for reuse or safe discharge to the environment. A review on membrane processes for slurry treatment has recently been published (Massé et al., 2007b), which gives details of efficiency and usability, and therefore only a short description is included here.

7.2.1. Microfiltration and ultrafiltration

7.2.1.1. Technical description

Microfiltration removes solid particles in the range of about 0.1–10 μm, while ultrafiltration retains solid particles in the range from about 5 to 200 nm (Baker, 2004). Thus, they are well suited to remove nutrients associated with small particles such as *P* (Massé et al., 2007b).

The design of membrane units is based on the membrane flux (J_{liquid}), which is the amount of liquid removed per area of membrane. In micro- and ultrafiltration, J_{liquid} can be described by the general equation:

$$J_{liquid} = \frac{\Delta P}{\mu_{liquid} \cdot (R_m + R_{rev} + R_{irrev})} \tag{19}$$

where J is the flux (kg m^{-2} s^{-1}), μ_{liquid} is the viscosity of the permeate, R_m is the resistance to flow from the membrane (m^{-1}), R_{rev} is the reversible fouling resistance often ascribed to filter cake formation and concentration polarization (m^{-1}), R_{irrev} is the irreversible fouling resistance normally ascribed to pore blocking and adsorption of materials to the membrane (m^{-1}), and ΔP is the transmembrane pressure over the membrane (Pa).

During micro- and ultrafiltration, the slurry is pressed through a porous membrane. If dead-end filtration is used, a very dense filter cake build-up will occur. Therefore, micro- and ultrafiltration have to be carried out as cross-flow filtration, where only a fraction of the liquid is removed as permeate through the membrane, while solids and part of the liquid are retained as retentate. The cross flow removes most of the solids deposited on the surface, but some flow-controlled reversible filter cake formation cannot be avoided. Worse still, irreversible adhesion of minor particles can occur in the membrane pores, partly blocking the path for the liquid. In addition, bacterial growth can occur on the membrane surface, further reducing the flow through the membrane. This kind of membrane fouling will be especially severe for the treatment of slurry. Reversible filter cake formation can be removed by flushing with water. In contrast, the irreversible fouling can, at best, only partly be removed by cleaning the membrane in the system (CIP) with dilute base followed by dilute acid and, if necessary, enzymatic treatment.

Because of fouling, micro- and ultrafiltration membranes can only be used to separate pre-treated slurry, such as effluent streams from biogas reactors or runoff streams from centrifuges.

7.2.1.2. Operation and separation efficiency

For slurry microfiltration, transmembrane pressure will typically be around 100–180 kPa. At this pressure, filter cake formation and fouling become rate-determining, and increasing the transmembrane pressure no longer increases the flux over the membrane to any significant extent. Increasing the feed flow can increase the flux by reducing the filter cake thickness, but at velocities above around 2 m s^{-1} this becomes uneconomic (Owen et al., 1995). Therefore, the maximum flux attainable is limited to around 160 $L \cdot m^{-2} \cdot h^{-1}$, although long-term fluxes down to 10–40 $L \cdot m^{-2} \cdot h^{-1}$ should be expected, due to fouling. Depending on the size distribution, a retention efficiency of 75% of *DM* can be expected (Massé et al., 2007b). Membrane filtration retains small particles; therefore, the large amount of P contained in particles between 0.45 and 10 μm is retained with membrane filtration, and a high P removal can be expected (Massé et al., 2007b). Dissolved N, K and *DM* will not be retained.

For ultrafiltration, transmembrane pressures up to 800 kPa can be used, depending on membrane pore size. The larger the pore size, the lower the transmembrane pressure (Baker, 2004). For filtered pig slurry, fluxes between 10 and 40 $L \cdot m^{-2} \cdot h^{-1}$ at a transmembrane pressure of 100 kPa have been reported with 100% *DM* removal and a P removal efficiency of up to 87%, depending on operational conditions (Massé et al., 2007b). For partially digested non-filtered pig slurry, flushing the membrane every 5 minutes with permeate leads to a fall in flux of 25% over a 70-day period compared with a flux decline of 75% if only a single cleaning procedure is carried out (du Preez et al., 2005). In this study, though, the maximum flux was only 16 $L \cdot m^{-2} \cdot h^{-1}$.

7.2.2. Nanofiltration and reverse osmosis

7.2.2.1. Technical description

The liquid fraction from an ultrafiltration membrane can contain large amounts of dissolved K^+, NH_4^+ and NH_3. Reverse osmosis and, to some extent, nanofiltration membranes can retain dissolved nutrients, and deliver high concentrate retentate and purified water permeate. Depending on the membrane chosen, nanofiltration will retain uncharged molecules larger than 200–400 Da and, to a lesser extent, smaller charged molecules such as Ca^{2+}, Mg^{2+} and NH_4^+. Nanofiltration can thus be used to remove *DM* and, to some extent, charged molecules. If a pure water permeate is needed, reverse osmosis can retain NH_4^+ and K^+ and, to a lesser extent, NH_3 (Massé et al., 2007b).

The fouling problems are even more severe for nanofiltration and reverse osmosis than for micro- and ultrafiltration. In connection with slurry, nanofiltration or reverse osmosis can therefore only be used for separation of dissolved components from the permeate produced in an ultrafiltration unit. The direct filtration of raw slurry will foul the membrane within minutes.

The water flux through nanofiltration and reverse osmosis membranes has been described by Baker (2004) as follows:

$$J_{liquid} = A \cdot (\Delta P - \Delta \Pi) \tag{20}$$

where A is the water permeability (kg m^{-2} $s^{-1}Pa^{-1}$) and $\Delta\Pi$ (Pa) is the osmotic pressure difference between retentate and permeate. The maximum possible retentate concentration will be determined by the osmotic pressure difference and the maximum possible transmembrane pressure.

As concentration polarization influences the osmotic pressure on the membrane surface during nanofiltration and reverse osmosis, experimental permeability constants depend on the liquid cross flow and, because of unavoidable fouling, on time in use. As for micro- and ultrafiltration membranes, cleaning will need to be performed regularly in order to avoid fouling.

7.2.2.2. Operation and separation efficiency

For nanofiltration transmembrane operation, pressure will be around 350–3000 kPa. Although not well suited for the removal of K or N, nanofiltration membranes have been shown to be capable of removing up to 52% of the NH_4^+ and 78% of the K (Massé et al., 2007b) and, if a suitable membrane is chosen, all the soluble *DM* with a molecular weight above 200 Da will be removed.

For more demanding applications, reverse osmosis has to be used. The transmembrane pressure for reverse osmosis operations is typically around 3.5–6.5 MPa, although up to 150 MPa can be achieved for specially designed membranes. The retention of K is usually high and independent of pH but, as NH_4^+ is retained better than NH_3, the separation is very pH-dependent and also depends on the ionic strength of the retentate (Massé et al., 2008). Therefore, N separation will depend on pH, slurry origin and the final volume reduction of the retentate. For pig slurry, the retention of NH_4^+ thus decreased from 90% to 70% and for K from 93% to 87% when the reduction in retentate volume was increased from 50% to 90% (Massé et al., 2007b).

As the flux for nanofiltration and reverse osmosis is very dependent not only on fouling but also on the osmotic pressure of the retentate, the flux will change dramatically during a concentration process, with maximum fluxes reaching up to 65 L m^{-2} h^{-1} at the initial conditions, but approaching zero at the final reduction volume, where the osmotic pressure approaches the transmembrane pressure.

8. CONCLUSIONS

Separation indexes, which express the distribution of the specific component between the solid and liquid fractions (see Eqs. (5, 6)), have proved useful for the comparison of the efficiency of the different separation techniques. From a literature review it was found that only about 25% of the papers on solid–liquid separation included sufficient data to assess the separation index of the technology tested. This emphasizes the need for a standard method for characterizing slurry separation efficiency, including a thorough characterization of the animal slurry treated and the fractions produced, and flow measurements of the slurry being treated.

Slurry can be treated with separation technologies that produce a solid fraction in which much of the P and dry matter (*DM*) and significant amounts of the N in the slurry are retained. These technologies are simple to use and reliable. More complex technologies may, although with a relatively high energy consumption, remove nitrogen, including NH_4^+, from the slurry. By combining solid–liquid separation technologies with pre- and post-treatments, end-products having an optimal composition for a specific end-use may be produced.

In order to achieve these objectives, there is a need for studies on the physical and chemical properties of slurry and their effects on separation efficiency, which include a functional physical-chemical characterization of slurry and identification of how the treatment affects the physical-chemical characteristics of the separation product. Only if this knowledge is available can existing separation technologies be optimized and combined in a systematic way in order to achieve the desired end-products.

At present, the most efficient solid–liquid mechanical separators for the removal of *DM*, P and, to some extent, total N and NH_4^+, can be ranked in the following order: centrifuge > sedimentation > filtration without pressure > filtration with pressure. Struvite crystallization prior to the solid–liquid separation improves the N and P separation. Flocculation before separation also improves the separation of *DM*, N and P significantly. The best flocculant available at present (polyacrylamide – PAM) is a cationic, medium-charge-density (20–40 mol%), linear, large-molecular-weight polymer, and the best coagulants are $Al_2(SO_4)_3$ and $FeCl_3$. Filtration without pressure is the best slurry separation technique for slurry with added flocculants.

After the separation of *DM*, P and N from the slurry, the liquid fraction produced may be treated with membrane separation, evaporation of water or NH_3 stripping. Regarding membrane separation, attention must be paid to fouling problems. Stripping and evaporation have a high energy consumption, and efficient heat recovery or cheap surplus heat is necessary for these technologies to be of interest at present.

In order to set up an animal slurry separation operation, a whole-system approach is important either with or without pre- and post-treatments. Just as in any industrial farm operation, it is of paramount importance to balance investment, running and labor costs against product added value, environmental impact and process complexity. This seems to be a promising area for future intensive research and development.

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