Evaluation of mechanical separation of pig and cattle slurries by a decanting centrifuge and a brushed screen separator

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Executive Summary

Mechanical separation of animal slurry produces a liquid fraction with a lower dry matter concentration than the input slurry and a solid fraction with a higher dry matter concentration than the input slurry. Plant nutrients in the slurry are partitioned between the liquid and solid fractions. Differential partitioning occurs if one or more component of the input slurry is partitioned in excess of the weight/volume split between the liquid and solid fractions.

In the current work, AFBI-Hillsborough evaluated the performances of a brushed screen separator and a decanting centrifuge with pig and cattle slurries. The effects of adding coagulant and polyelectrolyte to the slurries (chemical treatment) on separator efficiencies were also evaluated.

For the brushed screen control treatment (no chemicals added), separation efficiency for all components measured was positively correlated with input pig slurry dry matter concentration. There was some differential partitioning of dry solids into the separated solid fraction; otherwise the brushed screen separator partitioned nutrients more or less in proportion to the fresh mass of the liquid and solid fractions. The weight of fresh solids produced from the brushed screen per tonne of slurry was dependent on the input slurry dry matter concentration e.g. with pig slurry dry matter concentrations of 25g/kg and 60g/kg, 10kg and 91kg fresh solids were produced respectively. Chemical treatment of slurry inputted to the brushed screen resulted in some differential partitioning of total nitrogen (TN), total phosphorus (TP) and dry solids, though the effect was small.

The decanting centrifuge partitioned a much greater proportion of pig slurry TN, TP and dry solids into the separated solid fraction than the brushed screen separator. The weight of fresh solids produced from the decanting centrifuge per tonne of pig slurry separated without chemicals was dependent on input slurry dry matter concentration e.g. at pig slurry dry matter concentrations of 25g/kg and 60g/kg, 58kg and 111kg fresh solids were produced respectively. Chemical treatment of pig slurry further increased the quantity of fresh solids produced from the decanting centrifuge e.g. at 60g/kg slurry dry matter concentration, 185kg of fresh solids were produced. Without chemical additions, 79% of the TP in pig slurry and 64% of the TP in cattle slurry was partitioned to the separated solid fraction by the decanting centrifuge. Adding chemicals to slurry inputted to the decanting centrifuge increased the TP in pig and cattle slurry partitioned into the separated solids to 93% and 82% respectively, but had very little effect on the partitioning of potassium (K) and ammonia nitrogen (NH_3-N). The brushed screen separator without chemical addition transferred means of 6% and 17% of the TN from pig and cattle slurry respectively into the solid fraction, increasing to 7% and 23% with chemical additions. The corresponding figures for the decanting centrifuge were 21% and 25% for pig and cattle slurry respectively, increasing to 34% and 41% with chemical additions.

For both separator types, adding chemicals to pig slurry to improve separation efficiency significantly increased the volume of supernatant by between 9% (medium rate of polyelectrolyte addition) and 28% (high rate of polyelectrolyte addition) as a result of dilution with water. The cost of the chemicals used in this experiment ranged from £1.50 (low rate coagulant/medium polyelectrolyte addition) to £3.74 (high rate coagulant/high polyelectrolyte addition) per tonne of slurry inputted to the separators. The increased volume of supernatant that resulted from the high rate of polyelectrolyte addition would not be practical for many farms.

Pig slurry treated with chemicals prior to decanting centrifuge separation produced a supernatant that contained approximately 9g/kg dry matter concentration, 2g/kg total nitrogen and 0.04g/kg total phosphorus

For an annual throughput of 4,000 tonnes of pig slurry, it was estimated that the cost of separation without chemicals with the decanting centrifuge, could be approximately £4.50 per tonne of input slurry and about £0.85 per tonne for the brushed screen. At this annual throughput of pig slurry and without chemical addition, the estimated costs for partitioning phosphorus and nitrogen into the separated solids could be in the order of £6,000/t of TP and £5,000/t TN for the decanting centrifuge and £13,000/t TP and £3,000/t TN for the brushed screen. All these costs are dependant, inter alia, on the quantity of slurry separated per year, depreciation and interest charges. For example, at a throughput of 8,000 tonnes per year, costs could be approximately halved.

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General Introduction

Mechanical separation of slurry is not a new technology, but has come back into focus, mainly due to the implementation of the EU Nitrates Directive. The Guidance Booklet from DARD and EHS for Farmers, on the Requirements of the Nitrates Action Programme (Northern Ireland) Regulations 2006 and the Phosphorus (Use in Agriculture) (Northern Ireland) Regulations 2006 allow for a maximum volume reduction of 20% for separated animal manures (except pig).

A mechanical separator separates animal slurry into liquid and solid fractions. The solid fraction of separated cattle manure can be stored as farmyard manure, and can be applied to land throughout the year, provided soil and weather conditions are suitable (see Guidance Booklet for details). The solid fraction from separated pig slurry is subject to the same restrictions as raw slurry in regard to when it can be land spread. The liquid fraction, often termed supernatant, is lower in volume and dry matter concentration than the original slurry and should not require mixing before being applied to the land. It is suitable for a number of methods of application such as irrigation, injection or application by trailing-shoe tanker. This is because a mechanical separator removes the larger fibre particles from the liquid fraction that might otherwise block delivery pipes. The supernatant will generally have a higher N : P ratio compared to the raw slurry and may therefore be better matched to crop requirements. Due to the lower dry matter concentration of the supernatant, the efficiency of use of the ammonia-N concentration in the supernatant should be improved, even if applied by splash-plate. This is because the supernatant will percolate into the soil more readily than raw slurry, thus decreasing the amount of time exposed to the atmosphere and as a consequence, volatilisation of ammonia should be reduced.

Under the Nitrates Action Programme regulations, farmers are currently restricted to a total farm limit of 170 kg/ha/year of organic nitrogen. In reality, this means that a significant minority of livestock farmers in Northern Ireland do not have enough land for the amount of organic nitrogen produced on their farms. One possible solution may be to separate the slurry produced and transport the separated solids (and the nutrients they contain) to another farm, where there is a requirement for these nutrients, e.g. arable farms. In this situation, the ability to differentially partition plant nutrients (nitrogen and phosphorus) into the solid fraction could be of benefit.

In the light of these possible scenarios, AFBI, Hillsborough instigated a research programme on mechanical slurry separation, in order to provide the industry with relevant information. Although cattle slurry comprises 88% of the total slurry produced by housed livestock in Northern Ireland (Frost 2005), pig slurry was the primary focus of this experiment, as many pig farmers have insufficient land to meet the 170 kg/ha/year of organic nitrogen limit stipulated in the Nitrates Action Programme.

Separators evaluated

Two types of separator were evaluated: a ‘farm-type’ brushed screen separator (NC Engineering, Northern Ireland) (Figure 1) and a decanting centrifuge

(Westfalia UCD 205, Germany) (Figure 2). The decanting centrifuge had a maximum throughput of 5 tonnes/hr (depending on the dry matter concentration of the slurry) while the brushed screen separator had a nominal capacity of 10-15 tonnes/hour. The brushed screen separator was powered by a 0.75kW electric motor, while the centrifuge was powered by a 7.5kW electric motor. The rotational speed of the centrifuge was 4500 revs/minute (not adjustable).

Figure 1. *Brushed screen separator.*

Figure 2. *Decanting centrifuge.*

Decanting centrifuges are widely used in the wastewater industry, such as domestic sewage works. They have a higher cost, employ higher technology, but are generally more efficient at separating the nutrients in the slurry into the separated solid fraction, compared to a ‘farm type’ separator. Decanter centrifuges work on the principle of different specific gravities of the material in the centrifuge. Slurry is pumped into a conical shaped cylinder, which rotates at high speed, normally between 2000 and 4500 revs per minute. The solid material, which is denser than the liquid fraction, is forced towards the outside of the bowl. An auger, commonly called a screw, rotates inside the bowl, normally between 2 and 12 revs per minute faster than the bowl. The net effect is that the auger collects the solids that are centrifuged to the outside of the bowl and brings them to the tapered end of the bowl, where they are squeezed out of the centrifuge and removed to a collection point. The liquid drains back from the cone and is decanted over a weir plate at the opposite end of the centrifuge. The dryness of the solids can be changed by adjusting the speed of the auger, relative to the bowl speed, or by adjusting the weir plates so that there is a longer or shorter ‘beach’ in the centrifuge. On many decanting centrifuge the auger will automatically speed up when its resistance (torque) reaches a preset reading, so that solids are removed more quickly. This is a safety feature to prevent the machine blocking.

The brushed screen separator works by a sieve action. Slurry is pumped over a weir where the slurry flows onto a concave semi-circular screen with a choice of mesh sizes (1.6mm mesh was used in the current work). A rotating brush takes the material left on the screen into the next section, where there is another concave semi-circular screen. A rotating roller squeezes the material left on the screen to force liquid out and the solids remaining are subsequently brushed off the screen to the solids collection container beneath the separator. The liquid that passes through the screens is collected and stored for future land application.

Chemicals are often added to enhance the dewatering process. The two basic types of chemical that used are:

1. a metal base which causes small particles and dissolved material in the slurry to coagulate
2. a polyelectrolyte that adheres these particles into larger separable particles called flocs.

The polyelectrolyte normally used is a synthetic water soluble polymer, such as polyacrylamide (PAM).

The amount of polymer required to produce a supernatant of a given quality can be reduced by the addition of a coagulant (sometimes called a conditioner). The 2 types of chemical work best when combined and their combination reduces the amount of PAM required to produce a given quality of supernatant. The polymer is the more expensive of the 2 chemicals and hence it is desirable to minimize the requirement for it. The chemicals aid the separation process by coagulating solids in the slurry, which combine into larger flocs that are easier to separate, due to their higher density, relative to the liquid medium.

Separator Efficiency

There are several different ways to measure the effectiveness of a separator in its ability to partition nutrients between the liquid and solid fractions:

1. The concentration of a constituent in the solid fraction

2. The reduction in concentration of a constituent in the supernatant, relative to the raw slurry as given in Equation1:

   Equation 1:

   (Concentration in slurry – concentration in supernatant) / concentration in slurry

3. The proportion of a constituent partitioned to the solid fraction, relative to the amount in the slurry, as given in Equation 2:

   Equation 2:

   (Concentration in solid fraction, g/kg) X weight of solid fraction, kg) / (concentration in slurry, g/kg X weight of slurry, kg) = (E)

4. The reduced separation efficiency index. This was developed by Moller *et al.* (2000), to give an indication of the increase in concentration of a constituent in the solid fraction. A value of 0 indicates that a constituent is equally distributed between the liquid and solid fraction. A value of 1 indicates that the constituent is all in the solid fraction. The formula for the reduced separation efficiency index is give in Equation 3 using E as defined above in Equation 2 and (R) which equals fresh weight of solid fraction / fresh weight of slurry

   Equation 3:

   Reduced separation efficiency index = (E - R) / (1 - R)

Materials and Methods (pig slurry)

Pig slurries with a wide range of dry matter concentrations were sourced from dry sows, farrowers and fatteners. On each occasion, slurry from a single source was stored in a 9000 litre covered PVC cylindrical tank (diameter 2.5m, height 1.9m) and continually mixed with an electrically operated submersible pump (Landia, 4kW). This tank was fitted with a sight tube that enabled the depth of slurry and consequently the volume of slurry in the tank to be measured. The tank was calibrated with known weights of slurry, the weight of slurry per unit height calculated and the sight tube was marked accordingly. The specific gravities of slurries with a range of dry matters were measured and a density of 1kg/litre was found to be appropriate for all slurries being tested.

Slurry was pumped to the respective separator through a flow meter using a variable speed electrically driven mono pump (Seepex). The volume change in the feed tank was used to verify the flow meter readings. Slurry was sampled throughout each treatment run, as were the supernatant and separated solids. The samples obtained were subsequently analysed for dry matter (DM), total nitrogen (TN), ammonia nitrogen (NH_3-N), total phosphorus (TP), potassium (K) and sulphur (S). A subset of the samples from the decanting centrifuge was further analysed for total suspended solids (TSS). The volumes of slurry inputted to the separators and the separated liquid volumes were measured, together with the weights of the solids separated. This allowed the mass balance and efficiency of separation to be determined.

The chemical treatments applied to pig slurry were:

1. Control, i.e. no chemical addition.
2. Chemical conditioner - low, medium and high rate (0.16%, 0.25% and 0.38% of slurry volume) along with a constant rate of polymer (17% of slurry volume).
3. High polymer/high conditioner - high rates of both polymer and conditioner (0.38% and 47% respectively of slurry volume) to obtain the 'best' supernatant possible i.e. the lowest dry matter concentration in the supernatant.

These treatments were applied to both separators, with the exception of Treatment 3, which was applied to the decanting centrifuge only. Treatments were replicated a minimum of 5 times with a range of slurry dry matter concentration, so that a database of results could be established.

Each replication was timed over an average of 40 minutes, with the input and corresponding outputs being measured and sampled. This allowed a double check on the mass balance to be taken, i.e. one based on the volumes in and out and the other on the flow rates in and dry matter concentration of the materials in and out. An equation derived to calculate supernatant volume is given by Equation 4.

Equation 4. Formula derived to calculate flow rate of supernatant from each separator.

Supernatant throughput (kg/hr fresh) = {{solids DM (kg/kg) x {slurry + chemical input (kg/hr)} - DM throughput of slurry (kgDM/hr)}} / {{solids DM (kg/kg)} -{supernatant DM (kg/kg)}

Throughput of fresh solids was determined by subtracting the calculated supernatant volume from the total input of slurry and chemicals inputted. The calculated weights of supernatant and cake produced per hour were adjusted pro rata for the length of time of each run.

The chemical conditioner, (an aluminium salt in liquid form, product name PC31, manufactured and supplied by Celtic Water Care, Cork, Ireland), was stored in a 1m^3 polycube. Conditioner was pumped into the slurry supply line via a variable speed Milton Roy pulse pump (range 0 –15l/hr). The pump was calibrated using an inline measuring cylinder, with the volume change recorded over a set time period. Conditioner was added to the slurry on outlet side of the slurry pump feeding the separator. The polymer used was a water soluble polyacrylamide (PAM), (product name C1900P, manufactured and supplied by Celtic Water Care, Cork, Ireland). A computerised polymer makeup station was supplied in the same containerised unit as the centrifuge. It was calibrated by a chemist employed by Celtic Water Care and set to dilute the polymer to a solution of 0.4% by volume. The diluted polymer (approximately 750L) was continually stirred prior to being added to the slurry. The mass balance calculations took into account the amount of liquid being supplied by the chemical/water additions. The polymer was added to the centrifuge directly into the bowl, via a variable speed pump, whereas for the brushed screen separator, the polymer was applied in line to the slurry as it was being pumped to the separator. There was a time lag of approximately 4 minutes between chemical addition and separation through the brush screen separator. The slurry feed pump was set at approximately 2.6m^3/hr. The polymer pump was set at approximately 440 l/hr and the conditioner pump at 4.1, 6.2 and 10.0 l/hr for the low, medium and high conditioner treatments respectively. For the high rate polymer and conditioner combined treatment, the polymer averaged 1220 l/hr and the conditioner 10 l/hr, at a slurry feed rate of 2.6 m^3/hr. These combinations were determined by the chemical supplier's chemist on site, who carried out bench tests with the slurry and chemicals and then applied the results to the separator. The polymer dosing rates were not adjusted for changes in slurry dry matter concentration, which was assumed to be fairly constant. In practice, slurry dry matter concentration were more variable than anticipated and this meant that the quality of the supernatant may not always have been as good as might have been expected.

Results of Pig Slurry Separation

Brushed screen separator with pig slurry

The chemical composition of the pig slurry feedstock prior to separation through the brushed screen separator, are summarised in Table 1.

Table 1. Composition of pig slurry before separation through the brushed screen separator.

Slurry (g/kg fresh)	Mean	Min	Max	Stdev
DM	45.4	22.2	71.0	15.67
TN	3.73	1.76	5.68	1.106
NH_3-N	2.48	1.14	3.86	0.758
TP	1008	440	1583	337.3
K	2484	1163	3865	729.9
S	396	177	638	129.8
N:P ratio	3.70	1.11	8.61	1.812

The pig slurry had a mean dry matter concentration of 45g/kg with a range between 22 and 71g/kg. This range of dry matter concentrations is reflected in the considerable variation in concentration of the constituents measured in the slurry. There were significant ($P<0.001$) positive linear correlations between the dry matter concentration of the slurry and either TP or K slurry concentration (R^2 = 0.87 and 0.68 respectively). The slurry TN and NH_3-N concentrations were very variable and there was no correlation with slurry dry matter concentration. The results for pig slurry separated through a brushed screen are presented in Table 2.

Table 2. Characteristics of the supernatant and solid fractions of pig slurry after separation through a brushed screen separator.

Supernatant (fresh weight)	Chemical	Control	F-value	S.E.M
DM (g/kg)	32.6	35.7	0.460	3.36
Total N (g/kg)	3.07	3.76	0.118	0.343
NH_3-N (g/kg)	2.06	2.62	0.078	0.245
TP (mg/kg)	892	857	0.736	81.6
K (mg/kg)	2098	2631	0.079	231.9
S (mg/kg)	301	319	0.689	35.3
N:P ratio	3.81	4.39	0.404	0.556
Solids (fresh weight)				
DM (g/kg)	176	168	0.398	7.7
TN (g/kg)	4.90	4.68	0.376	0.200
NH_3-N (g/kg)	1.72	1.98	0.110	0.128
TP (mg/kg)	2202	1275	<0.001	96.1
K (mg/kg)	1966	2445	0.041	177.8
S (mg/kg)	1004	868	0.005	35.2
N:P ratio	2.26	3.77	<0.001	0.226
Separator Efficiency[1]				
Total solids	0.19	0.19	0.946	0.037
TN	0.07	0.06	0.509	0.016
NH_3-N	0.03	0.03	0.874	0.007
TP	0.10	0.07	0.207	0.021
K	0.04	0.05	0.787	0.011
S	0.13	0.12	0.753	0.025
Supernatant volume change (as % of slurry inputted)	12.1	-5.2	<0.001	1.33

Footnote 1. see Equation 2.

None of the measured supernatant nutrient concentrations were significantly altered by chemical addition, compared to the control treatment. However, there were significant reductions (P<0.001) in the concentration of nutrients, relative to the slurry concentration of the respective constituent (see Equation1). For the chemical treatments, the dry matter concentration of the supernatant was reduced by 28% relative to the slurry dry matter concentration, while the corresponding figure for the controls was a 15% reduction. This difference is largely due to the dilution effect of the chemical additions, which added 17% extra volume to the slurry. There was almost no reduction in the TN concentration of the supernatant for the control treatments, relative to the slurry TN concentration, whereas the respective figure for the chemical treatments was a reduction of 16% in the supernatant TN concentration, relative to the slurry TN concentration.

Irrespective of treatment, the dry matter concentration of the supernatant was positively correlated to the dry matter concentration of the slurry (P<0.001), as described by Equations 5 and 6. The data are presented in Figure 3.

Equation 5. Relationship between pig slurry dry matter concentration and the supernatant dry matter concentration for the brushed screen separator, without chemical addition.

Control treatment: Supernatant DM (g/kg) = Slurry DM (g/kg) X 0.642 + 8.167

R^2 = 0.99 (P<0.001)

Equation 6. Relationship between pig slurry dry matter concentration and the supernatant dry matter concentration for the brushed screen separator, with chemical addition.

Chemical treatment: Supernatant DM (g/kg) = Slurry DM (g/kg) X 0.544 + 7.184

R^2 = 0.91 (P<0.001)

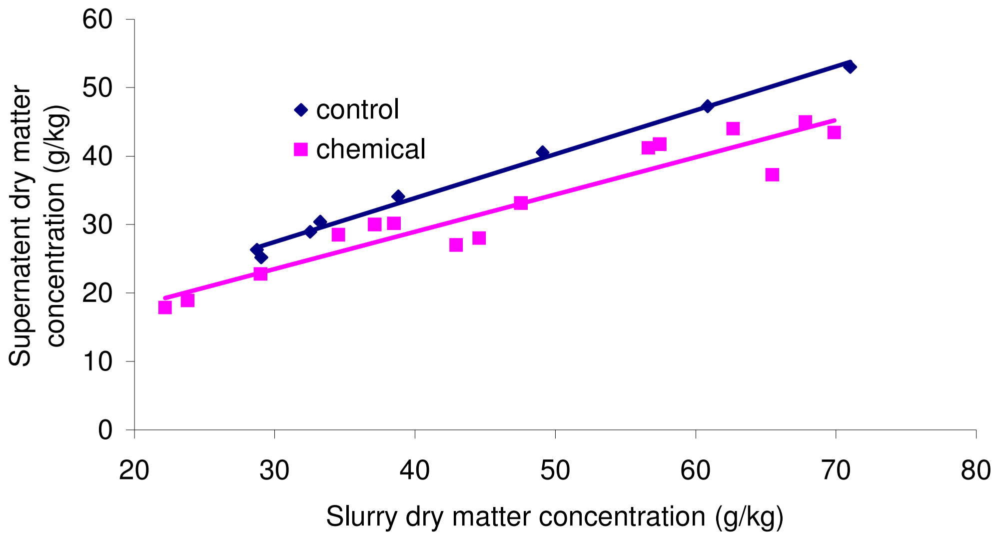


Figure 3. Brushed screen: Relationship between pig slurry dry matter concentration and supernatant dry matter concentration.

The amount of dry solids partitioned to the solid fraction was positively correlated with the dry matter concentration of the slurry, as described by Equations 7 and 8. The data are presented in Figure 4.

Equation 7. The relationship between pig slurry dry matter concentration and the percentage of dry solids partitioned to the separated solid fraction, for the brushed screen without chemical addition

Control treatment: % solids removal = Slurry DM (g/kg) X 0.539 – 4.126

R^2 = 0.94 (P<0.001)

Equation 8. The relationship between pig slurry dry matter concentration and the percentage of slurry dry solids partitioned to the separated solid fraction, for the brushed screen with chemical addition

Chemical treatment: % solids removal = Slurry DM (g/kg) X 0.513 – 4.606

R^2 = 0.53 (P <0 0.01)

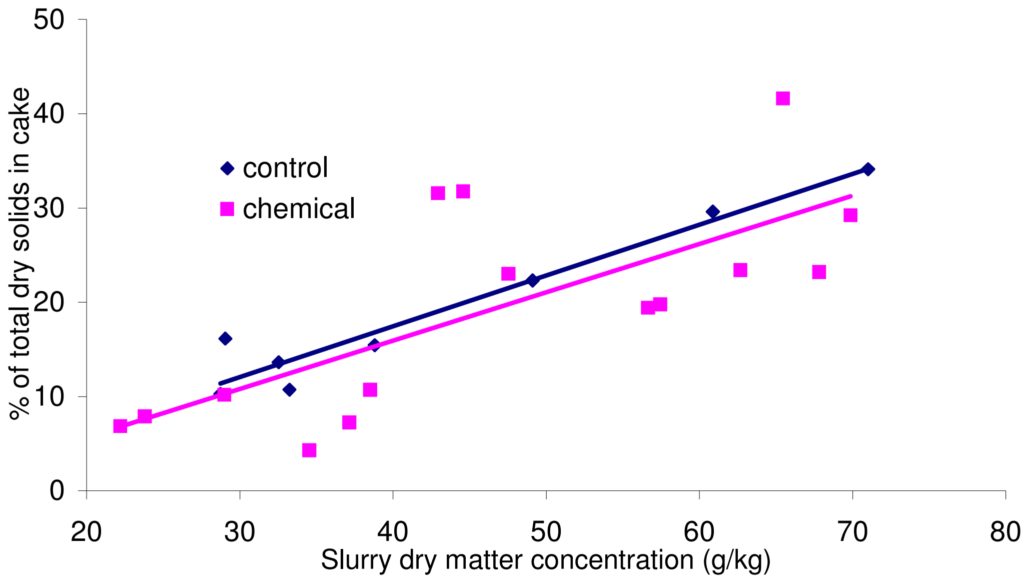


Figure 4. Brushed Screen: Relationship between pig slurry dry matter concentration and percentage of dry solids partitioned to the separated solid fraction.

Figure 4 indicates that while there was more variation in the relationship between slurry dry matter concentration and the percentage of total dry matter partitioned to the solid fraction for the chemical treatment, compared to the control treatment, the two lines are almost identical. This indicates that the chemical addition had very little impact on the amount of dry solids partitioned to the solid fraction. The difference between the two lines in Figure 3 can be attributed to the dilution of the slurry with the chemical addition, as chemical addition increased the slurry volume by a mean of 17%. At slurry dry matter concentrations below 30g/kg, approximately 10% of the dry solids was partitioned to the solid fraction, whereas as slurry dry matter concentration increased, the amount partitioned increased to approximately 30% of the total dry solids at 60g/kg slurry dry matter concentration.

Pos *et al.* (1984) evaluated a brushed screen separator with pig slurry without chemical addition. They reported, that with a slurry dry matter concentration of 52 g/kg, 17.3% of the dry solids were partitioned to the solid fraction. The equivalent value from the results presented above is 23.9%. Chemical addition had very little effect on the amount of dry solids partitioned to the solid fraction. However, the concentration of TP in the solid fraction for the chemical treatments was significantly ($P<0.001$) greater than for the control treatment. While the percentage of TP partitioned to the solid fraction for the chemical treatments was 50% greater than for the control treatment, the difference was not statistically significant, as large variations in the percentage of TP partitioned to the solid fraction were observed with the chemical treatments (2-16%). There was very little differential partitioning into the solid fraction of any of the constituents measured, with the exception of dry solids. Approximately 5% of the mass was partitioned to the solid fraction, irrespective of treatment and the percentage of the measured nutrients partitioned was similar (Table2). Chemical addition resulted in some differential partitioning of TN and TP into the solid fraction, but the effect was not statistically significant. Chemical addition resulted in 5.4% of the mass, 7.4% of TN and 10.2% of the TP partitioned to the solid fraction. The figures for the control treatment were 5.2%, 6.0% and 6.9% respectively (Table 2).

The volume change of the liquid fraction was significantly ($P<0.001$) affected by addition of chemicals, compared to the control treatment. There was a mean reduction in the volume of liquid for the control treatment of 5%, compared to the slurry volume, whereas the volume of liquid for the chemical treatments increased by 12%, relative to the volume of slurry inputted to the separator (Table 2). For every ton of pig slurry separated without chemical addition, the mean volume of the supernatant was 948 litres, with 52 kg of fresh solids, whereas with chemical addition, 1121 litres of supernatant were produced and 55 kg of fresh solids. There was no significant difference between treatments in the dry matter concentration of the solid fraction. At a mean concentration of 176 g/kg, the solids were stackable, but effluent was observed to seep out and must be contained. The dry matter concentration of the separated solids was significantly ($P<0.001$) and positively correlated ($R^2=0.92$) to the slurry dry matter concentration, irrespective of treatment (Equation 9).

Equation 9. Brushed Screen: Relationship between slurry dry matter concentration and separated solids dry matter concentration across all treatments

Solids DM concentration (g/kg) = Slurry DM concentration (g/kg) X 1.327 + 112.7

$R^2 = 0.92$ ($P<0.001$)

For the brushed screen separator, increasing the levels of conditioner along with a constant rate of polymer, did not produce any significant improvement in separation efficiency (as measured by the amount of a nutrient partitioned to the solid fraction, or the change in concentration of the nutrient in the supernatant, relative to the concentration of the nutrient in the slurry). There was no discernable trend in increased partitioning to the solid fraction with increasing amounts of conditioner. Therefore all the chemical treatments applied to the brushed screen separator were combined into one treatment, for the purpose of comparison with the no-chemical control treatment.

Decanting centrifuge with pig slurry

The composition of pig slurry prior to separation through the decanting centrifuge is presented in Table 3. The variation in nutrient concentrations reflects the large range in dry matter concentration of the feedstock pig slurries prior to separation.

Table 3. Composition of pig slurry prior to separation through a decanting centrifuge.

Slurry (fresh weight)	Mean	Min	Max	Stdev
DM (g/kg)	38.4	23.8	68.4	13.85
TN (g/kg)	3.53	2.29	5.68	0.876
NH_3-N (g/kg)	2.52	1.56	3.86	0.546
TP (mg/kg)	896	484	1351	224.6
K (mg/kg)	2450	1679	3923	664.0
S (mg/kg)	325	164	557	109.1
Slurry N:P ratio	3.94	2.68	8.06	0.980

Data from the separation of pig slurry through the decanting centrifuge are presented in Table 4. Compared to the control treatment, the chemical treatments had a significant ($P<0.001$) effect on most of the parameters measured. One exception to this was the concentration of TN in the solid fraction, which was unaffected by chemical addition. However, the concentrations of both NH_3-N and K partitioned to the solid fraction were significantly influenced by chemical addition, even though these constituents are largely found in the soluble fraction of pig slurry.

Data in Table 4 indicate that for the control treatment, the decanting centrifuge partitioned 53% of the DM and 79% of the TP into the separated solid fraction. The figures for the chemical treatments were 69% and 93% respectively. This indicates that TP was differentially partitioned to the solid fraction, even without chemical addition. The NH_3-N and K were partitioned almost exactly in proportion to the mass of supernatant and separated solids for the control treatment, with the chemical addition having a small positive, but significant ($P<0.01$) influence on the partitioning of these constituents to the separated solid fraction. These constituents are mainly in the soluble fraction and do not flocculate with chemical additions. The TP is relatively easy to separate into the solid fraction, as it is mainly found in the fine organic particles that the decanter can easily remove (Giusquiani *et al.* 1998). There was some differential partitioning of TN into the solid fraction with the control treatment and this was enhanced by chemical addition. For the control treatment, 8% of the mass and 21% of the TN was partitioned to the solid fraction. The corresponding figures for the chemical treatments were 9% and 33% respectively.

The dry matter concentration of the solids was significantly reduced ($P<0.001$) with the addition of chemicals, but the material was still being stackable with no effluent released from it. For the control treatment, a linear relationship was developed between the slurry dry matter concentration and the supernatant dry matter concentration as described by Equation 10. The results are expressed in Figure 5. There was no relationship between slurry dry matter concentration and supernatant dry matter concentration for the chemical treatments.

Table 4. Characteristics of the supernatant and separated solids from pig slurry separated through a decanting centrifuge.

Supernatant (fresh weight)	Mean Chemical[1]	Mean control	F-value	S.E.M.
DM (g/kg)	9.8	19.8	<0.001	1.31
TN (g/kg)	2.05	3.23	<0.001	0.153
NH_3-N (g/kg)	1.89	2.55	<0.001	0.126
TP (mg/kg)	54	200	<0.001	10.4
K (mg/kg)	1909	2571	<0.001	138.1
S (mg/kg)	69	193	<0.001	13.1
N:P ratio	44.1	16.5	<0.001	3.56
Solids (fresh weight)				
DM (g/kg)	226	258	<0.001	6.26
TN (g/kg)	10.13	10.18	0.875	0.276
NH_3-N (g/kg)	2.50	3.04	0.006	0.141
TP (mg/kg)	7274	9115	<0.001	338.0
K (mg/kg)	2198	2665	<0.001	90.4
S (mg/kg)	1797	1816	0.805	57.8
N:P ratio	1.41	1.14	<0.001	0.041
Separator Efficiency[2]				
Dry solids	0.69	0.53	<0.001	0.020
TN	0.33	0.21	<0.001	0.015
NH_3-N	0.12	0.08	0.039	0.008
TP	0.93	0.79	<0.001	0.009
K	0.11	0.08	0.01	0.007
S	0.72	0.45	<0.001	0.020
Supernatant volume change (as % of slurry inputted)	9.40	-7.90	<0.001	1.78

Footnote 1. Excludes high rate conditioner/high rate polymer. Footnote 2. Percentage of total inputted that was partitioned to the solid fraction (see Equation 2.)

Equation 10. Relationship between pig slurry dry matter concentration and supernatant dry matter concentration for the control treatment in a decanting centrifuge.

Supernatant DM concentration (g/kg) = slurry DM concentration (g/kg) X 0.504 + 0.1314
R^2 =0.91 (P<0.001)

Equation 10 is very similar to that developed by Sneath *et al.* (1988), following separation of pig slurry through a centrifuge, across a range of dry matter concentrations. The change in volume of the liquid mass (or weight transferred to the solid fraction), for the control treatment, expressed as a percentage of the slurry volume, showed a positive linear relationship with the slurry dry matter concentration as expressed in Equation 11. The data are presented in Figure 6. The volume reduction (maximum 12%) of the liquid mass is small, especially with low slurry dry matter concentrations, but is in line with the findings of Sneath *et* al. (1988). The small volume change has implications for the amount of liquid storage required for the supernatant.

Equation 11. Relationship between pig slurry dry matter concentration and the liquid volume reduction, relative to the slurry volume, for the control treatment in the decanting centrifuge.

% volume reduction of liquid mass = slurry DM concentration (g/kg) X 0.152 + 2.015
R^2 = 0.75 (P<0.001)

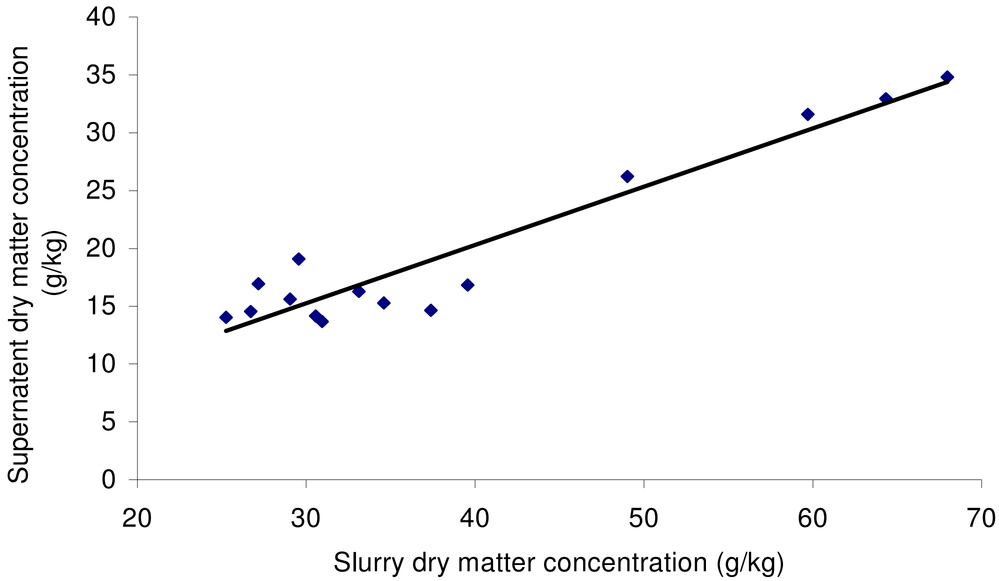


Figure 5. Relationship between pig slurry dry matter concentration and supernatant dry matter concentration for the decanting centrifuge, without chemical addition.

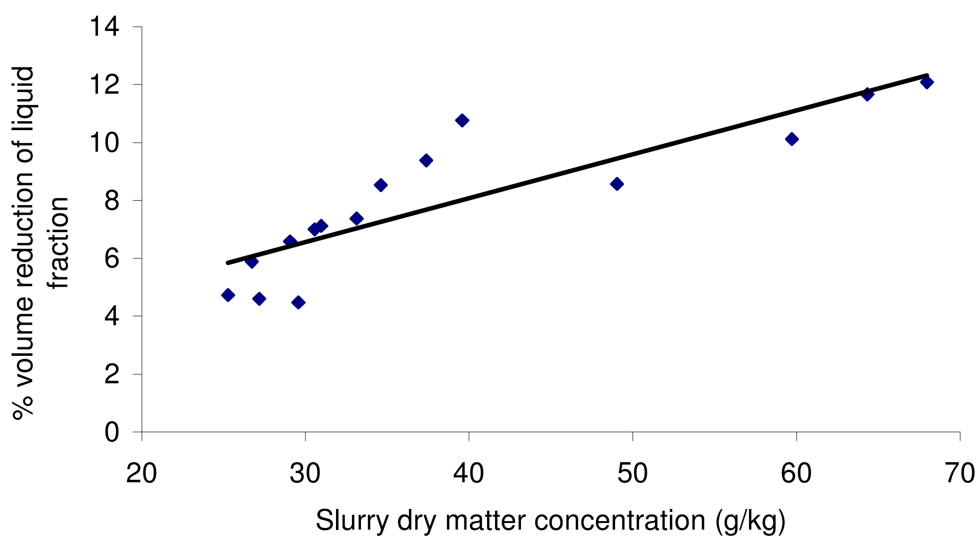


Figure 6. Relationship between percentage volume reduction of supernatant (relative to slurry input volume) and slurry dry matter concentration for the control treatments with the decanting centrifuge.

There was a positive linear relationship between the dry matter concentration of the slurry and the dry matter concentration of the solid fraction, for the control treatment. This is in contrast to Sneath *et al*. (1988), who found that the dry matter concentration of the solid fraction increased with decreasing slurry dry matter concentration. The reasons for this difference in findings are unexplained.

For the chemical treatments, there was no clear relationship between the dry matter concentration of the slurry and supernatant dry matter concentration, or the percentage of total dry solids partitioned to the separated solid fraction. The dry matter concentration of the slurry accounted for 50% of the variation in the dry matter concentration of the solid fraction, compared to 75% for the control treatment (Equation 11).

Equation 11. Relationship between pig slurry dry matter concentration and the liquid volume reduction, relative to the slurry volume, for the control treatment in the decanting centrifuge.

% volume reduction of liquid mass = Slurry DM concentration (g/kg) X 0.152 + 2.015
R^2 = 0.75 (P<0.001)

The volume change of the liquid fraction, relative to the slurry volume, for the chemical treatments (excluding high conditioner/high polymer treatment) is presented in Figure 7. This shows that with pig slurry below 50g/kg dry matter concentration, there was an increase in the volume of the supernatant relative to the slurry volume and this increased with decreasing slurry dry matter concentration. The relationship is given in Equation 12. The volume increase was due to the water that was used to dilute the polymer to 0.4%. If the polymer application rates were increased in line with increased slurry dry matter concentration, then the volume of the supernatant would increase even more. In the current work, the polymer application rates were not altered for differing slurry dry matter concentrations.

Equation 12. Relationship between volume of supernatant, relative to pig slurry volume, for the chemical treatments with the decanting centrifuge**.**

% volume change in liquid mass = 18.72 - 0.387 X Slurry DM concentration (g/kg)
R^2= 0.58 (P<0.001)

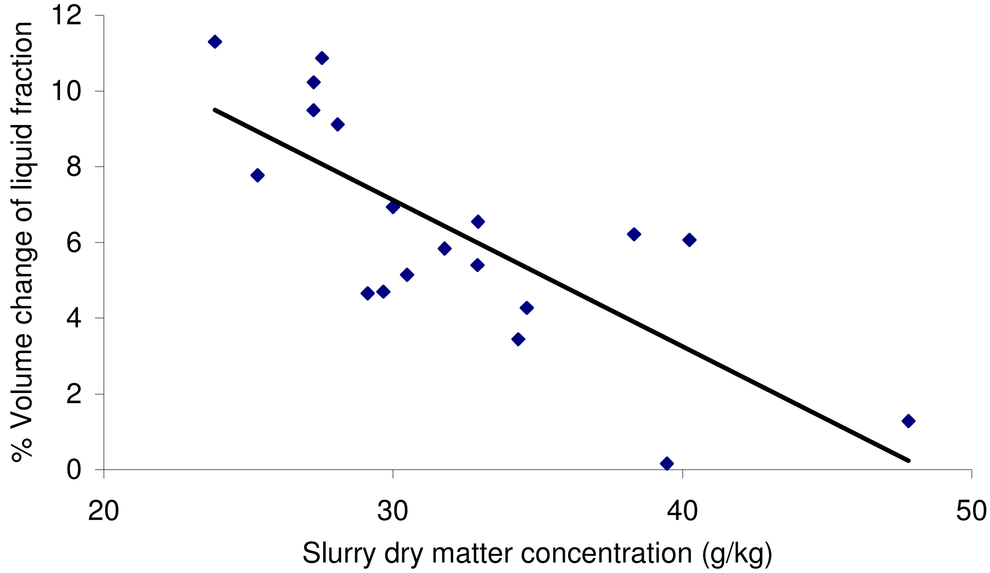


Figure 7. Relationship between pig slurry dry matter concentration and percentage volume change in supernatant, relative to the slurry volume, for the chemical treatments in the decanting centrifuge**.**

Comparison of chemical treatments in the decanting centrifuge

The data from this part of the experiment are presented in Table 5. Increasing the rate of conditioner applied at a constant rate of polymer, resulted in small, but mostly non-significant improvements in the separation efficiency of the decanting centrifuge (Table 5). The exception to this was the reduction in TP concentration of the supernatant and the increase in the amount of TP transferred to the solid fraction. The high conditioner/high polymer treatment resulted in significantly ($P<0.05$) lower TP concentration in the supernatant and significantly ($P<0.05$) increased the amount of TP partitioned to the separated solid fraction, compared to the low conditioner treatment. The supernatant TP concentration was reduced from 65 to 23 mg/kg, while the amount of TP partitioned to the separated solid fraction increased from 91.3% to 95.3% for the low and high conditioner treatments respectively. The high conditioner/high polymer treatment did not significantly improve the partitioning of TP to the solid fraction, relative to the normal rate polymer and high rate conditioner. This was despite the fact that the polymer application rate was increased from the normal 17% of slurry volume, to an average of 47% of slurry volume. This resulted in a 28% volume increase of the supernatant, relative to the volume of the slurry inputted to the separator, due to the water additions with the polymer.

Table 5. Characteristics of the supernatant and separated solids from pig slurry with added polymer and conditioner, separated through decanting centrifuge.

Conditioner	Low	Medium	High	High		
Polymer	Normal	Normal	Normal	High	F-value	S.E.M.
Slurry DM (g/kg)	37.2	37.2	37.3	42.7	0.925	7.31
Supernatant (fresh)						
DM (g/kg)	10.3	9.9	9.3	7.3	0.181	1.07
TN (g/kg)	2.10	2.08	1.97	1.70	0.346	0.185
NH_3-N (g/kg)	1.89	1.96	1.81	1.65	0.428	0.160
TP (mg/kg)	65	58	37	23	0.006	9.7
K (mg/kg)	1971	1927	1825	1671	0.485	163.5
S (mg/kg)	80	72	55	56	0.108	10.4
N : P ratio	34.6	39.2	59.1	76.7	0.081	13.94
Solids (fresh)						
DM (g/kg)	229	228	220	231	0.758	9.8
TN (g/kg)	10.63	10.17	9.57	10.30	0.385	0.564
NH_3-N (g/kg)	2.55	2.46	2.51	2.19	0.744	.274
TP (mg/kg)	7483	7348	6981	7635	0.802	590.7
K (mg/kg)	2237	2242	2111	1989	0.554	163.0
S (mg/kg)	1923	1801	1668	1897	0.184	111.2
N : P ratio	1.44	1.40	1.38	1.38	0.919	0.094
Separation efficiency[1]						
Dry solids	0.68	0.69	0.71	0.77	0.269	0.039
TN	0.33	0.33	0.35	0.40	0.306	0.031
TP	0.91	0.92	0.95	0.96	0.028	0.015
K	0.10	0.11	0.11	0.12	0.818	0.015
S	0.70	0.71	0.77	0.79	0.076	0.033
Liquid volume increase (as % of slurry in)	10.7	8.7	9.0	27.9	0.048	5.61

Footnote 1. using Equation 2.

There was a very marked increase in the N:P ratio of the supernatant with increasing rates of conditioner applied (Table 5). However the changes were not statistically significant, due to large variations in the ratio, which were mainly attributable to the variations of TP concentration in the supernatant (range 7 - 92 mg/kg). The supernatant NH_3-N concentrations were between 90 – 97% of the TN concentrations for the chemical treatments (Table 5), indicating that most of the organic N fraction had been removed by the decanting centrifuge.

Removal of suspended solids in pig slurry with a decanting centrifuge
A subset of the slurry and supernatant samples from the decanting centrifuge tests were analysed for total suspended solids (TSS), using a standard operating procedure (Lind, 1974). 500ml of sample (diluted as necessary) was filtered

using a 1micron Whatman GF/C filter paper. The filter paper was dried for 24h at 100^0C and the weight difference used to calculate the amount of suspended solids (g/kg). The supernatant samples were selected on the basis that they came from a common source of slurry. The results, presented in Table 6, show the effect of the treatments applied on the removal of suspended solids from pig slurry with the decanting centrifuge, for 3 different slurries (mean dry matter concentration 43.1 g/kg, 18.3 g/kg suspended solids). .

Table 6. Effect of treatment on the removal of suspended solids from pig slurry in the decanting centrifuge

Conditioner[1]	None	Low	Medium	High	High		
Polymer	None	Normal	Normal	Normal	High	S.E.M	F-value.
DM (g/kg)	20.6	9.4	9.4	9.2	6.9	3.13	0.072
TSS (g/kg)	7.69	1.04	0.86	0.67	0.34	1.192	0.006
Proportion TSS removed	0.60	0.94	0.95	0.96	0.98	0.036	<0.001

Footnote 1 See materials and method section for details of application rates.

The TSS in the supernatant for the control treatment showed a reduction of 60% compared to the raw slurry. This is a similar reduction to that reported by Sneath *et al.* (1988), (65% reduction with 8% DM pig slurry). Compared to the control treatment, the proportion of TSS removed by the chemical treatments was significantly ($P<0.001$) higher. Comparing chemical treatments only, there was a non-significant trend of decreasing suspended solids concentration with increasing conditioner applied and this was reflected in the proportion of suspended solids removed, with the high polymer/high conditioner treatment removing 98% of the suspended solids that was present in the raw slurry. The remaining dry matter concentration of the supernatant must therefore be largely attributed to the soluble fractions (dissolved solids), such as NH_3-N and K.

Comparison of brushed screen separator and decanting centrifuge with pig slurry

An analysis of variance was performed on the data from every test run using pig slurry with each separator (excluding high conditioner/high polymer treatment), to get a direct comparison of each machine's potential, across a wide range of slurry dry matter concentrations and chemical combinations. The data are presented in Table 7.

Table 7. Characteristics of supernatant and separated solids from pig slurry, separated through the brushed screen or decanting centrifuge (mean of chemical and control treatments)

Supernatant (fresh)	Brushed screen	Decanting centrifuge[1]	Ratio decanting centrifuge: brushed screen	F-value	S.E.M.
DM (g/kg)	33.7	13.6	0.40	<0.001	1.58
TN (g/kg)	3.07	2.37	0.77	<0.001	0.143
NH_3-N (g/kg)	2.07	2.05	0.99	0.878	0.098
TP (mg/kg)	880	112	0.13	<0.001	29.8
K (mg/kg)	2284	2165	0.95	0.454	130.1
S (mg/kg)	307	115	0.38	<0.001	17.0
N : P ratio	3.9	35.8	9.18	<0.001	4.87
Separated Solids (fresh)					
DM (g/kg)	172.9	240.7	1.39	<0.001	5.35
TN (g/kg)	4.78	10.24	2.14	<0.001	0.194
NH_3-N (g/kg)	1.75	2.67	1.53	<0.001	0.096
TP (mg/kg)	1880	7916	4.21	<0.001	262.0
K (mg/kg)	2133	2380	1.12	0.038	96.4
S (mg/kg)	957	1821	1.90	<0.001	40.6
N : P ratio	2.52	1.31	0.52	<0.001	0.074
Separation efficiency[2]					
Dry solids	0.19	0.65	3.38	<0.001	0.023
TN	0.07	0.31	4.72	<0.001	0.016
NH_3-N	0.04	0.12	3.36	<0.001	0.008
TP	0.09	0.88	9.71	<0.001	0.015
K	0.05	0.10	2.31	<0.001	0.007
S	0.13	0.64	5.01	<0.001	0.027
Liquid volume increase (as % of slurry in)	6.3	2.4	0.38	0.164	2.17

Footnote 1. Excludes high conditioner/ high polymer treatment. Footnote 2. Using Equation 2

There were no significant differences in the mean chemical compositions of the slurries separated through each machine. Data in Table 7 indicate that compared to the brushed screen separator, the decanting centrifuge was much superior in partitioning nutrients into the separated solid fraction, with a consequential reduction in the concentration of nutrients in the supernatant. Most of the effects were statistically significant at the 0.1% level, with the exception of NH_3-N and K, which are soluble and not differentially partitioned to the separated solid fraction. For each parameter, the ratio of: decanting centrifuge / brushed screen gives a good indication of the difference between the 2 machines. As indicated in Table 7, the differential partitioning of TP by the decanting centrifuge, compared to the brushed screen separator stands out very clearly. The supernatant TP concentration from the brushed screen was 8 times higher than that for the decanting centrifuge and nearly 10 times the TP was partitioned to the separated solid fraction from the decanting centrifuge, compared to the brushed screen. The partitioning of TN to the solid fraction was greatly improved with use of the decanting centrifuge, compared to the brushed screen, with 4.7 times more TN partitioned.

Separation of Cattle Slurry

Introduction

Cattle slurry accounts for 88% of all manure from housed livestock in N Ireland (Frost 2005). A significant minority of cattle farms are producing in excess of the 170 kg organic nitrogen/hectare limit imposed by the Nitrates Action Programme (DARD personal communication). In the light of this information, it was decided that cattle slurry should be processed through both the brushed screen and the decanting centrifuge, so that relevant information could be made available to the industry.

Materials and Methods (cattle slurry)

The majority of cattle slurry separated was sourced from lactating dairy cows. The same separators and ancillary equipment were used as for pig slurry. The polymer and conditioner application rates were again determined on site by a chemist from the chemical supply company (Celtic Watercare, Cork, Ireland). The slurry feed pump was set at 1.8 tonnes/hour (approximate) and the polymer pump at 500 litres/hour (approximate). The conditioner pump was set to deliver 3.3, 8.8 and 14.3 litres/hour for the low, medium and high rates of conditioner respectively. The test runs were reduced in time to approximately 12 minutes, so that the same source slurry could be used for both machines across all treatments, thus removing a possible source of variation due to different slurries. The separated solids were collected and weighed, but not the supernatant. Froth on top of the supernatant collected made it difficult to accurately measure the volume of the supernatant in the polycube container. Equation 4 (page 10) was used to determine the volume of supernatant produced. Previous data collected from the pig slurry test runs, where both the supernatant and separated solids were collected and measured, had verified Equation 4 to give an accurate measure of the supernatant volume. Intensive sampling of slurry, supernatant and cake was carried out during each test run. The volume of slurry removed from the slurry source was also recorded via sight tube readings, so mass balance calculations could be verified.

Cattle slurry tends to have a much higher dry matter concentration compared to pig slurry, which is often diluted with washings. To obtain a supernatant from cattle slurry with a low dry matter concentration would require very high inputs of chemical. This may not be justified economically, nor the greatly increased storage capacity required for the extra volume of liquid produced. However, it was considered beneficial to gather some information on the effects of adding polymer / conditioner to cattle slurry during separation, to compare with the results of the control treatment.

The treatments applied to cattle slurry were:

1. Control (no chemical additions)
2. Low, medium and high conditioner (0.18%, 0.49%, 0.79% of slurry volume) with constant rate of polymer (28% of slurry volume)

Results of Cattle Slurry Separation

Brushed screen separator with cattle slurry

Cattle slurry with a range of dry matters was separated through the brushed screen separator. The characteristics of the slurry used in the tests are summarised in Table 8.

Table 8. Composition of cattle slurry separated through the brushed screen separator

Fresh weight	Mean	Min	Max	Stdev
DM (g/kg)	60.4	40.5	79.3	13.00
TN (g/kg)	2.68	2.27	3.71	0.333
NH_3-N (g/kg)	1.53	1.47	1.74	0.068
TP (mg/kg)	441	312	747	103.5
K (mg/kg)	3907	3287	4397	378.4
S (mg/kg)	525	393	648	101.3
pH	7.44	7.04	7.65	0.171
N : P ratio	6.22	4.97	7.27	0.785

Cattle slurries with a wide range dry matter concentrations (40 to 80g/kg) were separated, to enable development of relationships between slurry dry matter concentration and a number of parameters measured. The same screen size was retained in the brushed screen separator for the cattle slurry as for the pig slurry. i.e. 1.6 mm diameter openings. The results of cattle slurry separated through a brushed screen separator are presented in Table 9. The addition of water via chemical additions was, on average, 28% of the slurry volume treated. The addition of polymer / conditioner had a significant effect in reducing the concentration of many of the constituents measured in the supernatant (Table 9). However, this was not reflected in a significant increase in the percentage of the constituent partitioned to the solid fraction. The only exception to this was the percentage of TN partitioned to the solid fraction, where chemical addition resulted in a significant ($P<0.05$) improvement in the amount partitioned. The reduction in concentration of nutrients in the supernatant with chemical additions, must therefore be largely due to the dilution effect of the water added, rather than increased partitioning of nutrients to the solid fraction.

The dry matter concentration of the separated solids was significantly reduced ($P<0.001$) with the addition of chemicals. This resulted in a solid fraction that was unstackable, had the consistency of thick slurry and had to be contained. There was also a considerable amount of effluent seepage from this material. The solids produced from the chemical treatments were generally unsatisfactory, both in terms of the consistency and dry matter concentration of the material. There was a visible trend of decreasing quality of the separated solids with increasing rates of conditioner applied.

Table 9. Characteristics of the supernatant and solids from cattle slurry separated through a brushed screen separator.

Supernatant (fresh weight)	Chemical	Control	F- value	S.E.M.
pH	7.43	7.52	0.345	0.077
DM (g/kg)	33.0	46.5	<0.001	2.03
TN (g/kg)	1.93	2.80	<0.001	0.126
NH_3-N (g/kg)	1.26	1.66	<0.001	0.058
TP (mg/kg)	270	430	0.003	37.6
K (mg/kg)	3100	4042	<0.001	141.0
S (mg/kg)	379	464	0.101	40.1
N:P ratio	7.26	6.94	0.606	0.505
Solids (fresh weight)				
DM (g/kg)	129.9	163.5	<0.001	2.27
TN g/kg	3.50	3.53	0.827	0.104
NH3-(N g/kg)	1.10	1.23	0.006	0.033
TP (mg/kg)	835	889	0.618	86.4
K (mg/kg)	2996	3766	<0.001	116.9
S (mg/kg)	766	772	0.879	33.9
N : P ratio	4.28	4.21	0.844	0.300
Separation efficiency[1]				
Dry solids	0.40	0.36	0.224	0.027
TN	0.23	0.18	0.022	0.033
NH_3-N	0.15	0.13	0.551	0.030
TP	0.32	0.26	0.137	0.034
K	0.14	0.15	0.801	0.023
S	0.24	0.22	0.548	0.028
Supernatant volume change (as % of slurry volume)	6.6	-14.2	<0.001	2.57

Footnote 1. Using Equation 2

A relationship was developed between slurry dry matter concentration and supernatant dry matter concentration for both the control and chemical treatments as given by Equations 13 and 14 respectively. The results are presented in Figure 8.

Equation 13. Relationship between slurry dry matter concentration and supernatant dry matter concentration for the control treatment, with cattle slurry separated through a brushed screen separator

Supernatant DM concentration (g/kg) = Slurry DM concentration (g/kg) X 0.605 + 8.465
R^2=0.93 (P<0.001)

Equation 14. Relationship between slurry dry matter and supernatant dry matter for the chemical treatments, with cattle slurry through brushed screen separator

Supernatant DM concentration (g/kg) = Slurry DM concentration (g/kg) X 0.307 + 15.09
R^2=0.86 (P<0.001)

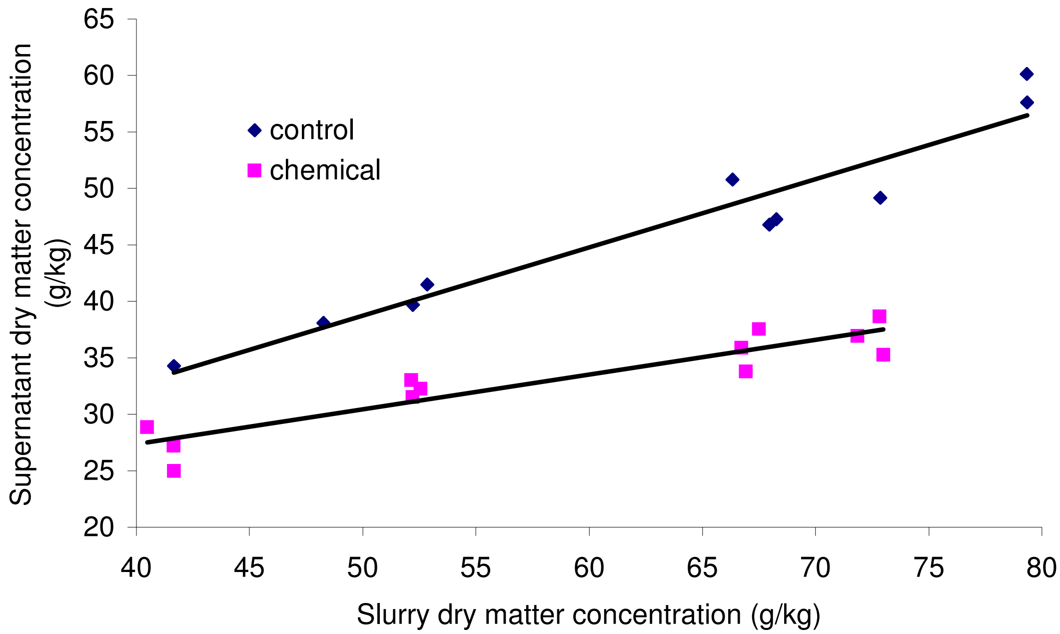


Figure 8. Relationship between cattle slurry dry matter concentration and supernatant dry matter concentration for the brushed screen separator.

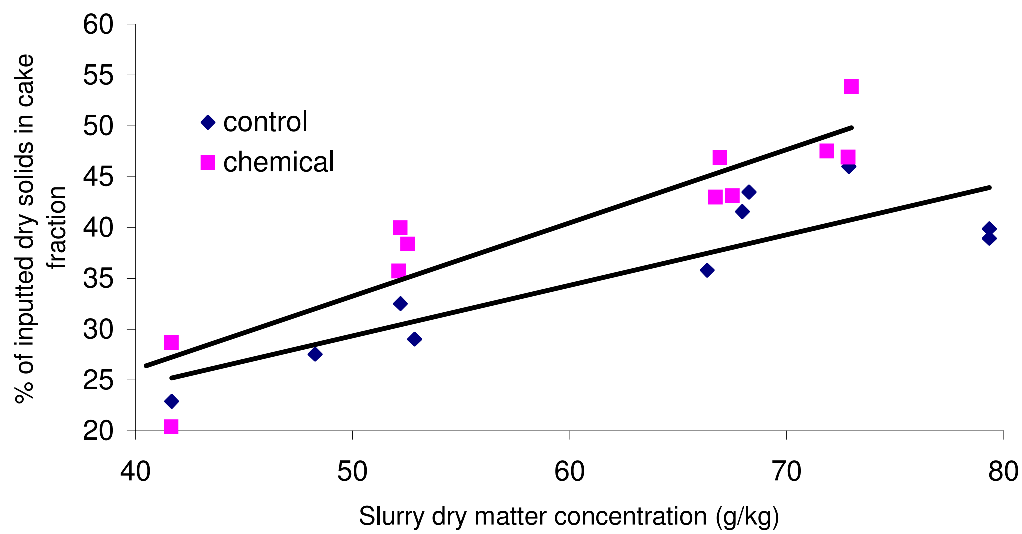


Figure 9. Relationship between cattle slurry dry matter concentration and the percentage of dry solids partitioned to the separated solid fraction with the brushed screen separator.

Figure 9 indicates that there was a linear relationship between cattle slurry dry matter concentration and the amount of dry solids partitioned to the separated solid fraction with the brushed screen separator. Pain *et al.* (1978) found a similar relationship over the same range of dry matter concentration, but tailing off as slurry dry matter concentration increased above 100g/kg. The addition of polymer / conditioner improved the partitioning of dry solids at any given level of slurry dry matter concentration and this increased with increasing slurry dry matter concentration. However, the response was not statistically significant (Table 9). These relationships are described by Equations 15 and 16. There was no relationship between the cattle slurry dry matter concentration and the dry matter concentration of the separated solids, which is in contrast to Pain *et al.* (1978), who obtained a positive correlation between these parameters.

Equation 15. Relationship between cattle slurry dry matter concentration and the percentage of total dry solids partitioned to the separated solid fraction, for the brushed screen separator without chemical additions**.**

Control treatment:
Percentage of total dry solids in solid fraction = Slurry DM (g/kg) X 0.497 + 4.50
$R^2 = 0.76$ $(P<0.001)$

Equation 16. Relationship between cattle slurry dry matter concentration and the percentage of total dry solids partitioned to the separated solid fraction for the brushed screen separator with chemical additions.

Chemical treatment:
Percentage of total dry solids in solid fraction = Slurry DM (g/kg) X 0.721 – 2.82
$R^2 = 0.86$ $(P<0.001)$

Comparing the chemical only treatments for the brushed screen, there was no improvement in partitioning of nutrients into the solid fraction with increasing rates of conditioner. There was a non-significant trend of increasing dry matter concentration in the supernatant with increasing conditioner rates. This is the opposite of what would have been expected and shows that there must be other factors influencing the partitioning of nutrients. With the chemical treatments, the white diluted polymer could be seen in the pre-separation container on the brushed screen separator. It seemed that there was inadequate mixing of the slurry with the polymer, despite the fact that it was added inline to the slurry, some 5 metres from the separator. With the pig slurry, there was no visible sign of the polymer not mixing with the slurry. However, even when the cattle slurry and polymer were applied at the same rate as for the pig slurry plus polymer, the polymer was still visible in the in the pre-separation weir.

Decanting centrifuge with cattle slurry

The composition of cattle slurry separated through the decanting centrifuge is presented in Table 10. The dry matter concentration ranged from 41 to 83 g/kg and this range is considered representative of the majority of the cattle slurry produced in Northern Ireland.

Table 10. Composition of cattle slurry separated through a decanting centrifuge.

Fresh weight	Mean	Min	Max	Stdev
pH	7.60	7.30	7.72	0.125
N:P ratio	7.09	5.31	8.40	1.194
DM (g/kg)	59.7	41.4	82.9	11.38
TN (g/kg)	2.93	2.44	3.99	0.366
NH_3-N (g/kg)	1.63	1.37	2.07	0.216
TP (mg/kg)	430	290	726	112.2
K (mg/kg)	4023	3066	4829	499.9
S (mg/kg)	511	399	662	95.0

The results of slurry separated through the decanting centrifuge are summarised in Table 11. The volume of the supernatant, compared to the slurry volume, was reduced by a mean of 12.5% for the control treatment, but was increased by a mean of 9.1% for the chemical treatments. The soluble components measured i.e. NH_3-N and K, were not differentially partitioned into the solid fraction. This is evidenced by the fact that the percentage of these constituents partitioned to the solid fraction is almost the same as the percentage of fresh weight partitioned to the solid fraction.

As with the separation of pig slurry, the TP in cattle slurry showed the highest degree of partitioning into the solid fraction, with 64% partitioned without chemicals and 82% with chemicals. This is somewhat lower than for pig slurry, and may be due to the form of the TP in the cattle slurry. Compared to the control treatment, addition of polymer / conditioner had a very significant effect ($P<0.001$) on most of the parameters measured. The dry matter concentration of the separated solids was significantly ($P<0.001$) lowered by chemical addition, compared to the control treatment, but at 213 g/kg, they were easily stackable with no effluent leaching out.

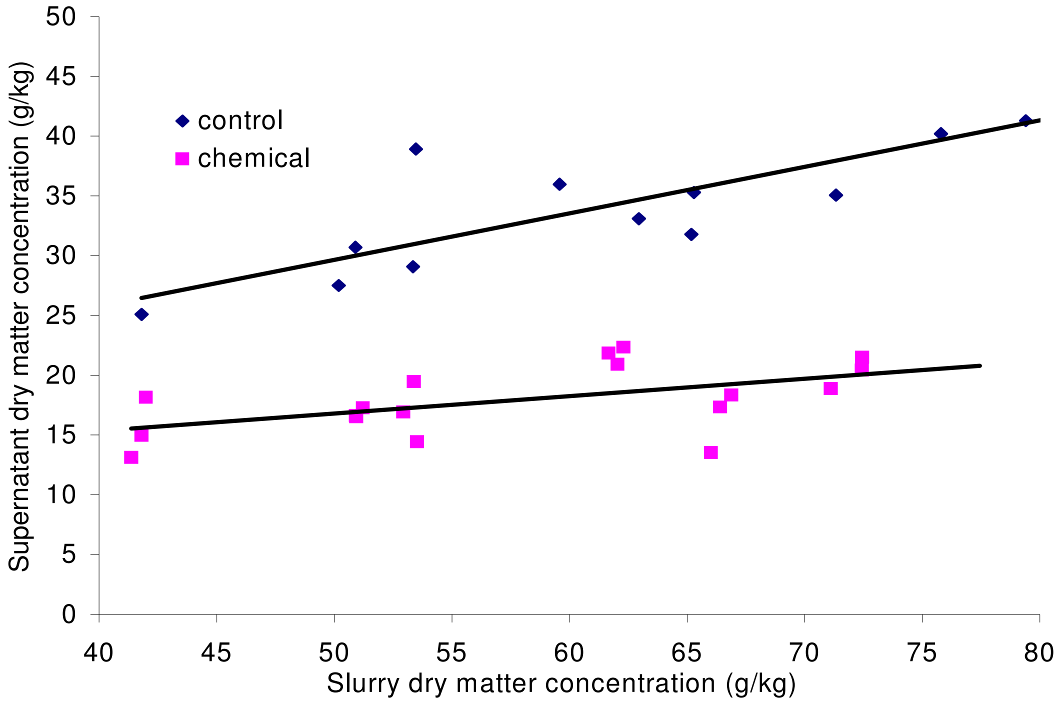
The concentrations of the parameters measured in the supernatant are somewhat confounded by the dilution effect of the water addition with the chemicals. The percentage of each constituent in the separated solid fraction gives a clearer picture of the effect of treatment on the separation process. The chemical treatments significantly reduced ($P<0.001$) the concentration of all the constituents measured in the supernatant, but also reduced the concentration of some of these constituents in the solid fraction e.g. TP and K, compared to the control treatment. On a dry matter basis, the concentration of TP and K in the solid fraction were almost identical

Table 11. Characteristics of the supernatant and solids from cattle slurry separated through a decanting centrifuge.

Supernatant (fresh weight)	Treatment			
	Chemical	Control	F- value	S.E.M.
pH	7.61	7.67	0.254	0.04
DM (g/kg)	17.9	34.5	<0.001	1.18
TN (g/kg)	1.51	2.75	<0.001	0.109
NH_3-N (g/kg)	1.47	2.04	<0.001	0.094
TP (mg/kg)	62.8	200.8	<0.001	12.42
K (mg/kg)	3129	4056	<0.001	131.5
S (mg/kg)	243	386	<0.001	22.0
N:P ratio	41.8	14.1	0.099	12.95
Solids (fresh weight)				
DM (g/kg)	213.4	258.2	<0.001	4.38
TN (g/kg)	6.38	5.71	0.005	0.178
NH_3-N (g/kg)	1.21	1.47	0.147	0.143
TP (mg/kg)	1783	2275	0.001	108.5
K (mg/kg)	3352	3880	0.002	126.0
S (mg/kg)	1352	1238	0.161	63.7
N:P ratio	3.60	2.58	<0.001	0.104
Separation efficiency[1]				
Dry solids	0.65	0.51	<0.001	0.020
TN	0.41	0.25	<0.001	0.020
NH_3-N	0.17	0.14	0.217	0.018
TP	0.82	0.64	<0.001	0.022
K	0.15	0.13	0.118	0.009
S	0.47	0.34	<0.001	0.017
Liquid volume change (as % of slurry volume)	9.1	-12.5	<0.001	1.13

Footnote 1. Using Equation 2

The relationship between cattle slurry dry matter concentration and supernatant dry matter concentration, with and without chemical additions for the decanting centrifuge, are presented in Figure 10.



.Figure 10. Relationship between cattle slurry dry matter concentration and supernatant dry matter concentration, for cattle slurry separated through a decanting centrifuge.

The relationship between cattle slurry dry matter concentration and supernatant dry matter concentration, without chemical additions for the decanting centrifuge, are given in Equation 17.

Equation 17. Relationship between cattle slurry dry matter concentration and supernatant dry matter concentration for control treatments with the decanting centrifuge

Supernatant DM concentration (g/kg) = Slurry DM concentration (g/kg) X 0.389 + 10.19

R^2 = 0.72 (P<0.01)

The relationship between cattle slurry dry matter concentration and supernatant dry matter concentration for the chemical treatments was significant (P<0.05) but the R^2 was only 0.25, thus other parameters must have had a major impact on this relationship.

Comparison of chemical treatments in the decanting centrifuge

Increasing the rate of conditioner with a constant rate of polymer, tended to improve the partitioning of nutrients into the solid fraction, with the exception of NH_3-N and K. There was a consequential reduction in the respective concentration of the nutrient in the supernatant. However, only the partitioning of TP and S to the separated solid fraction were significantly increased (P<0.01) with increasing levels of conditioner. A summary of the data is presented in Table 12.

Table 12. Summary of results from the addition of low, medium and high levels of conditioner to cattle slurry (with constant rate of polymer), separated through a decanting centrifuge.

	Conditioner				
Supernatant (freshweight)	Low	Medium	High	F-value	S.E.M.
DM (g/kg)	19.4	17.9	16.5	0.198	1.10
TN (g/kg)	1.63	1.52	1.39	0.202	0.090
NH_3-N (g/kg)	1.19	1.22	1.23	0.878	0.061
TP (mg/kg)	84.2	65.3	39.0	0.015	9.55
K (mg/kg)	3114	3164	3108	0.970	175.2
S (mg/kg)	267	244	217	0.341	23.1
Separation efficiency[1]					
Dry solids	0.62	0.66	0.69	0.219	0.027
TN	0.36	0.41	0.45	0.092	0.028
NH_3-N	0.15	0.17	0.18	0.480	0.021
TP	0.76	0.81	0.90	0.007	0.02.6
K	0.14	0.15	0.16	0.596	0.013
S	0.42	0.47	0.53	0.002	0.017

Footnote 1. Using Equation 2

Removal of suspended solids in cattle slurry with a decanting centrifuge

A subset of the slurry and supernatant samples from the decanting centrifuge tests were analysed for TSS using a standard operating procedure (Lind, 1974). The samples selected were those that enabled the input slurry TSS to be compared with supernatant TSS from the same slurry for different treatments (5 reps per treatment). The results are presented in Table 13. The DM of the cattle slurry ranged from 42 to 71g/kg and the slurry TSS from 16 to 33 g/kg.

Table 13. Analysis of suspended solids in supernatant from cattle slurry separated in a decanting centrifuge.

Supernatant	Control	High conditioner/polymer	S.E.M.	F-value
DM concentration (g/kg)	29.7	15.3	1.44	<0.001
Suspended solids (g/kg)	6.43	0.72	1.133	0.007
Proportion of suspended solids removed	0.72	0.97	0.031	<0.001

The decanting centrifuge reduced the suspended solids in the supernatant of the control treatment by 72%, relative to the raw slurry, (Table 13). The corresponding figure for the high conditioner treatment was 97% and this was significantly (P<0.001) better than control treatment. The mean DM concentration of the supernatant for the high conditioner treatment was 15.3

g/kg. The dry matter content remaining must have been mainly dissolved solids, as only 4.7% remaining was in the form of suspended solids ((0.72/15.3)*100). The addition of chemicals (conditioner and polymer) would not have any effect on the partitioning of these dissolved solids, since they would need to be brought out of solution by addition of other chemicals before separation. A relationship was developed between the DM concentration of both the slurry and supernatant and the concentration of TSS in them (Equation 18). It may be possible to use this relationship to estimate the TSS of cattle slurry or the supernatant, without direct measurement.

Equation 18. Relationship between cattle slurry and supernatant dry matter concentration and the suspended solids concentration in that dry matter, for cattle slurry separated through a decanting centrifuge.

Suspended solids (g/kg) = Slurry or supernatant dry matter concentration (g/kg) X 0.551 – 8.76
$R^2 = 0.96$ ($P<0.001$)

Comparison of brushed screen separator and decanting centrifuge with cattle slurry

The results of all the test runs with cattle slurry separated through each machine for all treatments are summarised in Table 14. In general, compared to the brushed screen separator, the decanting centrifuge was significantly better at partitioning nutrients into the solid fraction, with a consequential reduction in the concentration of the respective nutrient in the supernatant. The decanting centrifuge partitioned 61% more dry matter into the solid fraction, compared to the brushed screen separator. The corresponding figure for TP was 154%. The amount of NH_3-N and K partitioned to the solid fraction was unaffected by separator type. These constituents were generally partitioned in proportion to the partitioning of the fresh mass of the solid and liquid fractions, i.e. no differential partitioning to the solid fraction. The TN partitioned to the separated solid fraction was increased by 67% for the decanting centrifuge, compared to the brushed screen. This may have important implications for farmers thinking of exporting the separated solids to help comply with the Nitrates Action Programme.

The mean reduction across the control and chemical treatments in the concentration of measured nutrients in the supernatant, relative to the raw slurry, was significantly ($P<.001$) affected by separator type, with the exceptions of NH_3-N and K. With the decanting centrifuge, the supernatant TP concentration was reduced by 75%, relative to the raw slurry. The corresponding figure for the brushed screen was 28%.

Table 14. Comparison of brushed screen separator and decanting centrifuge for all treatments with cattle slurry.

Supernatant (fresh weight)	Mean brushed screen (control and chemical)	Mean centrifuge (control and chemical)	Ratio decanting centrifuge : brushed screen	F- value	S.E.M.
pH	7.46	7.63	1.02	<0.001	0.036
DM (g/kg)	39.1	24.9	0.64	<0.001	1.99
TN g/kg	2.22	1.95	0.88	0.170	0.149
NH_3-N (g/kg)	1.39	1.39	0.99	0.853	0.065
TP (mg/kg)	323	112	0.35	<0.001	22.5
K (mg/kg)	3377	3460	1.02	0.644	139.0
S (mg/kg)	408	294	0.72	<0.001	23.6
N:P ratio	7.2	31.9	4.43	0.018	7.83
Solids (fresh weight)					
DM (g/kg)	145	232	1.60	<0.001	5.1
TN (g/kg)	3.51	6.14	1.75	<0.001	0.124
NH_3-N (g/kg)	1.14	1.30	1.14	0.167	0.087
TP (mg/kg)	853	1959	2.30	<0.001	82.1
K (mg/kg)	3253	3540	1.09	0.048	110.1
S (mg/kg)	768	1311	1.71	<0.001	39.7
N:P ratio	4.26	3.24	0.76	<0.001	0.151
Separation efficiency[1]					
Dry solids	0.37	0.59	1.61	<0.001	0.022
TN	0.21	0.35	1.67	<0.001	0.022
NH_3-N	0.15	0.16	1.07	0.612	0.015
TP	0.30	0.76	2.54	<0.001	0.025
K	0.14	0.14	1.00	0.972	0.010
S	0.23	0.42	1.82	<0.001	0.019

Footnote 1. Using Equation 2

The weight of fresh solids produced from 1 ton of cattle slurry, separated through either machine, without chemicals, was positively correlated with the dry matter concentration of the slurry. Similar weights of solids were produced from each machine, especially with cattle slurry of low dry matter concentration (Figure 11) but the decanting centrifuge partitioned a mean of 42% more dry solids to the cake fraction compared to the brushed screen (Figure 12). Conversely, the brushed screen partitioned 29% more water to the separated solids and hence similar fresh weight of separated solids for both machines.

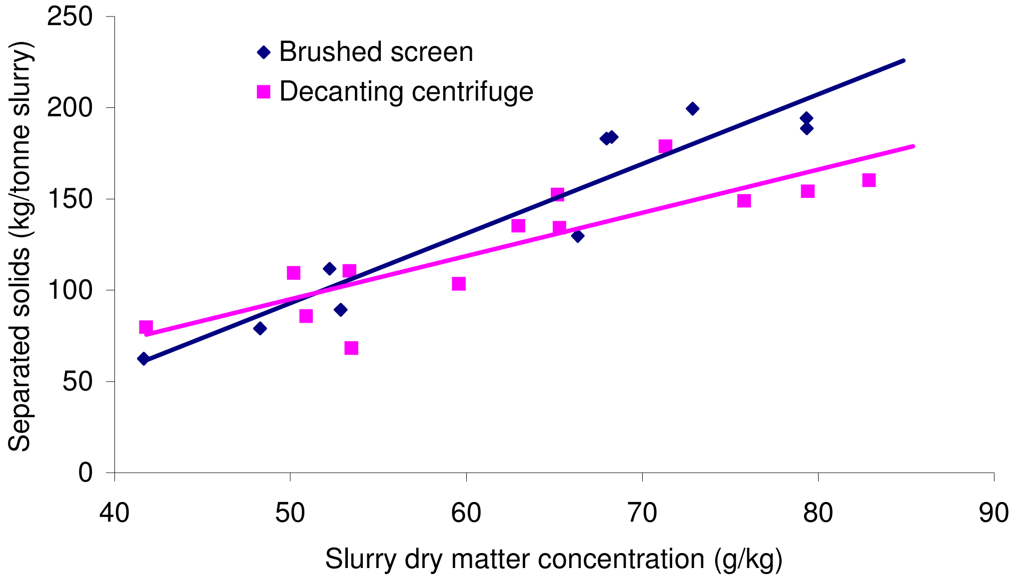


Figure 11. Relationship between cattle slurry dry matter concentration and the weight of fresh solids produced from 1 tonne of cattle slurry without chemicals.

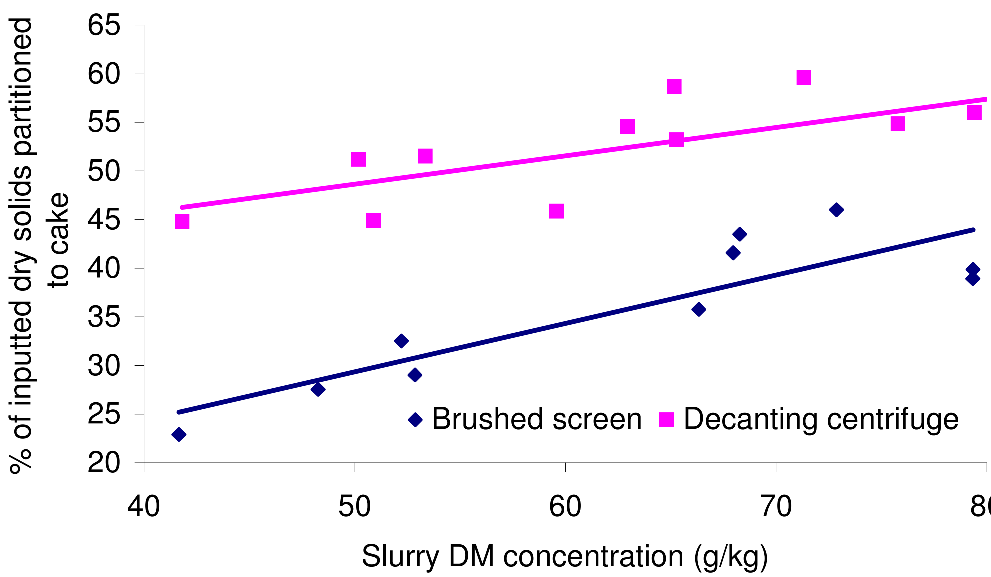


Figure 12. Relationship between cattle slurry dry matter concentration and the percentage of inputted dry solids partitioned to the separated solids fraction for the control treatments in the decanting centrifuge and brushed screen separator.

Discussion

The results from this work demonstrate that the decanting centrifuge differentially partitioned more nutrients into the solid fraction of separated pig or cattle slurry, with the exception of NH_3-N and K, than did the brushed screen separator. The NH_3-N and K components being soluble, do not differentially partition into the separated solid fraction (Moller *et al.,* 2000). It is likely that most of the nitrogen transferred into the separated solid fraction was from the organic N fraction, i.e. in the suspended solids. The concentrations of TN and NH_3-N in the supernatants from pig slurry separated through the decanting centrifuge with chemical additions, were almost identical, thus the organic N fraction has been almost completely partitioned to the separated solid fraction.

The brushed screen separator performed much better with cattle slurry than with pig slurry. This was probably because the cattle slurry had, on average, a much higher dry matter concentration and was also much more fibrous that the pig slurry. The normal screen size for the brushed screen separator, recommended by the manufacturer for cattle slurry is 3mm, rather than the 1.6mm pore diameter used in the current work with both slurry types. The larger screen size would allow faster throughput of material, but is also likely to reduce the amount of dry solids partitioned to the separated solids fraction, as larger particles pass through the pores. Using Equations 7 and 13 (which give the relationships between slurry dry matter concentration and dry matter partitioned to the separated solid fraction with the brushed screen, for pig slurry and cattle slurry control treatments respectively) it can be concluded that cattle slurry separated through a brushed screen separator will always partition more dry matter to the separated solid fraction than pig slurry at the same dry matter concentration. At 40g/kg dry matter, 40% more of the dry matter was partitioned to the separated solid fraction with cattle slurry, compared to pig slurry. This decreases to 17% more at 70g/kg dry matter. As there was no good relationship between slurry dry matter concentration and dry solids partitioned to the separated solid fraction, with the decanting centrifuge for the control treatment, with either pig or cattle slurry, it is not possible to draw firm conclusions about the differences between pig and cattle slurry separation efficiencies in the decanting centrifuge. However, at a mean dry matter concentration for pig slurry of 39 g/kg, 53% of the dry matter was partitioned to the separated solids. The corresponding figures for cattle slurry were 63 g/kg and 51% respectively. The mean dry matter concentration of the cattle slurry was more than 50% greater than the mean dry matter concentration of the pig slurry and yet a similar amount of dry matter was partitioned to the solid fraction. It is likely that at any given dry matter concentration, for both pig and cattle slurry, a similar amount of dry matter will be partitioned to the solid fraction.

Relationships were developed between the dry matter concentration of slurries and supernatants with the respective TP concentration. For pig slurry separated in either machine, there was a very high correlation (R^2 = 0.90) between dry matter concentration and TP concentration, irrespective of the separator or treatment applied (Equation 19). A similar relationship was developed for cattle slurry and supernatant across both machines and treatments (Equation 20). These equations could be used to obtain an estimate of the TP concentration of either pig or cattle slurry, or the TP of supernatant, without the requirement for chemical analysis. At any given dry matter concentration, the TP concentration was always higher in the pig slurry or supernatant, compared to cattle slurry or supernatant. The data are presented in Figure 13.

Equation 19. Relationship between pig slurry and supernatant dry matter concentration and the respective TP concentration.

TP concentration (mg/kg fresh) = Dry matter concentration (g/kg) X 26.5 – 123.6
R^2 =0.90 (P<0.001) (n = 126)

Equation 20. Relationship between cattle slurry and supernatant dry matter concentration and the respective TP concentration.

TP concentration (mg/kg fresh) = Dry matter concentration (g/kg) X 8.75 – 96.6
R^2 =0.98 (P<0.001) (n = 58)

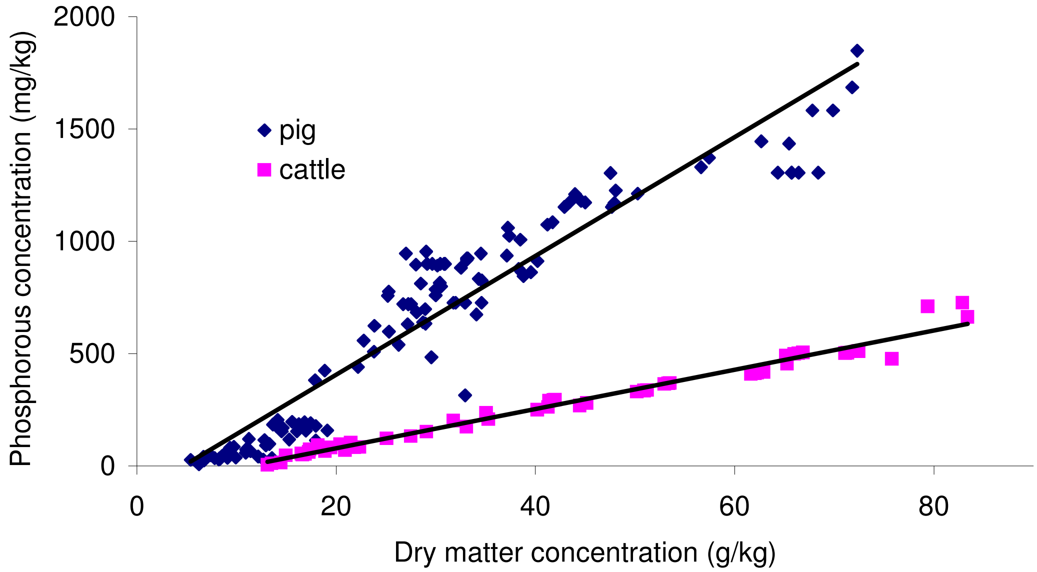


Figure 13. Relationship between dry matter concentration of cattle or pig slurry and supernatant dry matter concentration with the corresponding TP concentration.

Separator efficiency

The separator efficiency (% of total input, partitioned to the separated solid fraction) is summarised in Tables 15 to 20 below. The chemical treatments in the brushed screen are not presented, as chemical addition had little significant impact on the partitioning of nutrients with this machine. Where there was a good relationship between dry matter concentration and the parameter measured, this is used in the tables across the range of dry matter concentrations, otherwise the range for the parameter is quoted. The tables could be used as a guide when choosing a separator, with or without chemicals to meet particular objectives, depending on the dry matter concentration of the slurry.

Table 15. Separator efficiency of the brushed screen separator, without chemical additions, across a range of cattle slurry dry matter concentrations.

Slurry DM concentration (g/kg)	40	50	60	70	80
Weight of solids per tonne of slurry (kg)	55	93	131	170	208
DM of solids (g/kg)	152	-------------	-------------	-------------	173
Supernatant DM (g/kg)	32.7	38.7	44.8	50.8	56.9
Separator efficiency					
% of DM in solid fraction	24.4	29.3	34.3	39.3	44.3
% of TN in solid fraction	9.6	13.0	16.3	19.7	23.0
% of TP in solid fraction	15.7	19.8	23.9	28.0	32.1
% of K in solid fraction	9.1	11.4	13.7	16.0	18.3

Table 16. Separator efficiency of the brushed screen separator, without chemical additions, across a range of pig slurry dry matter concentrations.

Slurry DM concentration (g/kg)	25	30	40	50	60
Weight of solids per tonne of slurry (kg)	10	21	44	67	91
DM of solids (g/kg)	145	149	163	178	192
Supernatant DM (g/kg)	24.2	27.2	33.8	40.3	46.7
Separator efficiency					
% of DM in solid fraction	9.3	12	17.4	22.8	28.2
% of TN in solid fraction	2.5	3.5	5.5	7.4	9.4
% of TP in solid fraction	3.2	4.2	6.3	8.4	10.5
% of K in solid fraction	1.3	2.3	4.2	6.1	8.0

Table 17. Separator efficiency of the decanting centrifuge without chemical additions, across a range of cattle slurry dry matter concentration.

Slurry DM concentration (g/kg)	40	50	60	70	80
Weight of solids per tonne of slurry (kg)	71	95	119	142	166
DM of solids (g/kg)	235	245	256	266	276
Supernatant DM (g/kg)	25.8	29.6	33.5	37.4	41.3
Separator efficiency					
% of DM in solid fraction	46	49	52	54	57
% of TN in solid fraction	21 --- 30				
% of TP in solid fraction	59 --- 70				
% of K in solid fraction	9	11	12	14	15

Table 18. Separator efficiency of the decanting centrifuge with chemical additions, across a range of cattle slurry dry matter concentrations.

Slurry DM concentration (g/kg)	40	50	60	70	80
Weight of solids per tonne of slurry (kg)	102	144	187	229	271
DM of solids (g/kg)	182 --229				
Supernatant DM (g/kg)	13 --- 22				
Separator efficiency					
% of DM in solid fraction	57	62	66	71	75
% of TN in solid fraction	28 --- 57				
% of TP in solid fraction	63 --- 98				
% of K in solid fraction	10	13	15	18	21

Table 19. Separator efficiency of the decanting centrifuge without chemical additions, across a range of pig slurry dry matter concentrations.

Slurry DM (g/kg)	25	30	40	50	60
Weight of solids per tonne of slurry (kg)	58	66	81	96	111
DM of solids (g/kg)	232	241	260	279	298
Supernatant DM (g/kg)	12.7	15.2	20.3	25.3	30.4
Separator efficiency					
% DM partitioned to solids	40 --- 60				
% TN partitioned to solids	13 --- 30				
% TP partitioned to solids	74 --- 86				
% K partitioned to solids	4 --11				

Table 20. Separator efficiency of the decanting centrifuge with chemical additions[1], across a range of pig slurry dry matter concentrations.

Slurry DM (g/kg)	25	30	40	50	60
Weight of solids per tonne of slurry (kg)	80	95	125	155	185
DM of solids (g/kg)	201------------------------------------258				
Supernatant DM (g/kg)	5 ---------------------------------------13				
Separator efficiency					
% DM partitioned to solids	49 -------------------------------------- 81				
% TN partitioned to solids	22 -------------------------------------- 46				
% TP partitioned to solids	86 -------------------------------------- 99				
% K partitioned to solids	5 --16				

Footnote 1. Excludes high conditioner/high polymer treatment

Practical Points to Consider

Separator type

The brushed screen separator is a simple machine to operate, does not require much maintenance or supervision and has a low power requirement for single phase electricity. Conversely the decanting centrifuge requires a trained operator, has a high maintenance cost, a high power consumption and requires 3 phase electricity. The purchase price of a decanting centrifuge is approximately 5 times that of a brushed screen separator, i.e. £20,000 versus £100,000 and consumes approximately 10 times the amount of electricity of the brushed screen. The decanting centrifuge needs a homogenous source of slurry pumped into the machine, especially if chemicals are being added. This means that slurry being separated (particularly pig slurry) must be constantly mixed, otherwise the heavier solids will quickly gravitate to the base of the store and the dry matter concentration of the supply will vary greatly. It may not be possible to adequately mix slurry on farms, as many storage tanks are underneath the animals and cannot be mixed safely with animals in the house, due to the possible release of hydrogen sulphide gas, which can be lethal to livestock and people. However the use of low rate aeration systems such as the aeromixer (Milbury Systems Ltd), have been shown to maintain cattle slurry in a homogenous state during storage, without release of dangerous levels of H_2S. In contrast to the decanting centrifuge, the brushed screen separator can function with an inconsistent supply of slurry, both in terms of quantity and dry matter concentration. All these factors must be taken into account when considering the suitability of a separator to meet objectives.

Separation of pig slurry

Exporting organic nitrogen in separated solids may benefit pig farmers who exceed the 170kg N/ha limit imposed by the Nitrates Action Programme. A brushed screen separator is going to be of limited benefit, as, even with chemical addition, only 7% of the TN (range 1-19%) was partitioned to the solid fraction. However, when the decanting centrifuge was used, without chemical, 21% of the TN (range 13-31%) was partitioned into the separated solid fraction. This increased to a mean of 34% (range 22-46%) with the addition of chemicals, depending upon dry matter concentration of the slurry separated. By separating all pig slurry produced on farm and exporting the solids off farm, the organic nitrogen loading can be reduced by between 1% and 46%, depending on the slurry dry matter concentration, the separator type and whether chemicals are used in the separation process. The land areas required for a 200sow pig unit (birth to bacon) to comply with 170kg/ha/yr organic N limit, with and without mechanical separation of all slurry produced are presented in Table 21 (assuming separated solids are exported off farm).

Table 21. Land areas required for 200sow pig unit (birth to bacon) to comply with 170kg/ha/yr organic N limit, with and without mechanical separation of all slurry produced and export of separated solids.

	No	Brushed Screen		Decanting Centrifuge	
	separation	control	chemical	control	chemical
200 sows birth to bacon Land area required (ha)	100	94	93	79	66

The Nitrates Action Programme requires pig farmers to have slurry storage capacity for a minimum of 22 weeks (26 weeks for most pig farms, depending on the number of pigs). A pig farmer may decrease the volume of liquid to be stored by slurry separation, but this volume reduction is not considered in the theoretical storage capacity required under the Nitrates Action Programme. In the current study, separating pig slurry without chemical addition resulted in a liquid volume reduction of a mean of 5% (range 2-12%) with the brushed screen and a mean of 8% (range 4-12%) with the decanting centrifuge (mean slurry dry matter concentration 40 g/kg, which is considered typical of many pig slurries in Northern Ireland). Separated liquid is still subject to the closed period spreading restrictions under the Nitrates Action Programme and as such, cannot be land spread from 15th October to 31st January. Hence there is little advantage in separating pig slurry solely to reduce the volume of the liquid fraction. The separated solids from pig slurry are also subject to the same spreading restrictions as raw pig slurry and cannot be spread during the closed period.

While chemical addition was effective in enhancing partitioning of nutrients into the solid fraction with the decanting centrifuge, the volume of water added along with the chemicals is a very important consideration. In the current work, the mean additional storage required for separated liquid compared to the raw pig slurry was 9% (excluding high conditioner/high polymer treatment). Therefore, for each tonne of pig slurry centrifugally separated, accompanied by use of chemicals, there will be a mean of 1.09 tonnes of liquid plus 115kg of separated solids to handle. Unless the separated solids are exported to assist compliance with the Nitrates Action Programme and/or have a financial value, there is not likely to be any financial benefit in separating pig slurry.

Separation of cattle slurry

Cattle slurry is normally separated to produce a liquid fraction that is easier to manage, compared to raw slurry and/or reduce the storage capacity required. Raw cattle slurry requires mixing before land application to ensure a homogenous product. This has inherent problems, e.g. the possible release of toxic gases, such as H_2S. The separated liquid fraction would probably be stored away from livestock and if mixing was required, could be done without removing animals from buildings. The solid fraction can be treated as farmyard manure and as such, can be applied throughout the year, provided that ground conditions are suitable. This may have attractions for some farmers with land at a considerable distance from the slurry source, as more nutrients per unit weight can be transported compared to raw slurry. The liquid fraction should be more easily applied by alternative spreading methods, such as trailing shoe tanker, that allow grass to be grazed soon after application, thus increasing the flexibility of when the liquid can be applied.

The volume reduction of the liquid fraction relative to the raw slurry volume was much greater, compared to pig slurry. Each separator resulted in a similar volume reduction for the control treatment, ranging between 6-20% (mean 13%) and this was positively correlated with the slurry dry matter concentration. However as already noted, this does not indicate similar efficiencies of partitioning of dry matter into the separated solid fraction. The combined mass of water and dry matter in the separated solid fraction was similar for both machines. However, the decanting centrifuge on average, partitioned 42% more dry matter into the solid fraction and 29% less water, compared to the brushed screen.

It is unlikely that chemicals would be used in the on-farm separation of cattle slurry as, the amount of chemical needed and the subsequent increase in mass of both the solid and liquid fraction (mean increase of 26%) would for most farmers, make the process impractical and uneconomic. The 'best' supernatant obtained with chemical additions in the decanting centrifuge was 13g/kg DM and 1.1g/kg TN. Both these concentrations exceed current dirty water standards and therefore the supernatant is subject to the same restrictions as raw cattle slurry under the Nitrates Action Programme. The TSS results indicated that 95% of the dry matter remaining in the supernatant after chemical addition, was in a soluble form and therefore it is unlikely that the DM and TN could be lowered much more by this process, no matter how much chemical is added.

The land area requirements for 155 dairy cows and followers under different scenarios are presented in Table 22. This assumes that all separated solids are exported off farm. As cattle are normally housed for 6 months, the potential to reduce the organic nitrogen loading is restricted to slurry that is collected, i.e. approximately half the total production. Hence the impact of mechanical separation (compared to no separation), on the land area requirement to comply with the 170kgN/ha/yr is small, ranging from 9% reduction with a brushed screen separator without chemical additions, to a 20% reduction with a decanting centrifuge with chemical additions.

Table 22. Land areas required for 155 dairy cows (plus followers) to comply with 170kg/ha/yr organic N limit, with and without mechanical separation of winter slurry produced and export of separated solids.

	No	Brushed Screen		Decanting Centrifuge	
	separation	control	chemical	control	chemical
155 dairy cows + followers[1] Land area required (ha)	100	91	89	88	80

Footnote 1. Winter production separated (6 months)

End use of separated fractions

It is extremely important to have a sustainable end use for the 2 fractions produced by separation. Benefits to farmers from separation could include extra income from the separated solids, via sales as a soil conditioner or as an organic fertiliser. It may be possible to further dry the solids and combust them to produce heat and/or electricity. The market opportunities for the solid fraction are, as yet, underdeveloped and therefore uncertain.

Compared to raw slurry, the liquid fraction of separated slurry is easier to pump (less viscous), requires little or no mixing before application and does not crust. It may be applied using alternative application methods, such as irrigation or by trailing-shoe tanker. Whilst raw slurry must be handled as a liquid, separation results in both a liquid and a solid, which need different storage and handling equipment. This could present logistical issues as well as increase handling costs. Furthermore, the costs of separation can be substantial (see below). Separation may afford more flexibility in the use of the nutrients contained in the 2 fractions, as the N:P ratio may be altered by separation, especially in the decanting centrifuge. Even without chemical additions, the decanting centrifuge altered the N:P ratio from a mean of 4.4:1 in the raw pig slurry, to 1.1:1 in the separated solids and 16:1 in the supernatant. The brushed screen separator had a minimal effect on the N:P ratio, due to little differential partitioning of either nutrient into the separated solid fraction.

At present, the liquid fraction from a separator is subject to the closed period restrictions under the Nitrates Action Programme. The 'best' supernatant produced from pig slurry was by the decanting centrifuge with chemical addition (DM 5.4g/kg, TP 7mg/kg, TN 1.21g/kg). Dirty water is defined in the Nitrates Action Programme Regulations (Northern Ireland) 2006 as DM<10g/kg, TN<0.3g/kg and BOD<2000mg/l. In the current work, the lowest TN in the supernatant was 1.2g/kg, which is 4 times the permitted limit of the current dirty water standard. Therefore on this basis, the supernatant cannot be classified as 'dirty water' and is subject to the same regulations as raw slurry. Whilst further treatments of the supernatant are possible (such as intensive aeration and reverse osmosis) to further lower concentrations of TN and BOD, these will add additional costs, and may remove nitrogen to the atmosphere as elemental nitrogen or as ammonia. This would represent a loss of a valuable nutrient, which is not desirable, either economically or environmentally.

Costs of Separation

The fixed and variable costs of separation include capital, depreciation, interest, electricity, chemicals, labour and maintenance. In addition, there may be other costs associated with slurry separation that are not necessarily apparent.

Different equipment and facilities are needed to handle and store the separated solids. Similarly, equipment and facilities are required to handle and store the separated liquid fraction, as well as the un-separated slurry.

There was no measure of electricity consumption for each machine in the current work. However, Moller *et al.* (2000) reported electrical consumption at 0.11kWh/tonne slurry separated for a brushed screen separator and 4.0kWh/tonne and 2.9kWh/tonne for cattle and pig slurry respectively, separated in a decanting centrifuge. This equates to an electricity cost of between 1.2p/tonne for the brushed screen and 44p/tonne for the centrifuge with cattle slurry (assuming 11p/kWh for electricity). Moller *et al.* (2000) also calculated the cost of separation for a screw press and a decanting centrifuge at a throughput of 4,000 tons/year. Adapting these figures to current prices and using the same assumptions as Moller *et al.* (2000), i.e. 10 year depreciation, interest at 7% pa. the price of a brushed screen separator at £20,000 and a decanting centrifuge at £100,000, with 4,000 tonnes of slurry separated per annum, the price per tonne of slurry separated is approximately £0.85 and £4.50 for the brushed screen separator and decanting centrifuge respectively. This calculation does not include the cost of any chemicals or labour. 4,000 m^3 of slurry equates to the annula production from approximately 200 sows plus finishers, or 300 dairy cows over 6 months, allowing for some slurry dilution. Moller *et al*, (2000) showed that the cost per tonne separated decreased rapidly with increasing throughput. At a slurry throughput of 8,000 tonnes per annum, the cost per tonne would be approximately half the cost at 4,000 tonnes.

Another way to measure cost of separation is to calculate the cost per tonne of TN or TP removed in the separated solid fraction. At an annual throughput of 4,000m^3 of pig slurry without chemical addition, the estimated costs for partitioning nutrients into the separated solids from pig slurry could be in the order of £6,000/t of TP and £5,000/t TN for the decanting centrifuge and £13,000/t TP and £3,000/t TN for the brushed screen separator. Hence if removal of TP is the objective, the decanting centrifuge may be considerably less expensive than the brushed screen separator per unit of TP removed, depending on the annual throughput of slurry.

The average livestock farm size in Northern Ireland produces considerably less than 4,000 tonnes of slurry per annum. Therefore, the capital and running costs of separation are major considerations, especially for the decanting centrifuge. In order to lower the cost per unit volume of slurry separated it may be possible to use a mobile separator that could service a number of farms. Alternatively a separator could be set up in a central location, maybe as part of a centralised slurry treatment system, to separate slurry from a number of farms. Bio-security and end use of separated fractions then become major issues that must be addressed.

The cost of separation must be compared to the costs of other possible treatments, or no treatment, that could be used to help farms meet the requirements of the Nitrates Action Programme. Livestock farmers who normally export slurry to other farms may find that these farmers are no longer willing to accept slurry, due to the requirements of the Nitrates Action Programme. This may result in some farmers reducing stock numbers, or employing some type of slurry processing technology, such as separation, if they want to stay in production.

The use of chemicals (coagulants and flocculants) to improve separation efficiency was shown to be of particular benefit in centrifugal separation with pig slurry. The cost of these chemicals must also be considered. In the current study, the polymer cost approximately £1.80 per litre undiluted and the conditioner £0.18 per litre. The costs per tonne of pig slurry separated, using the application rates in this study are presented in Table 23. The application rates were similar for each separator, with the exception of the high polymer / high conditioner treatment, which was applied to the decanting centrifuge only.

Table 23. The cost of chemicals per ton of pig slurry separated, for each treatment in the decanting centrifuge.

	Conditioner		Polymer		
Treatment	Litres/tonne slurry	Cost/tonne slurry	kg/tonne slurry	Cost/tonne slurry	Total cost / tonne slurry
Low conditioner	1.60	0.28	0.68	1.22	1.50
Med conditioner	2.46	0.43	0.68	1.22	1.65
High conditioner	3.85	0.67	0.68	1.22	1.89
High poly + conditioner	4.08	0.71	1.68	3.02	3.74

The volume of slurry produced per sow and offspring per year is estimated at 20 m^3 (depends on feeding system and amount of washing). If all the slurry is separated with chemical applied as per Table 23, the cost per sow place would range between £30 and £75. For a sow producing 20 pigs/year, the chemical cost per pig fattened would be between £1.50 and £3.75.

The cost of chemicals used in the separation of cattle slurry in this experiment ranged between £2.40 and £3.40 per tonne. The cost of chemicals for cattle slurry separation would add on at least 50% to the cost of operating the decanting centrifuge without chemicals, bringing the total cost per tonne separated to between £6.66 and £7.66. For a dairy cow producing 70kg slurry per day (including parlour washings), the cost for 180day winter slurry production would range between £84 and £96 per cow for the decanting centrifuge in a 300cow herd. The corresponding figure for the brushed screen without chemical additions would be £10 per cow.

Length of storage before separation

While length of storage time before separation was not investigated in this experiment, it is nevertheless an important consideration in relation to efficiency of separation. Zhu *et al.* (2001) found that after 10 days storage, the total suspended solids in pig slurry tended to decompose at an increased rate and concluded that separation should take place within 10 days of excretion, to maximise separator efficiency, as measured by the proportion of dry solids partitioned to the solid fraction. In the current study it was not possible to quantity whether storage time had any effect on separator efficiency, as the pig slurry was from taken different tanks with variable amounts of slurry in them.

The effect of storage time on manure constituents was evaluated by Pos *et al.* (1984), using pig and cattle slurries. They found that dry matter concentration for all types of slurry decreased with length of storage time. For example, the dry matter concentration of beef slurry decreased from 7.26 % at 57 days of storage to 3.29 % at 102 days and 2.53 % at 129days. Moller *et al.* (2002) found a similar trend with stored pig slurry, with dry matter concentration decreasing with length of storage time. This decrease was attributed to the biological degradation of organic matter, which increased with length of storage time. As the organic matter is broken down during storage, an increasing proportion of this component is transferred from the solid fraction to the liquid fraction. Hence it is recommended that slurry is separated as soon as possible after excretion, to improve dry matter and nutrient removal to the separated solids fraction.

Odour

A separator may be employed by pig farmers with the aim of reducing odour, both during the storage and spreading phases. Jamieson *et al.* (2001) reported that many of the compounds in pig slurry that contribute most to odour generation are contained within the finest fraction of the suspended solids (<0.105 mm). They also found that a substantial portion of the nutrients and organic matter were also contained within this fine fraction (46% of DM, 70% of TN, 47% of chemical oxygen demand (COD), and 75% of TP. Finer fractions of waste are more readily decomposed than larger fractions, and typically contribute more to odour generation (Zhang and Westerman, 1997). Moller *et al.* (2002) found that a decanting centrifuged removed all particles greater than 0.025 mm in pig slurry. This was similar to the findings of Sneath *et al* (1988) who found that all particles greater than 0.02 mm were removed by a centrifuge. Ndegwa *et al.* (2002) concluded that it may be necessary to remove particles less than 0.075 mm to reduce odour potential of the supernatant. Zang *et al.* (2006) found that there was a significant correlation between dry matter concentration and the concentration of volatile fatty acids associated with odour production.

The brushed screen separator used in the current work had pore sizes of 1.6 mm and while the supernatant was not analysed for particle size distribution, it can reasonably be assumed that small particles are mostly not removed during separation and therefore, the odour potential of the supernatant will not be much different compared to the raw slurry. The decanting centrifuge was much more efficient at removing finer particles and total solids and therefore, should lead to reduced odour potential in the supernatant, at least in the short term (30 days) especially with chemical addition. However, during storage the volatile fatty acid concentrations increase and so will the potential for odours (Ndegwa *et al.,* 2002).

Conclusions

1. Mechanical separation was not effective in differentially partitioning K or the ammonia N fraction of total N in into the separated solid fraction, irrespective of separator type or addition of coagulants/flocculants.

2. The decanting centrifuge partitioned significantly more nutrients into the separated solid fraction than the brushed screen separator. This was

particularly marked for total phosphorus. The difference in separation efficiency (as measured by the percentage of input partitioned to the solid fraction) between the 2 separator types was less pronounced with cattle slurry, compared to pig slurry.

3. Addition of coagulants/flocculants significantly enhanced the partitioning of nutrients into the separated solid fraction (except K and NH_3-N) for the decanting centrifuge, but not for the brushed screen. Hence coagulants/flocculants are not recommended for use with a brushed screen separator.

4. Addition of coagulants/flocculants significantly increased the volume of the supernatant produced, compared to the control treatment. This has important implications for storage capacity requirements.

5. There was a positive linear correlation between the dry matter concentration of the slurry (pig or cattle) and the supernatant dry matter concentration, for all treatments applied with either separator. The dry matter concentration of the slurry also displayed a linear positive relationship with the amount of dry matter partitioned to the separated solid fraction for all treatments with the brushed screen.

6. When comparing separation efficiencies with and without chemical additions, the reduction in the concentration of a nutrient in the supernatant, compared the slurry nutrient concentration, is not a useful measure. Water addition along with the chemicals dilutes the slurry and confounds the comparison of concentration of nutrients in the supernatant. In these circumstances the quantity of nutrients partitioned to the separated solid fraction is a better measure of separator efficiency.

7. The cost per tonne of animal slurry separated is approximately 5.5 times greater for the decanting centrifuge compared to the brushed screen separator, (£0.85 versus £4.50/tonne) excluding chemical additions.

8. The cost of chemicals, at the rates used in the current experiment, ranged between £1.50 and £3.74 per tonne of slurry separated.

9. There was a very good relationship between TP concentration and the dry matter concentration of slurry and supernatant. The equations developed in this paper could be used to predict TP concentration from the dry matter concentration of slurry or supernatant.

10. Mechanical separation may be an option for farmers who need to export organic nitrogen and phosphorus in the separated solid fraction to meet the requirements of the Nitrates Action Programme.

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