NUTRIENT RECOVERY BY SOLID-LIQUID SEPARATION AND METHANE PRODUCTIVITY OF SOLIDS

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ABSTRACT. Solid-liquid separation of manure is a method to produce nutrient and dry matter rich fractions with higher volumetric methane potential than that of the original liquid manure. Centrifugation and chemical precipitation and flocculation are efficient options for such separation. Centrifugation efficiency depends on factors such as manure type, G-force, and dewatering volume, while chemical precipitation and flocculation depend on the amount and type of chemicals and polymers used. We assess all these factors in this study. The methane yields of the solids from centrifugation and precipitation were assessed by batch digestion. Dewatering volume and G-force had great influence on separation efficiency and on the chemical composition of the solids. Centrifugation transferred increasing amounts of nutrients and dry matter to the solid fraction as gravitational force increased to approximately 2200G. However, increasing gravitational force beyond 2047G did not significantly improve separation efficiency. The quantity of solids and separation efficiency of dry matter and nutrients varied for different manure types. Separation efficiencies for total N and dry matter greatly depended on the manure's dry matter content, while separation efficiency for total P was little affected by the same factors. Because different manure types were used for the tests with precipitation and flocculation, it was impossible to determine the effect of changing the chemicals. However, the separation efficiencies achieved for N and P were higher than those achieved with centrifuged manure of the same dry matter content. The methane yield from the solids separated by chemical precipitation and flocculation were significantly higher than the yield from centrifuged solids. The yields from the solids produced by centrifugation of pig manure were 161 to 186 L CH₄/kg VS compared to 253 L CH₄/kg VS from centrifuged dairy cow manure, while the yields from the solids produced by coagulation and flocculation were 392 to 404 L CH₄/kg VS.

Keywords. Biogas potential, Separation efficiency, Slurry separation.

Large quantities of pig and cattle slurry are produced in Denmark (Poulsen et al., 2001). In Denmark, as in other western European countries, livestock farming is increasingly specialized, leading to a reduction in the number of farms. At the same time, specialization in livestock production has led to the concentration of animals in restricted areas on large farms, a pattern found throughout Europe (Burton and Turner, 2003). Animal manure contains large amounts of organic matter and nutrients, but because of their low concentration in liquid manure, it is difficult to recover the energy and nutrients. Slurry separation is a key process in nutrient recovery strategies (Møller et al., 2000, 2002). Slurry separation is traditionally done either as a post-treatment after anaerobic digestion or independently, although it could also be used as a pre-treatment to improve the volumetric methane potential. Anaerobic digestion is a key process in any energy recovery strategy. Because of the low organic matter concentration of liquid manure, however, digestion is only economic in large-scale co-diges-

tion plants if liquid manure is co-digested with wastes of high organic matter concentration (Nielsen et al., 2002). However, if a dry matter rich fraction can be produced by solid-liquid separation, digestion of the solid part might improve the economic performance of plants.

When animal manure is physically separated using centrifuges or chemical treatment (addition of coagulants and flocculants) in combination with screening, liquid and solid fractions are produced, the latter containing a higher concentration of dry matter and nutrients than the original manure (Zhang and Lei, 1998; Møller et al., 2000, 2002). Different separation methods produce very different results in transferring dry matter and nutrients to the solid fraction (Møller et al., 2000), but few studies have examined the performance of decanting centrifuges when the operational variables are changed. Several studies have been done to optimize the amounts and types of coagulant and flocculant for separation efficiency (Krumpelman et al., 2005; Timby et al., 2004; Zhang and Lei, 1998), but they have mainly considered flushed dairy manure. The tests of chemical treatment in the present study are done merely so the results can be compared with those obtained with a decanting centrifuge, and to be able to compare the methane yields during anaerobic digestion of the solids produced by the two different technologies. Popular metal coagulants such as Al and Fe have been successfully used in combination with polyacrylamides (PAMs), especially high-charge-density cationic polymers (Krumpelman et al., 2005). Alum (Al₂(SO₄)₃) and Fe₂(SO₄)₃ were used as coagulants in this experiment, and PAM (Optifloc C6260) was used as the flocculant.

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An advantage of separation is that it produces solids that can be transported more economically to centralized anaerobic digestion plants. This enables the transport of excess phosphate from high-density animal production areas to areas of phosphate demand. The volumetric methane production of manure can be increased significantly by solid-liquid separation (Møller et al., 2002) that produces solid fractions of high VS concentration; however, some of the VS will still remain in the liquid fraction. If only the solid fraction is used as a substrate for anaerobic digestion, it is important that the separation units be efficient at transferring dry matter to the solid fraction. Møller et al. (2004) found that chemical precipitation, combined with screening and centrifugation, was an efficient method for transferring VS to a solid fraction.

This study assesses the influence of manure type, G-force, and dewatering volume on the separation of nutrients and solids when using a decanting centrifuge. We also compare the efficiency of centrifugation with that of coagulation and flocculation, and finally assess the methane yield from the solids produced by both centrifugation and chemical treatment when digested anaerobically.

MATERIALS AND METHODS

ANALYTICAL PROCEDURES

Total nitrogen (TN) was analyzed using the Kjeldahl standard method (APHA, 1995) and a Kjell-Foss 16200 autoanalyzer (Foss Electric, Hillerød, Denmark). Dry matter (DM) was determined after drying at 105°C for 24 h. Volatile solids (VS) was measured in accordance with standard methods (APHA, 1995). Total phosphorus (TP) was analyzed colorimetrically using a Spectronic 1001 UV-VIS spectrophotometer (Bausch & Lomb) after dry ashing, solubilization in acid, and a coloring reaction with ammonium molybdate vanadate. Ammonium (NH_4^+) in the slurry was analyzed using a QuickChem 4200 flow injection analyzer (Lachat Instruments, Milwaukee, Wisc.). Slurry pH was determined with a pH meter (Radiometer A/S, Copenhagen, Denmark). K, Mg, Cu, S and Ca were analyzed by ICP technology (Optima 2000DV, Perkin Elmer) after drying and destruction with H_2NO_3 in an autoclave.

In the tests with centrifugation and chemical coagulation/flocculation, respectively 20 to 40 m^3 and 10 to 20 m^3 of manure were subjected to separation.

FULL-SCALE SEPARATION TESTS AND SEPARATION EFFICIENCY

A Pieralisi Jumbo 3 (Italy) decanter centrifuge was used during the tests (fig. 1). In it, the raw slurry is subjected to considerable centrifugal force in a high-velocity rotating drum, typically rotating at 2000 to 4000 rpm. During this process, the particle components of the slurry sediment move toward the periphery of the drum where they can subsequently be removed by a rotating screw. This well-tested technology has been used in both industrial and municipal sewage treatment; in recent years, experience has been gained in using the technology with manure slurry as well (Møller et al., 2000, 2002).

The performance of a decanting centrifuge depends on factors such as the G-force, dewatering volume, and retention time. The term G-force or G-value (Møller et al., 2002) is frequently used to define the force acting on the solids: it is the multiple of the gravitational constant obtained in the centrifuge. An approximate formula for calculating the G-force in G (Vanderbeken, 2005) at the drum periphery is:

$$G = \frac{n^2 \times \theta}{1800} \quad (1)$$

where n is the drum speed (rpm), and θ is the drum's maximum inner diameter (m), which is 0.470 m in the Jumbo 3. Consequently, the centrifugal acceleration or G-value will increase with drum diameter and speed. The dewatering volume of a decanter is considered to be the total volume of the liquid zone in the cylindrical part of the drum. This volume may change in relation to the weir plate diameter. For the Pieralisi Jumbo 3 decanter, weir plate standard diameters are 310, 300, 285, 280, and 273 mm. During the "standard" tests performed with manure types 1a to 4c (table 1), the centrifuge rotated at 2900 rpm, thus causing a G-force of 2196G. During this "standard" testing, the weir plate diameter was 280 mm and the differential speed of the screw was on average 80 rpm slower than the speed of the drum, but the diameter was changed during some of the tests to measure the influence on performance and on separation efficiency. The G-force therefore changed during some of the tests.

The retention time (R) in seconds can be calculated as:

$$R = 3600 \times \frac{\text{Dew.Vol}}{Q} \quad (2)$$

where Q is the effluent input (L/h) and Dew.Vol is the dewatering volume (179 L, based on 273 mm diameter weir

Figure 1. Cross-section of a Pieralisi Jumbo 3 decanting centrifuge with dimensions.

plates). The retention time is the length of time that the liquid remains in the bowl before discharge. For a given input (Q) and no change in screw rpm, the retention time will change when the weir plate diameter is modified to change the dewatering volume, with a smaller weir plate diameter increasing the retention time. Longer retention time will produce more efficient solid-liquid separation. With an input of $Q = 22 \text{ m}^3/\text{h}$ and a dewatering volume of 179 L, the retention time will be 29 s. During the “standard” testing, the input to the centrifuge varied between 10 and $25 \text{ m}^3/\text{h}$, where the lowest capacity was in cattle manure and the highest capacity in pig and digested manure. In one test (HF), the capacity was increased to $40 \text{ m}^3/\text{h}$.

The Kemira Miljoe separator (Esbjerg, Denmark) had a capacity of approximately $8 \text{ m}^3/\text{h}$ and consists of three flocculation chambers (700 L each) in which added chemicals are mixed to form new compounds; this alters the physical state of the dissolved and suspended solids and facilitates their removal by a belt press. The dry matter was coagulated and flocculated, resulting in 2 to 10 mm flocs, and the dry matter was then removed and dewatered on a 4 m belt with 2 mm screen size and finally dewatered in a screw press with 1 mm screen size. The belt was continuously cleaned by washing with water. Alum, $(\text{Al}_2\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$, or Fe_2SO_4 was used as a coagulant ($0.5 \text{ kg}/\text{m}^3$ pig slurry) and a cationic polymer, Optifloc C6260, 40% active ($0.2 \text{ L}/\text{m}^3$ manure), was used to agglomerate the coagulated particles.

The rate at which manure was added to the centrifuge was measured with a magnetic-inductive flowmeter (Danfoss Mag 3100, Sønderborg, Denmark). The centrifuge produced solid and liquid fractions; the solids were measured by collecting the material in containers and weighing the containers after the separation tests, while the liquid was measured using the same model of magnetic-inductive flowmeter. The manure was stirred immediately before each test, and manure samples were taken three to six times during the test. Representative samples of the solid and liquid fractions were taken five times during a separation experiment. All samples were stored at -18°C until analysis.

The amount of water added to the Kemira Miljoe separator was determined by calculating the dilution factor. This was done by comparing the potassium concentrations in the raw manure and in the liquid after separation, since potassium is

regarded as completely soluble. The use of water was found to range between 100 and $500 \text{ L}/\text{m}^3$ of manure. The use of water has since been reduced by using the liquid from separation for cleaning the belt.

Separation efficiency is defined as the total mass recovery of solids and nutrients in the solid fraction, as a proportion of the total input of solids or nutrients (Svarovsky, 1985):

$$E_1 = \frac{U \times M_c}{Q \times S_c} \quad (3)$$

where E_1 is the index for simple separation efficiency, U is the quantity of the solid fraction in weight (kg/kg slurry treated), M_c is the concentration of the components (DM, TP, and TN) in the solid fraction (g/kg), Q is the amount of raw slurry treated (kg), and S_c is the concentration of the components in the slurry (g/kg).

GAS PRODUCTION

The ultimate methane yield (B_0) was determined in a batch experiment. The experiments were performed in 1100 mL infusion bottles, which were closed with butyl rubber stoppers, sealed with aluminum crimps, and incubated at $35^\circ\text{C} \pm 0.5^\circ\text{C}$, after flushing with N_2 . The test media were frozen until used in the batch. Inoculum from a farm-scale biogas plant was used; it had been stored at 35°C for two weeks before testing to ensure that most of the remaining methane production was complete. Each test medium was digested in triplicate, and the gas production was subtracted from the gas produced by the control medium (inoculum and water only). The volume of gas produced was measured by connecting the infusion vessel to a gas collection bag, and using a large syringe to measure the volume of gas, as described by Steed and Hashimoto (1994). The gas samples were analyzed for CO_2 and CH_4 content using gas chromatography. CH_4 was measured on a Hewlett Packard 5890 series II gas chromatograph equipped with an electron capture detector and a flame ionization detector. Methane was isolated using a $1.83 \text{ m} \times 3.1 \text{ mm}$ column with Poropak N 80/100; He was used as the carrier gas at $30 \text{ mL}/\text{min}$, and the injection port, oven, and detector temperatures were 110°C , 40°C , and 270°C , respectively. CO_2 was measured using a Varian 3350 gas chromatograph equipped with a ther-

Table 1. Composition of pig, dairy cow, and anaerobically digested slurry before separation (standard deviation indicated in parentheses). The letters in the manure IDs refer to manures from different farms.

Manure Type	Manure ID	No. of Manures	DM (%)	TN (g/kg)	$\text{NH}_4\text{-N}$ (g/kg)	TP (g/kg)	K (g/kg)	Mg (g/kg)	Cu (g/kg)
Tests with decanting centrifuge									
Pig manure, fattening (average)	1a – 1h	8	5.1 (2.4)	5.4 (1.2)	3.9 (0.7)	1.1 (0.6)	3.3 (0.6)	0.75	0.02
Sow manure (average)	2a – 2f	6	4.0 (2.4)	4.0 (0.8)	2.7 (0.4)	1.0 (0.7)	2.0 (0.7)	0.31	0.02
Digested pig manure (average)	3a – 3c	3	3.2 (2.5)	4.1 (0.6)	3.8 (0.7)	1.4 (0.9)	1.9 (0.3)	0.49	0.017
Dairy cow manure (average)	4a – 4c	3	7.0 (0.8)	4.2 (0.4)	2.2 (0.3)	0.8 (0.1)	3.0 (0.6)	0.60	0.005
Pig manure:									
G-force and weir plate diameter experiment	5	1	6.8 (0.6)	5.79 (0.2)	4.62 (0.1)	1.32 (0.1)	3.92 (0.1)	0.76	0.01
G-force experiment	6	1	8.9	6.86	4.56	2.3	5.4	0.75	0.02
Tests with chemical precipitation									
Pig manure (polymer)	7	1	1.21	2.45	2.15	0.32	1.6		
Pig manure (polymer + $\text{Fe}_2(\text{SO}_4)_3$)	7	1	1.21	2.45	2.15	0.32	1.6		
Pig manure (polymer + $\text{Fe}_2(\text{SO}_4)_3$)	8	1	2.08	5.27	4.28	0.29	3.1		
Pig manure (polymer + Alum)	8	1	2.08	5.27	4.28	0.29	3.1		
Pig manure (polymer)	8	1	2.84	4.58	4.43	0.53	2.9		
Pig manure (polymer + Alum)	9	1	4.2	4.52	3.25	0.82	2.19	0.37	0.046

mal conductivity detector. It was equipped with a 1 m × 3.1 mm column with a 2 m × 3.1 mm Haysep R 80/100 molecular sieve. The carrier gas was He at a flow rate of 30 mL/min; the oven and detector temperatures were 40 °C and 150 °C, respectively.

RESULTS AND DISCUSSION

MASS BALANCES AND CHEMICAL COMPOSITION

The chemical characteristics of the pig manure (from sows and fattening pigs), dairy cow manure, and anaerobically digested pig manure used in the standard tests are given in table 1. Manure characteristics are affected by the type of animal, but there is also a significant variation within individual animal categories.

After centrifugation under standard conditions, the quantities of solids and the separation efficiencies for dry matter and nutrients were found to be variable for different manure types (table 2 and fig. 2). The separation efficiencies (%) were 37 to 68, 50 to 83, and 8 to 33 for DM, TP, and TN, respectively. The separation efficiencies for total N ($R^2 = 0.6$) and dry matter ($R^2 = 0.4$) were correlated with the dry matter content of the manure, while the separation efficiency for total P ($R^2 = 0.0004$) was not significant affected by the dry matter content of the slurry. Møller et al. (2002) found a similar correlation using a different centrifuge (table 3), but the linear regression results were quite different. This indicates that different centrifuges have different separation characteristics. This is important in Denmark, where farmers

Figure 2. Quantity of the solid fraction in weight (U in eq. 3), DM, TP, and TN transferred from the manure to the solid fraction during centrifugation (under standard conditions) as a function of dry matter content of untreated slurry. The following linear regression equations were derived from the data: TP: $y = 0.08x + 66.059$ ($R^2 = 0.0004$); DM: $y = 2.29x + 41.824$ ($R^2 = 0.36$); TN: $y = 2.51x + 7.134$ ($R^2 = 0.66$); quantity of solids: $y = 2.3x - 1.54$ ($R^2 = 0.6268$).

need a separation efficiency of over 60% TP and 20% TN to obtain legal permission to increase herd size by 25% without buying more land (Seadi and Møller, 2003). For TP, it was possible for both centrifuges to achieve 60% TP, even with very dilute manure, while the Peralisi Jumbo 3 decanter centrifuge could only remove over 20% of TN if the DM of the manure was >5.5%. The Alfa Laval NX 309B-31 centri-

Table 2. Average separation efficiency for the different manure categories subjected to different treatments.

Manure ID	Decanting Centrifuge			Separation Efficiency										
	G-force (G)	Weir Plate Diameter		U[a] (%)	DM (%)	TN (%)	NH ₄ -N (%)	TP (%)	K (%)	Mg (%)	Cu (%)	Org. N (%)	Ca (%)	S (%)
1	2196	280	Avg:	9.2	51.1	16.6	9.8	70.5	8.4	79.4	23.7	39.5	--	--
	2196	280	SD:	6.0	12.4	7.7	6.6	9.4	5.8	11.5	7.9	15.7	--	--
2	2196	280	Avg:	6.6	51.8	17.1	7.4	70.0	7.7	82.1	27.9	41.3	--	--
	2196	280	SD:	3.8	6.2	6.5	4.3	5.8	4.1	8.3	9.5	9.3	--	--
3	2196	280	Avg:	4.3	47.5	13.4	6.0	62.6	5.1	92.6	31.7	40.0	--	--
	2196	280	SD:	1.5	0.9	5.8	2.8	5.7	1.7	2.7	12.7		--	--
4	2196	280	Avg:	22.5	62.7	28.7	16.1	55.2	20.7	60.0	35.4	40.5	--	--
	2196	280	SD:	6.4	5.2	6.5	8.5	6.4	4.3	5.7	10.0	2.9	--	--
5	2196	290		12.0	62.3	21.4	9.2	76.2	11.0	90.9	23.7	51.2	--	--
5	2196	280		16.0	69.1	27.3	12.6	81.2	14.3	92.9	31.9	61.1	--	--
5	2196	270 (HF)		18.7	69.7	28.9	21.0	83.1	17.9	94.8	37.6	47.9	--	--
5	2196	270 (LF)		26.0	70.4	35.5	26.0	81.7	25.0	94.2	39.9	61.3	--	--
5	1044	280		9.6	55.5	16.8	7.4	65.4	7.7	84.2	21.8	49.6	--	--
5	1504	280		11.0	58.4	18.6	9.9	71.7	9.6	87.9	21.2	42.4	--	--
5	2196	280		16.0	69.1	27.3	12.6	81.2	14.3	92.9	31.9	61.1	--	--
6	2047	280		21.8	69.4	33.5	22.3	87.2	33.0	94.6	36.2	51.9	81.3	--
6	2350	280		20.7	68.7	33.0	22.7	86.2	32.2	93.5	27.8	48.6	76.7	--
6	2558	280		17.6	69.3	28.6	18.0	84.5	25.8	94.2	33.9	45.9	77.2	53.5
Chemical Precipitation														
	Coagulate	Flocculate												
7	0	Optifloc C6260		4.5	55.1	19.7	7.6	72.4	3.9	--	--	71.9	--	--
7	Fe ₂ (SO ₄) ₃	Optifloc C6260		6.0	55.7	24.4	8.6	74.7	5.2	--	--	80.4	--	--
8	Fe ₂ (SO ₄) ₃	Optifloc C6260		4.5	53.8	16.1	6.6	72.6	4.5	--	--	61.8	--	--
8	(AL ₂ SO ₄) ₃	Optifloc C6260		9.5	73.3	34.5	15.3	91.3	10.4	--	--	83.4	--	--
8	0	Optifloc C6260		13.0	84.4	54.3	18.3	84.6	14.0	--	--	87.5	--	--
9	(AL ₂ SO ₄) ₃	Optifloc C6260		18.0	87.0	45.1	27.7	90.2	25.6	90.8	95.7	63.1	92.9	70.0

[a] U = quantity of solid fraction in weight.

Table 3. Linear regression equations for separation efficiency (y), in terms of dry matter in the manure subjected to separation (x), derived from the data from this study (Pieralisi Jumbo 3) and a previous study (Alfa Laval NX 309B-31; Møller et al., 2002) with a decanting centrifuge.

	Pieralisi Jumbo 3		Alfa Laval NX 309B-31	
	Linear Regression	R ²	Linear Regression	R ²
Quantity of solids	$y = 2.3x - 1.54$	0.63	$y = 2.665x - 0.6632$	0.76
DM	$y = 2.29x + 41.824$	0.36	$y = 3.3x + 41.824$	0.27
TP	$y = 0.08x + 66.059$	0.0004	$y = 0.2483x + 59.727$	0.1
TN	$y = 2.51x + 5.69$	0.66	$y = 4.28x + 7.134$	0.50

fuge (Møller et al., 2002) removed more than 20% of TN if the DM of the manure was >3%. This was mainly because the Pieralisi Jumbo 3 decanter centrifuge produced a solid fraction of considerably higher DM content than that produced by the Alfa Laval NX 309B-31 device, thus transferring less of the dissolved NH₄⁺ with the liquid associated with the solids.

The chemical characteristics of the solid fraction after centrifugation (standard conditions) are given in table 4. The solid fraction showed 6 to 10, 9 to 11, and 2 to 2.9 times higher average concentrations of DM, total P, and total N, respectively, than in untreated pig manure (from sows and fattening pigs) or digested pig manure, while the solid fraction showed 3, 2.5, and 1.2 times higher average concentrations of DM, total P, and total N, respectively, than in untreated dairy cow manure. This clearly indicates that centrifugation efficiently concentrates the DM and total P contents of the solid fraction of pig manure; however, the efficiency with which it concentrates the DM and total P contents of the solid fraction of dairy cow manure is relatively lower. The concentration efficiency for total N in the solid fraction is relatively low for all manure types because the centrifuge mainly transfers the

organic part of the nitrogen to the solid fraction, while most of the dissolved NH₄⁺ stays in the liquid (Møller et al., 2002).

With chemical treatment, the quantity of the solids and the separation efficiency for dry matter and nutrients also proved to be variable, depending on the different manure types and coagulants and flocculants (table 2). The separation efficiencies (%) obtained with chemical precipitation were 55 to 87, 72 to 91, and 16 to 45 for DM, TP, and TN, respectively, which were higher efficiencies than achieved with the centrifuge. However, direct comparison between centrifugation and chemical precipitation is not possible since the manure subjected to chemical precipitation had greatly reduced DM content. If the DM values in the two tests had been more comparable, the difference would probably have been greater. The chemical characteristics of the solid fraction after chemical precipitation (under standard conditions) are given in table 4. The solid fraction showed 5 to 13, 4.7 to 15, and 2.1 to 3.8 times higher average concentrations of DM, TP, and total N, respectively, than in untreated pig manure; however, the concentration of TP was lower than in the solids resulting from centrifugation, mainly due to lower DM concentration.

Table 4. Composition of the solid fraction after separation of the manure.

Manure ID	Decanting Centrifuge			Concentration in Solid Fraction								
	G-force (G)	Weir Plate Diameter		DM (g/kg)	TN (g/kg)	NH ₄ -N (g/kg)	TP (g/kg)	K (g/kg)	Mg (g/kg)	Cu (g/kg)	Ca (g/kg)	S (g/kg)
1	2196	280	Avg:	327	10.8	4.0	9.7	3.0	5.2	0.0909	--	--
	2196	280	SD:	22	1.3	1.1	1.7	0.5	1.9	0.0559	--	--
2	2196	280	Avg:	327	10.4	3.1	10.6	2.2	3.8	0.0770	--	--
	2196	280	SD:	19	1.5	0.7	2.2	0.4	1.0	0.0403	--	--
3	2196	280	Avg:	326	11.9	4.7	15.3	2.2	6.5	0.0957	--	--
	2196	280	SD:	10	0.9	0.5	1.2	0.1	1.1	0.0145	--	--
4	2196	280	Avg:	211	5.0	1.7	1.9	3.2	1.5	0.0080	--	--
	2196	280	SD:	13	0.6	0.6	0.3	0.4	0.4	0.0017	--	--
5	2196	290		343	11.0	3.3	8.2	3.6	5.1	0.0250	--	--
5	2196	280		325	10.9	3.5	7.7	3.6	4.8	0.0270	--	--
5	2196	270 (HF)		256	9.4	4.8	6.2	3.6	4.0	0.0210	--	--
5	2196	270 (LF)		186	8.5	4.6	3.8	3.8	2.3	0.0170	--	--
5	1044	280		279	10.3	3.6	6.6	3.7	4.0	0.0210	--	--
5	1504	280		319	10.4	4.1	7.8	3.7	4.7	0.0240	--	--
5	2196	280		325	10.9	3.5	7.7	3.6	4.8	0.0270	--	--
6	2047	280		330	11.4	4.72	12.0	6.93	4.62	0.0363	15.18	--
6	2350	280		339	12.4	5.13	12.0	7.119	4.407	0.0339	14.238	--
6	2558	280		410	12.1	4.74	12.0	8.2	5.33	0.04	15.99	2,501
Chemical Precipitation												
	Coagulate			Floculate								
7	0	Optifloc C6260		164	9.5	3.0	5.0	1.2	--	--	--	--
7	Fe ₂ (SO ₄) ₃	Optifloc C6260		122	8.9	2.4	3.7	1.2	--	--	--	--
8	Fe ₂ (SO ₄) ₃	Optifloc C6260		235	11.4	3.9	4.5	2	--	--	--	--
8	(AL ₂ SO ₄) ₃	Optifloc C6260		261	12.7	4.0	5.0	2.1	--	--	--	--
8	0	Optifloc C6260		236	14.5	2.4	3.3	1.2	--	--	--	--
9	(AL ₂ SO ₄) ₃	Optifloc C6260		222	9.9	3.1	3.9	2.28	1.5	0.21	9.2	1.65

Table 5. Composition of the liquid fraction after separation of the manure.

Manure ID	Decanting Centrifuge			Concentration in Liquid Fraction								
	G-force (G)	Weir Plate Diameter		DM (g/kg)	TN (g/kg)	NH ₄ -N (g/kg)	TP (g/kg)	K (g/kg)	Mg (g/kg)	Cu (g/kg)	Ca (g/kg)	S (g/kg)
1	2196	280	Avg:	27.6	4.9	3.8	0.3	3.4	0.13	0.026	--	--
	2196	280	SD:	10.5	0.9	0.9	0.1	0.7	0.09	0.018	--	--
2	2196	280	Avg:	20.7	3.3	2.6	0.3	1.8	0.06	0.015	--	--
	2196	280	SD:	9.4	0.7	0.4	0.2	0.7	0.04	0.011	--	--
3	2196	280	Avg:	16.3	3.5	3.4	0.4	1.9	0.03	0.012	--	--
	2196	280	SD:	5.8	0.4	0.4	0.3	0.5	0.02	0.009	--	--
4	2196	280	Avg:	37.7	3.9	2.3	0.5	3.2	0.32	0.004	--	--
	2196	280	SD:	3.2	0.3	0.3	0.1	0.7	0.07	0.001	--	--
5	2196	290		28.4	5.5	4.5	0.35	4	0.07	0.011	--	--
5	2196	280		27.7	5.5	4.6	0.34	4.1	0.07	0.011	--	--
5	2196	270 (HF)		25.6	5.3	4.2	0.29	3.8	0.05	0.008	--	--
5	2196	270 (LF)		27.5	5.4	4.6	0.30	4	0.05	0.009	--	--
5	1044	280		28.1	0.0	4.6	0.4	4.3	0.0800	0.011	--	--
5	1504	280		28.1	0.0	4.6	0.4	4.3	0.0800	0.011	--	--
5	2196	280		27.7	0.0	4.6	0.3	4.1	0.0700	0.011	--	--
6	2047	280		40.4	6.3	4.58	0.49	3.9188	0.0727	0.017776	0.9696	--
6	2350	280		40	6.56	4.55	0.5	3.9091	0.0806	0.022971	1.1284	--
6	2558	280		39	6.45	4.6	0.47	5.031	0.0697	0.017028	1.0062	0.4644
Chemical Precipitation												
	Coagulate	Flocculate										
7	0	Optifloc C6260		6.30	1.83	1.71	0.09	1.40	--	--	--	--
7	Fe ₂ (SO ₄) ₃	Optifloc C6260		6.20	1.75	1.65	0.08	1.40	--	--	--	--
8	Fe ₂ (SO ₄) ₃	Optifloc C6260		9.50	2.81	2.59	0.08	2.00	--	--	--	--
8	(AL ₂ SO ₄) ₃	Optifloc C6260		10.00	2.52	2.34	0.05	1.90	--	--	--	--
8	0	Optifloc C6260		6.50	1.83	1.57	0.09	1.10	--	--	--	--
9	(AL ₂ SO ₄) ₃	Optifloc C6260		7.00	2.55	1.71	0.09	1.40	0.03	0.0020	0.15	0.15

The nutrient concentration was significantly lower in the liquid fraction than in the unseparated manure, especially for DM content and for the concentration of nutrients associated with particles, such as P, Ca, and Mg (table 5). The concentration of soluble nutrients, such as K and NH₄⁺, was also lowered because the dewatering belt was continuously cleaned by washing with water, giving a significant dilution.

SEPARATION PERFORMANCE IN TERMS OF G-FORCE

Full-scale centrifuge experiments were conducted to determine the influence of the centrifuge operating variables on nutrient recovery. The centrifuge operating variables examined were gravitational force (G-force), feed rate, and weir plate diameter. The rotation speed of the centrifuge was changed within the 2000 to 3130 rpm range, resulting in gravitational forces between 1044G and 2558G. The separation results versus gravitational force are presented in table 2. Separation efficiency was, as expected, affected by the gravitational force. It can be seen that increasing amounts of nutrients were transferred to the solid fraction as the gravitational force was increased to approximately 2200G, in the case of pig manure 5. However, with pig manure 6, it seems that increasing the gravitational force beyond 2047G did not improve separation efficiency significantly. The separation efficiency seems rather stable between 2047G and 2558G for nutrients associated with particles, such as P, Ca, and Mg. However, the amount of solids (solid-to-slurry ratio) is reduced by increasing the gravitational force, as is the separation of nutrients associated with the liquids, such as NH₄ and K. The DM content and nutrient concentrations versus gravitational force are presented in figure 3. It can be

seen that DM content and nutrient concentration both increased when the gravitational force was increased to approximately 2200G in the case of pig manure 5. In the case of pig manure 6, increasing the gravitational force up to 2558G increased the DM concentration, but nutrient concentrations were barely affected.

Figure 3. Composition of the solid fraction after separation of pig slurry subjected to different G-forces. Two different manures from fattening pigs were used in the test: manure 5 had a normal dry matter content (6.9%), and manure 6 had a very high dry matter content (8.9%).

SEPARATION PERFORMANCE IN TERMS OF WEIR PLATE DIAMETER

The dewatering volume of a decanter is considered to be the total content of the liquid zone in the cylindrical part of the drum. This volume changes in relation to the weir plate diameter, so a smaller weir plate diameter will increase both the dewatering volume and retention time (Vanderbeken, 2005). When the retention time is longer, more efficient solid-liquid separation is expected. However, increasing the dewatering volume reduces the retention time in the dewatering zone, which might reduce the dewatering of the solid part.

The following weir plate diameters were tested: 270, 280, and 290 mm. Separation efficiency was found to be affected by changing the weir plate diameter, as increasing amounts of nutrients were transferred to the solid fraction as weir plate diameter was reduced in manure 5 with a constant G-force of 2196G (table 2).

Both the DM content and nutrient concentration increased in solids produced from manure 5 as the weir plate diameter was increased and the retention time in the dewatering zone was increased (table 4) with a constant G-force of 2196G. Sneath et al. (1988) found that the DM content of the solid fraction increased when the dewatering volume was reduced, thus increasing the retention time in the dewatering zone. The concentration of nutrients associated with particles, such as P and Mg, was also increased by increasing the weir plate diameter. However, the nutrient concentration of nutrients associated with liquids, such as NH_4 and K, was barely affected. By reducing the flow rate (LF) and using a weir plate of 270 mm diameter, both the DM content and the concentration of nutrients associated with particles, such as P, Ca, and Mg, were reduced. There is no obvious reason for this.

METHANE YIELD FROM FRACTIONS OF MANURE DERIVING FROM SEPARATION

Considerable research in developing biogas technology has been done in Denmark, and several co-digestion and farm-scale plants are currently running. However, biogas

production from manure in terms of yield per volume is low, and biogas plants depend on a supply of easily degradable waste products to be economically feasible (Nielsen et al., 2002). The development of new centralized plants is currently stagnant due to a limited supply of such waste products. The transport of slurry from the farm to the biogas plant is an important operating cost factor for the co-digestion plants, and it is one reason for the poor economic performance of biogas plants running mainly on manure. By reducing the transport cost per m^3 of methane produced and increasing the daily methane production per m^3 digester volume, the economic feasibility of co-digestion plants might be improved, as long as separation costs do not exceed the value of added benefits.

Drainage of water from the manure by separation creates a solid fraction with a higher VS concentration, thus producing a manure waste fraction with a higher volumetric biogas potential. Møller et al. (2004) found a methane yield of 194 L/kg VS from solids produced by centrifugation and 247 L/kg VS from those produced by precipitation and flocculation. This study found that the methane yield from solids separated by chemical precipitation and flocculation was significantly higher than that from solids separated by centrifugation. The yield after 60 days of batch digestion of solids from the centrifugation of pig manure was 161 to 186 L CH_4 /kg VS, compared to 253 L CH_4 /kg VS from dairy cow manure (fig. 4). Surprisingly, solids from the centrifugation of dairy cow manure gave a higher yield than did solids from pig manure, although the yield was higher from unseparated pig manure than from unseparated dairy cow manure, indicating that the centrifugation of pig manure gives a poor separation of the small highly digestible particles, while centrifugation of cattle manure to a higher extent separates both highly and slowly digestible particles in the same proportions. The yield from the solids produced by coagulation and flocculation after 60 days of batch digestion was 392 to 404 L CH_4 /kg VS. There was no significant difference between the yield from solids coagulated with Fe and that from solids only flocculated with polymer.

The methane yield from the flocculated solids was at the same level or even higher than yields from unseparated

Figure 4. Methane yield of solids separated by centrifugation and chemical treatment, plotted against time (standard deviations indicated by bars). The total VS content in the separated solids from manures 4, 5, 6, 7 (with polymer + Fe), and 7 (with polymer) prior to batch digestion were respectively 160, 251, 283, 112, and 124 g/kg.

manure in terms of VS as found in a previous study (Møller et al., 2004). Since the DM and VS content is 5 to 10 times higher in the solids than in the liquid manure, the solids are very suitable for transport to an anaerobic digestion plant. The methane yield from the centrifuged solids was 40% to 50% lower than that from unseparated manure in terms of VS; however, since the VS content is 5 to 15 times higher in the solids than in the liquid manure, the methane yield in terms of the volume of centrifuged solids is still 2 to 7 times higher than that of liquid manure.

CONCLUSIONS

Solid-liquid separation produces nutrient and dry matter rich fractions from liquid manure. Both centrifugation and chemical precipitation and flocculation proved to be efficient separation methods. The efficiency of centrifugation depends on factors such as manure type, G-force, and dewatering volume, while the efficiency of chemical treatment depends on the amount and type of chemicals and polymers used. The centrifuge transferred an increasing amount of nutrients and dry matter to the solid fraction as the gravitational force was increased to approximately 2200G; however, increasing the gravitational force beyond 2047G did not improve separation efficiency significantly. The separation efficiencies for total N and dry matter were highly dependent on the dry matter content of the manure, while the separation efficiency for total P was little affected by this factor. We used linear regression to determine the relationships between DM content in the manure and the achieved separation efficiencies. The relationships thus found differed from those found by a previous study using a different model centrifuge. This clearly indicates that different centrifuges have different performance and separation characteristics.

The DM content and nutrient concentration both increased when the gravitational force was increased to approximately 2200G. However, increasing the gravitational force up to 2558G only increased the DM, Mg, and Ca concentrations. When using chemical treatment, the separation efficiencies for dry matter and nutrients varied depending on the different types of manure and of added coagulants and flocculants. The separation efficiencies achieved with chemical treatment were higher than those achieved with centrifugation.

The yield after 60 days of batch digestion of the solids produced by centrifuging pig manure was 161 to 186 L CH₄/kg VS, compared to 253 L CH₄/kg VS from centrifuged dairy cow manure. Surprisingly, the solids from centrifuged dairy cow manure gave a higher yield than did the solids from pig manure, although the yield in general was higher from unseparated pig manure than from unseparated dairy cow manure in previous studies. The yield from the solids produced by coagulation and flocculation of pig manure, after 60 days of batch digestion, was 392 to 404 L CH₄/kg VS. There was no significant difference in terms of methane yield between the solids coagulated with Fe and those only flocculated with polymer.

This study indicates that solid-liquid separation, especially with addition of polymers, has potential for pre-separation of manure before transportation to a co-digestion plant. Pre-separation might improve the economical performance, since the methane yield in terms of VS is in the same

magnitude as unseparated manure and the VS content is 5 to 10 times higher than in liquid manure, thus significantly reducing the transport cost per unit of VS. However, the increased costs of separation should be taken into account when evaluating the total benefits.

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