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Research article

Optimising mechanical separation of anaerobic digestate for total solids and nutrient removal[☆]

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ABSTRACT

Mechanical separation of anaerobic digestate has been identified as a method to reduce pollution risk to waterways by partitioning phosphorus in the solid fraction and reducing its application to land. Separators have adjustable parameters which affect separation efficiency, and hence the degree of phosphorous partitioning, but information on how these parameters affect separation performance is limited in the literature. Two well known technologies were investigated, decanter centrifuge and screw press, to determine the most efficient method of separation. Counterweight load and the use of an oscillator were adjusted for the screw press, while bowl speed, auger differential speed, feed rate and polymer addition were modified for the decanter centrifuge. Separation efficiency was determined for total solids, phosphorus, nitrogen, potassium, and carbon, and the total solids content of resulting fractions was measured. The decanter centrifuge had higher separation efficiency for phosphorus in all cases, ranging from 51% to 71.5%, while the screw press had a phosphorus separation efficiency ranging from 8.5% to 10.9% for digestate of ~5% solids (slurry/grass silage mix). Separation by decanter centrifuge partitioned up to 56% of nitrogen in the solid fraction leaving a reduced nitrogen content in the liquid fraction available for land spreading; this nitrogen would most likely need to be replaced by chemical fertiliser which would add to the cost of the system. The decanter centrifuge is better suited to cases where phosphorus recovery is the most important factor, while the screw press could be advantageous in cases where cost is a limiting factor.

CRediT authorship contribution statement

Ashley Cathcart: Investigation, Methodology, Writing – original draft. Beatrice M. Smyth: Supervision, Writing – review and editing. Gary Lyons: Supervision, Writing – review and editing. Simon T. Murray: Supervision, Writing – review and editing. David Rooney: Funding acquisition, Supervision. Christopher R. Johnston: Funding acquisition, Writing – review and editing, Supervision.

1. Introduction

The EU 2030 Climate Action Plan sets a target for a 55% reduction in greenhouse gas (GHG) emissions relative to 1990 levels by 2030 (European Commission, 2020) with a target of net carbon neutrality by 2050 (European Commission, 2018). Among the technologies contributing to the drive to net zero is anaerobic digestion (AD), which produces a storable, gaseous fuel called biogas that can be used for electricity and heat generation or to displace reliance on natural gas through upgrading to biomethane. Investment in the sector has seen the total capacity of plants in Europe grow to 191 TWh in 2020, supplying 4.6% of EU gas consumption, with a target of 1000 TWh by 2050, which could provide 30–40% of total EU gas consumption (Sainz Arnau et al., 2022).

The increase in AD plant numbers has led to an increase in the digestate by-product. Agri-based AD typically utilises animal slurry and energy crops to produce biogas and the residual by-product digestate,

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which contains nitrogen (N) and phosphorus (P), is suitable as a fertiliser. Regions with large cattle, pig, and poultry sectors have a readily available feedstock for AD, but the digestate produced must be carefully managed as over-application to land can lead to run-off of nutrients to waterways and negative impacts on water quality (Smith et al., 1999). Energy crops are often added to slurry to improve biogas yield, so the resulting digestate can have a higher P and N content relative to the starting slurry, further increasing the nutrient load to be applied to land. In Europe, 95% of agricultural digestate is utilised as fertiliser (Dahlin et al., 2015) which can add pressure to nutrient vulnerable zones. The EU Water Framework Directive (European Commission, 2000) set targets for the quality of surface and groundwaters and has identified phosphorous compounds as one of the main pollutants in waterways.

Agriculture, in general, has been identified as one of the main drivers in the failure to achieve ‘good’ status in European water bodies (European Commission, 2021) with diffuse pollution of nitrates, phosphates, and pesticides a particular concern (European Environment Agency, 2018). Diffuse pollution sources, such as run-off from the application of fertiliser, are responsible for 38% of the pressure on surface water bodies, and 35% for groundwater bodies (European Environment Agency, 2018). Soils can become saturated with nutrients so leaching during rainfall events is more common. While nutrient surpluses are common in countries with large animal agriculture sectors, the distribution of nutrients to land is not uniform and instead pockets of land display nutrient surplus while others have a deficit. As slurry and digestate contain a large quantity of water (<90%) transporting to areas with low nutrient pressure can be costly which leads to a situation where easily accessed, productive land receives a higher nutrient load compared to less accessible, low productivity land.

Mechanical separation can preferentially partition P in the solid fraction, leaving a reduced volume of liquid with a lower P content and which poses less risk when land-spread. The solid fraction, containing a proportion of the P, can be utilised for other purposes which can help to avoid its application to nutrient vulnerable zones. The production of pellets from the solid faction reduces mass (drying of the solids reduces moisture content) and volume (the pellets are denser than the dried solids) which in turn reduces the expense of transport away from nutrient vulnerable zones. Studies in the literature have investigated the use separated solid fractions as a fuel (Cathcart et al., 2021; Kratzeisen et al., 2010), as feedstock for composting (Czekała et al., 2018; Tambone et al., 2015), and as a soil conditioner to provide some nutrients and restore soil carbon (Badagliacca et al., 2020).

Two of the most common methods of mechanical separation are by screw press and by decanter centrifuge (Cathcart et al., 2021). Screw presses separate based on particle size, by forcing digestate against a mesh screen, allowing liquids and solids smaller than the mesh to pass through and form the liquid fraction. Decanter centrifuges separate based on density; digestate is spun in a rotating bowl and an internal auger pushes the solids trapped against the bowl to a solids release port. Decanter centrifuges can recover smaller sized particles compared to the screw press, which is limited by the size of the mesh screen. The effectiveness of these separators to partition total solids (TS) and nutrients to the solid fraction can be represented with their separation efficiencies, i.e. the percentage of TS or nutrient present in the solid fraction relative to the starting material (Svarovsky, 2000). Research has previously been carried out comparing the performances of mechanical separators (Guilayn et al., 2019; Moller et al., 2000) with different feedstocks, however the details of operational parameters are often limited or absent in the literature (Guilayn et al., 2019).

Decanter centrifuges can operate at different bowl rotation speeds and feed rates, with the differential speed of the internal auger affecting the retention time of the material being separated. A higher bowl speed exerts greater force on the feedstock being separated which can lead to a greater proportion of small solid particles coming out of suspension during separation, and therefore a greater proportion of the solids can be recovered; a downside to higher bowl speeds is the higher electricity requirement. Screw presses can have different screen sizes and back pressure which affect how hard the solids are squeezed to remove liquid. Smaller screen sizes can retain smaller particles which are incorporated in the solid fraction. With a larger screen some of these particles will pass into the liquid fraction, which is reflected in a lower solids separation efficiency. There is however a balance to be struck with screen size, feedstock dry matter content, and feed rate to the separator, as fine mesh screens can be blocked by particularly high dry matter slurries and digestates and a build-up of pressure can lead to the solid plug being dislodged from the solids exit port of the screw press.

A recent review paper by the authors found that decanter centrifuges are more efficient at partitioning P in the solid fraction in comparison to screw presses however, there is a large variation in reported separation efficiencies overall (Lyons et al., 2021). The percentage of total P partitioned to the solid fraction ranged from 6 to 33% when separated by screw press, and from 40 to 82% when separated by decanter centrifuge (Lyons et al., 2021). The studies reviewed by Lyons et al. (2021) investigated separation of a wide range of feedstocks including cattle slurry, pig slurry, poultry manures, mixtures of these, and digestates derived from slurries and energy crops. The large variation in reported separation efficiencies, and the different feedstocks investigated, indicates that both the physical properties of the feedstock, the method of separation, and the individual separation parameters (e.g. separator specific settings) play a role in determining the separation efficiencies observed.

This research sought to find an on-farm solution to the optimisation of mechanical separation through adjustments of parameters easily accessible by the operator and without requiring specialised knowledge or tools. The aim of this paper was to investigate two mechanical separating technologies, screw press and decanter centrifuge, comparing the main parameters in each technology and ascertaining how they affect the different fractions produced. The following objectives were set to achieve this: (i) carry out a series of separation runs with each technology comparing the various adjustable parameters of each, (ii) characterise the resulting solid and liquid fractions (TS, mass, phosphorus (P), nitrogen (N), carbon (C), and potassium (K)) from each separation run, and compare to the input digestate feedstock, and (iii) analyse the data to determine the most efficient means of separating digestate based on the needs of the AD operator.

2. Material and methods

2.1. Sampling procedure and data collection

Mechanical separation was carried out using a Fan PSS 5.2–780 screw press separator (FAN SEPARATOR GmbH, Marktschorgast, Bavaria, Germany), fitted with a 1 mm^2 screen, and a GEA UCD345-00-32 decanter centrifuge (GEA Group AG, Dusseldorf, Germany) with a polymer mixing station, both located at the Agri-Food and Biosciences Institute (AFBI) Nutrient Management Centre in Hillsborough, Northern Ireland. Digestate was housed in a 100 m^3 process tank fitted with a mixer prior to separation (Fig. S1). Both separators use different techniques to separate the feedstock into solid and liquid fractions, hence different parameters were investigated for each machine. Each parameter test was completed during a 2-h run for the screw press and a 3-h run for the decanter centrifuge. Longer runs were carried out for the decanter centrifuge as there is a start-up period when the bowl accelerates to the set revolutions per minute (RPM) and fills with digestate.

Digestate feedstock, liquid fraction, and solid fraction samples from each run were taken for analysis to identify the effect the different parameters have on the separated fractions. All sampling was completed in triplicate to validate the data. Each of the triplicate samples consisted of 2 × 500 ml (or 2 × 500 g for solids) individual samples, which were mixed. The samples were taken at 20- and 30-min intervals for the screw press and decanter centrifuge respectively. Electricity usage was recorded at the same interval as the sample collection using the installed

Socomec Diris A-20 metering units (Socomec SAS, Benfeld, Bas-Rhin, France). The electricity used for each run for both the separator and digestate feedstock tank mixer was recorded. The capital cost of each separator was obtained from purchase orders for equipment purchased by the Agri-Food and Biosciences Institute (purchases made in 2016/17). The cost of polymer addition from a commercial supplier (quoted in 2020) was also considered for the decanter centrifuge.

2.2. Screw press set-up and operation

The two variables investigated (Table 1) for the screw press separator were the use of an oscillator to help suspend the solids in the digestate, and the counterweights used to create pressure at the discharge plates. These parameters were chosen as they are easily adjustable and require no specialised training or equipment, and are therefore suitable for on-farm application. A high-pressure and low-pressure configuration were tested. The high-pressure configuration had two 10 kg counterweights loaded on each side of the pressure plates (total 40 kg) while the low-pressure configuration consisted of one 10 kg counterweight on each side (total 20 kg). The oscillator speed was not adjustable so it was set to either on or off for each counterweight set-up, giving a total of four runs (Table 1). It would also have been possible to change the screen size of the screw press; however, preliminary experiments with a smaller screen size (0.5 mm^2 vs. the 1 mm^2 screen used in this study) found that cattle slurry and cattle slurry-based digestate were too fibrous and blocked the screen, meaning that the build-up of pressure in the screw press would overcome the counterweights and dislodge the plug.

Digestate flow was recorded from the inline Endress + Hauser Promag P flow meter (Endress + Hauser Ltd., Manchester, UK). A 1 L sample was taken from the mixed storage tank; this sample represented the feedstock for two runs carried out sequentially (e.g. runs 1 and 2 were carried out in a 4 h period, with the same digestate in the buffer tank feeding the separator). The electricity and digestate flow readings were taken at 20-min intervals along with a sample of both the solid and liquid fractions. The solid fraction was taken directly from the separator solids discharge, while the liquid fraction was collected from an in-line sample point. Three replications were completed sequentially with each covering 40 min. Each sample consisted of a mixture of product produced at the 20-min point and at the end of the 40-min period.

2.3. Decanter centrifuge set-up and operation

The four variables investigated for the decanter centrifuge were: the addition of polymer, the bowl speed, the feed rate, and auger speed differential (Table 2). These variables were chosen as they are easily adjustable on the control panel of the decanter centrifuge under investigation. Where polymer was added, Zetag 9016 (Brenntag UK Ltd), a cationic polymer, was used at a dose rate of 500 L/h as recommended by the supplier. The cost of the polymer used was £89 for a 25 kg drum which was diluted to 0.5% in water prior to dosing in the decanter centrifuge at a rate of 500 L/h. The addition of cationic (positively-charged) polymer causes flocculation by attracting negatively charged particles and forming floccules (Hjorth et al., 2010).

Feed rates of 4 m^3/h and 8 m^3/h were tested. Preliminary testing showed that feed rates greater than 8 m^3/h overloaded the bowl and the centrifuge shut down with a ‘high torque’ warning. The lower setting of 4 m^3/h was chosen to see if a lower feed rate would improve separation efficiency by keeping the bowl at a lower load. The rate of polymer dosage was kept constant for both feed rates meaning the runs at 4 m^3/h effectively had twice the polymer dose as the runs at 8 m^3/h. A higher and lower bowl speed setup was tested. The lower bowl speed was set to the 50% setpoint, which equals 4020 rpm, with the higher speed run at 80%, equalling 4320 rpm. 80% was chosen as an upper limit due to advice from the polymer supplier, who stated that excessively high bowl speeds can lead to the break-up of floccules and reduced separation efficiency.

Table 1
Screw press test schedule.

Run ID	Counterweight (kg)	Oscillator
1	**40**	**Off**
2	**40**	**On**
3	**20**	**Off**
4	**20**	**On**

Table 2
Experimental matrix for the decanter centrifuge.

Run ID	Polymer addition (On/Off)	Bowl speed (rpm)	Feed rate (m^3/h)	Auger speed (rpm)
5	Off	4020	4	8
6	Off	4020	4	12
7	Off	4020	8	8
8	Off	4020	8	12
9	Off	4320	4	8
10	Off	4320	4	12
11	Off	4320	8	8
12	Off	4320	8	12
13	On	4020	4	8
14	On	4020	4	12
15	On	4020	8	8
16	On	4020	8	12
17	On	4320	4	8
18	On	4320	4	12
19	On	4320	8	8
20	On	4320	8	12

A bowl speed set-point of 50% was chosen as a lower bowl speed requires less energy and the impact of lowering bowl speed on overall efficiency was unknown. The speed difference between the bowl and auger was also varied as this changed the retention time of the digestate in the bowl. The two auger differential speeds tested were 8 rpm and 12 rpm 12 rpm was the default setting of the decanter centrifuge used; performance at 8 rpm was also investigated due to the assumption that a lower differential speed increases the bowl retention time and could improve separation efficiency as the digestate would be in the bowl for a longer period. An experimental matrix was devised combining all parameters in every combination (Table 2). It is possible to make physical adjustments to the separator such as adjusting the pond depth of the bowl or the profile of the internal auger; however, due to time constraints and the requirement of specialised equipment and training, physical adjustments to the equipment were not considered in this work.

Polymer flow meter values were recorded using the Endress + Hauser Promag P flow meter on the polymer supply line. The centrifuge had two sample taps, one in the digestate supply line and one in the separated liquid outflow. This allowed the liquid samples to be easily collected every 30 min. The solid sample was collected directly from the collection trailer positioned beneath the centrifuge solids ejection port at the same time as the liquid samples.

2.4. Sample processing and analysis

All samples (unseparated digestate, separated solids, and liquid fractions) were analysed for TS content, while only the unseparated digestate and separated solids were analysed for nutrient content. The liquid fractions were not analysed for nutrient content as this was not required for the calculation of separation efficiency (Equation 1). TS content was determined by oven drying at 85 °C until constant mass. The dried samples were then milled with a Fritsch Pulveriette 15 grinding mill (Fritsch GmbH, Idar-Oberstein, Rhineland-Palatinate, Germany) prior to further lab testing to determine C, N, P, and K content. C and N content were determined using a Leco Trumac analyser (Leco, St. Joseph, Michigan, USA), while K and P content were quantified using an Agilent 5110 ICP-OES (inductively coupled plasma-optical emission spectroscopy) (Agilent Technologies LDA UK Limited, Cheshire, UK). Samples were first microwave digested in 10 ml of nitric acid using a CEM Mars 5 system (CEM Microwave Technology Ltd., Buckingham, UK), and then diluted 1:100 and sent for ICP-OES. Separation efficiency (Equation (1)) of N, P, K, C, and TS was calculated using the mean concentrations from the triplicate runs. Calorific value of separated solids was measured using a PARR6200 bomb calorimeter with 1108 oxygen bomb (Scientific & Medical Products, Stockport, UK). The coefficient of variance was calculated for all laboratory sample results before further analysis was completed (Kozak et al., 2013). This allowed the dispersion of the results for each test to be determined and any anomalous tests to be rechecked. The means of the triplicate runs were used to calculate separation efficiencies for TS, C, N, P, and K (Equation (1)).

Equation (1) - Simple separation efficiency calculation material (Svarovsky, 2000)

$$E_t = \frac{U \times M_c}{Q \times S_c}$$

E_t = Simple separation efficiency; U = Quantity of the solid fraction (kg); M_c = Concentration of component in solid fraction (g/kg); Q = Amount of digestate treated (kg); S_c = Concentration of the component in the digestate (g/kg).

3. Results

3.1. Electricity usage and mass partitioning

The total electricity used during the separation runs was split between the power required to run the storage tank mixer and the power required to operate the separator (Table 3). The 2-h screw press runs required approximately 10 kWh of electricity while the 3-h decanter centrifuge runs required approximately 15 kWh to run the mixer. Setups can vary, with different methods of mixing having different electrical requirements, therefore only the electrical requirement for the separators was considered. Run 20 (decanter centrifuge, with the addition of polymer and high settings for bowl speed, feed rate and auger speed) consumed the most energy at 47 kWh. The least energy intensive decanter centrifuge run was run 7 (with no polymer, low bowl and auger speeds, high feed rate). All of the screw press runs required less electricity than the decanter centrifuge runs. When displayed in terms of electricity usage per unit solid fraction produced, the least energy intensive decanter centrifuge run was run 14 at 14.7 kW h/t solid fraction (with polymer, low bowl speed, low feed rate, high auger speed). The screw press runs were still less energy intensive with a low of 6.1 kW h/t (low counterweight, oscillator on) and a high of 12.8 kW h/t (high counterweight, oscillator off).

Separation by decanter centrifuge produced a greater mass of solid fraction compared to screw press separation, despite processing a smaller volume of digestate in the tests carried out. Screw press mass partitioning ranged from 3.44% to 4.56% while the decanter centrifuge mass partitioning ranged from 10.06% to 16.77% (Table 3).

3.2. Total solids of digestate and resulting fractions

Separation by screw press resulted in solid fractions with higher TS contents compared to the solid fractions from decanter centrifuge separation (Fig. 1). The TS of the screw press separation runs ranged from 27.9% (low counterweight, oscillator on) to 32.6% (high counterweight, oscillator off), while the decanter centrifuge TS ranged from 18.5% (low bowl speed, low feed rate, high auger speed, with polymer) to 24.6% (low bowl speed, high feed rate, low auger speed, no polymer). The mean TS of the digestate fed to the separators was 4.9% with a range of 0.59%. The liquid fractions resulting from decanter centrifuge runs had a lower TS than the liquid fraction from screw press separation runs. The separation efficiencies (SEs) indicated that while more of the TS are partitioned to the solid fraction in decanter centrifuge separation, the screw press produces a drier solid fraction.

3.3. Nitrogen

The total N content remained consistent across the liquid fractions produced by the screw press but showed a noticeable change across the solid fractions varying from 2.14 g/kg (low counterweight, oscillator on) to 2.96 g/kg (high counterweight, oscillator off) (Fig. 2). The decanter centrifuge partitioned a greater proportion of N in the solid fraction across all runs with concentrations ranging from 3.69 g/kg (low bowl speed, low feed rate, low auger speed, no polymer) to 4.91 g/kg (high bowl speed, low feed rate, low auger speed, with polymer). The

Table 3
Separator electricity usage and feedstock throughput.

Run ID	Separator (kWh)	Mixer (kWh)	Run time (h)	Digestate separated (m^3)	Solid fraction produced (kg)	Mass in solid fraction (%)[a]	Electricity per m^3 digestate (kWh/m^3)[b]<	Electricity per t of solid fraction (kWh/t)[b]	Elec. per t total dry solids recovered (kWh/t)[b]	Elec. per kg P partitioned in solid fraction (kWh/kg)[b]
1	11	10	2	25	860	3.44	0.44	12.79	39.29	9.35
2	11	10	2	25	930	3.72	0.44	11.83	36.38	10.82
3	8	10	2	26	1130	4.35	0.31	7.08	24.36	7.79
4	7	10	2	25	1140	4.56	0.28	6.14	22.03	8.13
5	36	15	3	11.97	1420	11.87	3.01	25.35	115.11	10.90
6	36	15	3	11.94	1720	14.41	3.02	20.93	112.45	10.15
7	37	15	3	23.66	2380	10.06	1.56	15.55	63.22	6.47
8	39	15	3	23.66	2570	10.86	1.65	15.18	67.02	6.87
9	38	15	3	11.94	1440	12.06	3.18	26.39	115.66	11.32
10	42	15	3	11.94	1670	13.98	3.52	25.15	127.28	11.84
11	41	15	3	23.66	2490	10.53	1.73	16.47	67.84	7.05
12	45	15	3	22.58	2510	11.12	1.99	17.93	77.89	7.57
13	30	15	3	11.92	1740	14.59	2.52	17.24	87.14	8.39
14	29	15	3	11.92	1970	16.52	2.43	14.72	79.67	8.20
15	43	15	3	23.65	2680	11.33	1.82	16.04	69.73	6.97
16	45	15	3	23.65	2790	11.80	1.90	16.13	72.51	7.39
17	41	15	3	11.92	1720	14.43	3.44	23.84	117.93	11.26
18	30	15	3	11.92	2000	16.77	2.52	15.00	79.97	7.75
19	40	15	3	23.64	2650	11.21	1.69	15.09	64.79	6.40
20	47	15	3	23.64	2860	12.10	1.99	16.43	75.23	7.08

[a] Density of digestate assumed to be 1 Mg/m^3 for the purpose of mass partitioning calculation as digestate used was 95 ± 0.3% water.

[b] Electricity per unit mass calculated with the separator electricity usage only, as mixer design and electricity requirement can vary.

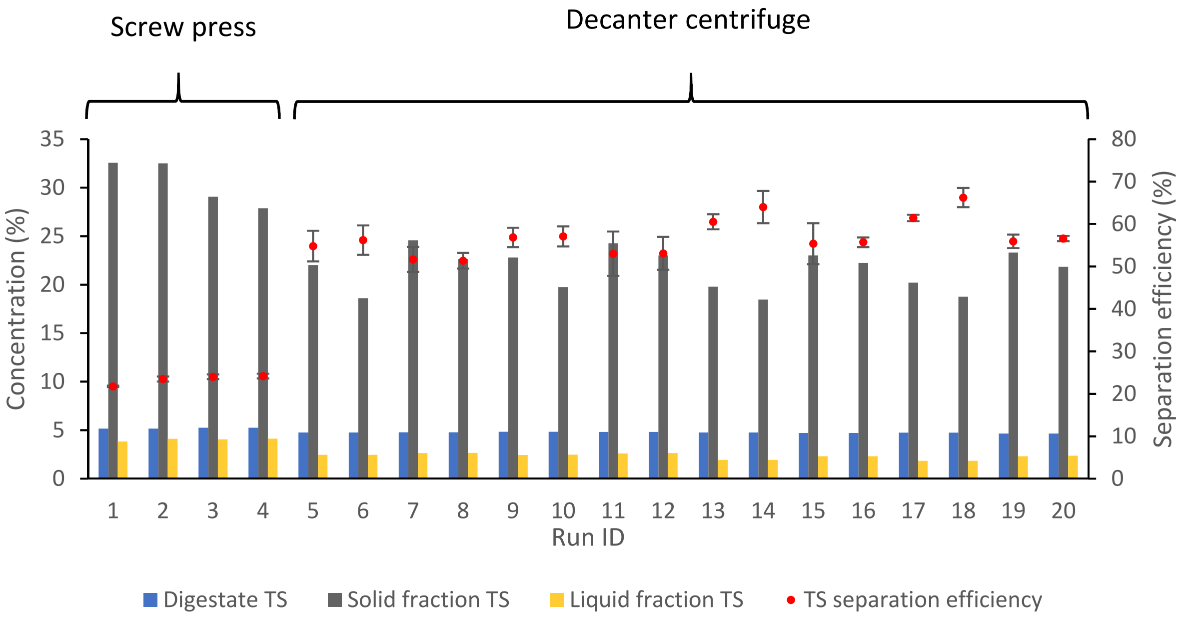

Fig. 1. Total solids content of digestate, solid fraction, and liquid fraction with separation efficiency.

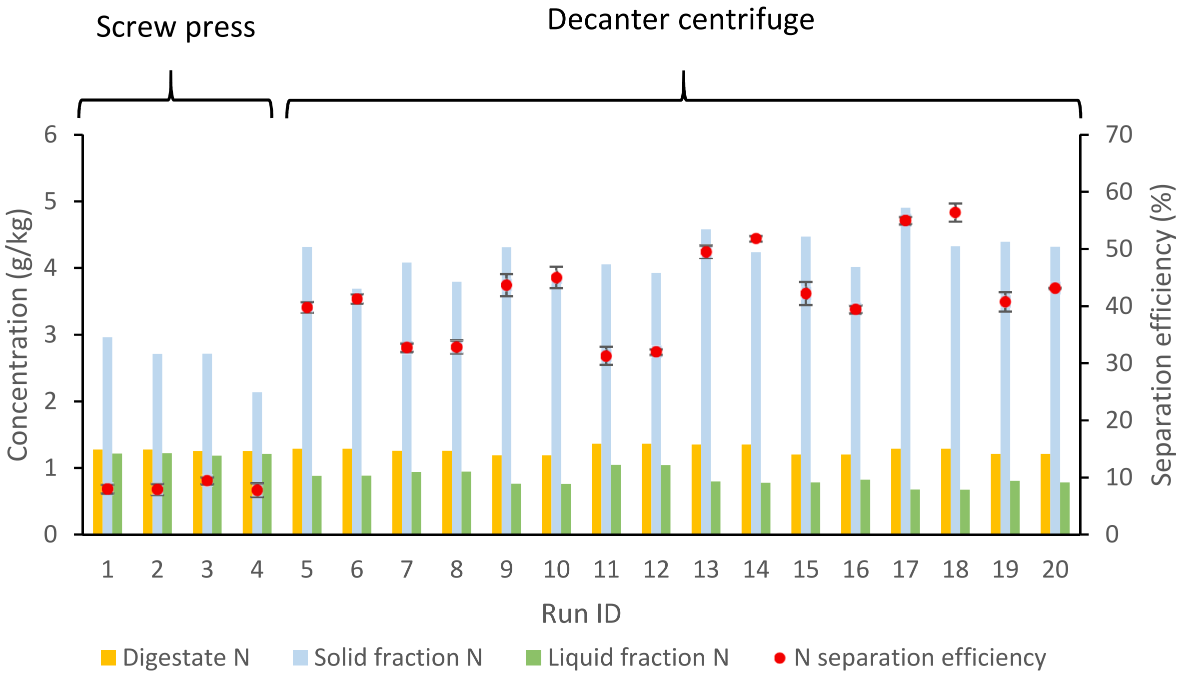

Fig. 2. Nitrogen concentration of digestate and resulting fractions with separation efficiency.

separation efficiencies were greater for the decanter centrifuge, ranging from 31.3% (high bowl speed, high feed rate, low auger speed, no polymer) to 56.4% (high bowl speed, low feed rate, high auger speed, with polymer) while the screw press ranged from 7.78% (low counterweight, oscillator on) to 9.42% (low counterweight, oscillator off).

3.4. *Phosphorous*

The decanter centrifuge was more efficient at partitioning P to the solid fraction compared to the screw press. The P concentration in the screw press separated solids ranged from 0.76 g/kg (low counterweight, oscillator on) to 1.37 g/kg (high counterweight, oscillator off), while the decanter centrifuge separated solids ranged in concentration from 1.79 g/kg (low bowl speed, low feed rate, high auger speed, with polymer) to 2.40 g/kg (low bowl speed, high feed rate, low auger speed, no polymer) (Fig. 3). The separation efficiencies of the decanter centrifuge were also greater, ranging from 51.1% (low bowl speed, high feed rate, high auger speed, no polymer) to 71.5% (high bowl speed, low feed rate, high auger speed, with polymer) compared to the screw press range of 8.45% (low counterweight, oscillator on) to 10.87% (high counterweight, oscillator off.

3.5. *Potassium*

The ability of the separators to partition K was lower in comparison to the other elements (N, P and C) investigated in this study. The concentration of K ranged from 2.70 g/kg (high counterweight, oscillator

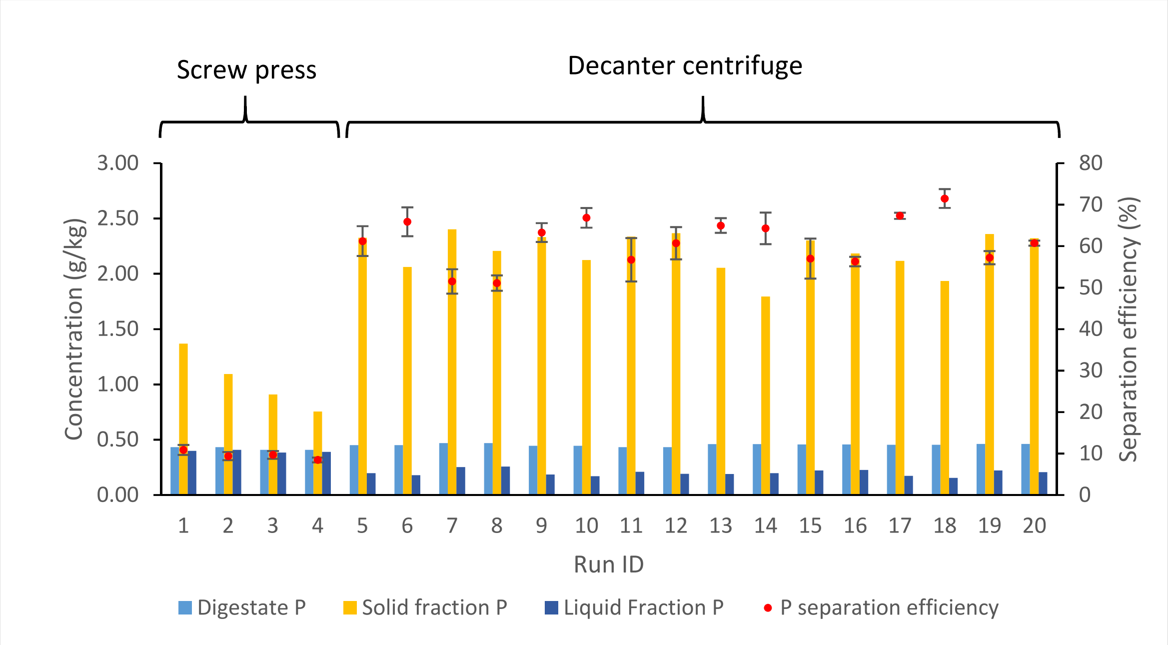

Fig. 3. Phosphorous concentrations of digestate and resulting fractions with separation efficiencies.

on) to 3.64 g/kg (low counterweight, oscillator off) in screw press separated solids while the decanter centrifuge separated solids ranged from 2.99 g/kg (low bowl speed, low feed rate, high auger speed, with polymer) to 3.50 g/kg (high bowl speed, high feed rate, high auger speed, no polymer). The separation efficiencies of screw press separation ranged from 2.75% (high counterweight, oscillator on) to 4.40% (low counterweight, oscillator off), while the decanter centrifuge ranged from 9.60% (high bowl speed, high feed rate, low auger speed, no polymer) to 15.38% (low bowl speed, low feed rate, high auger speed, with polymer).

3.6. *Carbon*

The screw press produced the solid fractions with the highest carbon concentration. The carbon content of the fractions was closely related to the TS content and the separation efficiencies followed the same pattern as that observed for TS separation (Fig. 4). The carbon content of the screw press separated solids was higher than that observed for the decanter centrifuge separated solids, but the separation efficiencies were lower as the mass of solid fraction recovered was lower.

3.7. *Correlations*

Pearson's correlation coefficients (Equation 2) were calculated to

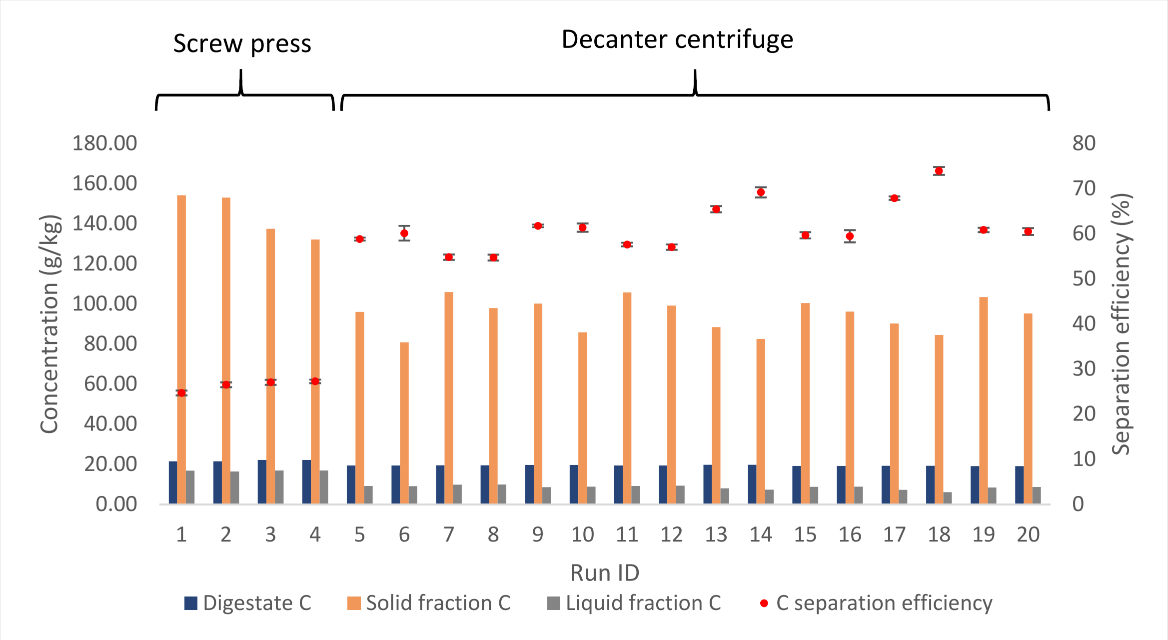

Fig. 4. Carbon concentration in digestate and resulting fractions, with separation efficiencies.

determine if there was a linear relationship between TS, the nutrients under investigation (N, P, K, and C), and separator electricity usage (Table 2). There was a strong correlation between TS and C in both the screw press (1.00) and the decanter centrifuge (0.99). The correlation between TS and P was also strong at 0.91 for both the screw press and decanter centrifuge.

Equation 2 - Pearson's correlation coefficient

$$\rho_{x,y} = \frac{\mathrm{cov}(x,y)}{\sigma_x \sigma_y}$$

$\rho_{x,y}$ = Pearson's correlation coefficient; cov = Covariance; σ_x = Standard deviation of x; σ_y = Standard deviation of y.

4. Discussion

4.1. Determinants of separation efficiency

Separation efficiency is influenced by feedstock physical characteristics as well as the method of separation used (Bauer et al., 2009). The digestate used in the study came from a single AD plant processing a consistent feed of 89% dairy slurry and 11% grass silage; feedstock consistency was assumed to be constant as variability was 0.17% TS for the decanter centrifuge runs and 0.11% TS for screw press runs. The separation efficiencies observed for the screw press, with the exception of P, were broadly in line with those observed in a study by Tambone et al. (2017) in a comparative analysis of 13 different digestates separated by screw press. The TS SE ranged from 17.2% to 49.2% with a mean value of 32.5%, while the findings of this study were lower, with a mean DM SE of 23.4%. The mean N SE in this study was found to be 8.3% while Tambone et al. (2017) found a range of 5.5%–23.9% with a mean of 13.1%. The mean P SE was found to be much lower in this study at a 9.6% while the results by Tambone et al. (2017) ranged from 17.1% to 54.0% with a mean of 28.4%. The low P SE observed may be due to the feedstocks tested by Tambone et al. (2017) having a higher mean TS content (6.1%) compared to the digestate used in this study (4.9%). The size of screen used by Tambone et al. (2017) is also unclear, which would also have an effect on separation efficiency.

For the screw press, separation efficiency of N, K, C, and TS was higher with the low counterweight set-up (mean separation efficiencies = 8.6%, 4.1%, 27.1%, and 24.1% respectively) compared to the high counterweight set-up (mean separation efficiencies 7.9%, 2.8%, 25.6%, and 22.6% respectively). In contrast, P separation was greater at the high counterweight setup (mean separation efficiency = 10.1%) than the low counterweight setup (9.1%). Additionally, the use of the oscillator improved the TS (23.8% vs 22.9%) and C (26.9% vs 25.9%) separation efficiency but reduced the N (8.7% vs 7.9%), P (10.3% vs 8.9%), and K (3.6% vs 3.3%) separation efficiencies. The higher counterweight set-up produced a higher back pressure meaning the digestate solids plug experienced a greater force and more liquid was pushed through to the liquid fraction.

The increased separation efficiency of TS and C observed when the oscillator was operating may be due to smaller digestate solids staying in suspension through the length of the separator and becoming trapped in the fibrous solids plug at the ejection port. Moller et al. (2002) investigated the effect of separation technology on particle size distribution in resulting fractions and found that, based on the particle distribution in the starting material and separated liquid fraction, there was little evidence for the aggregation of particles on the filter contributing to retention of particles smaller than 1 mm. In their experiment their screw press was not fitted with an oscillator so the particles may have come out of suspension prior to reaching the solids plug. Further research into the particle size distributions of the digestate and resulting fractions would be required to determine what role the oscillator played in this regard.

To determine the decanter centrifuge parameter with the greatest impact on separation efficiency, the mean separation efficiencies (for TS and each of the elements investigated) for all runs at each parameter value (auger speed, feed rate, polymer addition and bowl speed) were calculated (Table 5), e.g. the mean separation efficiency values were calculated for all runs carried out at 4020 RPM and compared with the mean separation efficiency of all runs carried out at 4320 RPM.

The data indicates that feed rate played the most important role in decanter centrifuge separation efficiency (Table 5). The lower feed rate of 4 m^3/h showed higher separation efficiencies of TS and all elements observed (with the absolute difference in separation efficiency between 10.3% and 29.9% higher than the feed rate of 8 m^3/h). The reduced performance at a higher feed rate is likely due to excessive loading of the bowl and flow of un-separated digestate through the liquid fraction exit ports of the decanter centrifuge. A lower feed rate ensures the bowl is not so heavily loaded and there is sufficient retention time for the digestate to separate into the two fractions. One of the major drawbacks of the lower feed rate is the reduced capacity for separation, which may be problematic if there is a large quantity of digestate or slurry to be processed. The data showed that twice the quantity of digestate could be processed with a P separation efficiency loss of just 10% and a total solid separation efficiency loss of just 5% (at 8 m^3/h as opposed to 4 m^3/h).

Polymer addition is the second most important parameter (increasing separation efficiency by between 4% and 27%), but it has less of an impact on N and K separation efficiency than feed rate (Table 5). The reduced impact is likely due to N and K in digestate being highly soluble, so production of floccules by the polymer, which improves TS and C separation efficiency, wouldn't carry as much liquid soluble N and K into the solid fraction. The small increase in N separation efficiency observed is likely due to the presence of insoluble or less soluble ammonium-N salts and other N containing compounds such as residual protein present in the digestate solids. Addition of polymer at the rates investigated in this study resulted in a mean increase of 2.76% P recovery and 5.22% TS recovery, while also losing 9.97% more nitrogen from the liquid fraction. The polymer used in this study cost £89 for 25 kg, which was diluted to 0.5% in water and mixed with incoming feedstock at a rate of 500 L/h 25 kg of polymer produces 5000 L at 0.5% concentration therefore each hour of running costs £8.90. At a feed rate of 4 m^3/h this cost £2.23/m^3 and at a feed rate of 8 m^3/h this cost £1.11/m^3. The average electricity requirement for runs with polymer addition was 2.29 kW h/m^3 (Table 3) which at an electricity cost of 30 p/kWh (average variable unit price for the UK in 2022 (Yurday, 2023)) equals a cost of 74 p/m^3 separated. The polymer cost at the higher feed rate was 50% higher than the cost of the electricity and at the lower feed rate was 300% higher although this doesn't take into account other operational and capital costs such as maintenance and depreciation.

Bowl speed and auger speed had similar impacts on TS separation efficiency (Table 5) but showed variation in their effect on the separation efficiencies of N, P, K and C. Bowl speed played a larger role in N, P, and C separation efficiency, while auger speed played a greater role in K separation efficiency. When looking at the combined effect of auger speed and bowl speed, the importance of auger speed is more noticeable at lower bowl speeds (Table 6). At low bowl speed an auger speed of 12 rpm shows a greatly reduced separation efficiency (11.7%–19.4% lower) for all observed elements and TS. In contrast, at the high bowl speed configuration, an auger speed of 12 rpm outperformed the 8 rpm auger speed (by 1.9–14.1%). The reason for the lower separation efficiencies is likely due to the higher auger speed decreasing the hydraulic retention time in the bowl and the lower bowl speed not separating the solids out quickly enough to form a dense solid fraction. This hypothesis is supported by the fact that all runs with an auger speed of 12 rpm produced a solid fraction with higher moisture content relative to the corresponding runs with an auger speed of 8 rpm, with a more noticeable difference at lower bowl speeds (Fig. 1).

The combination of parameters that provided the highest TS, P and C separation efficiencies was 4320 rpm bowl speed, 4 m^3/h feed rate, 12 rpm auger differential speed, with polymer addition (run number 18). This was also the run with the second least electricity usage per mass of

Table 4
Pearson’s correlation coefficients for TS, electricity and observed elements for screw press and decanter centrifuge separators.

	TS	N	P	K	C	Electricity usage	
TS		0.80	0.91	−0.53	1.00	1.00	Screw press
N	−0.07		0.88	0.07	0.81	0.70	
P	0.91	−0.06		−0.32	−0.92	0.90	
K	0.50	−0.57	0.66		−0.52	−0.58	
C	0.99	0.04	0.88	0.41		1.00	
Electricity usage	−0.63	0.18	−0.39	−0.03	−0.63		
	Decanter centrifuge						

Table 5
Mean separation efficiencies of decanter centrifuge separation runs at given parameter values with absolute differences.

Parameter	value	TS	N	P	K	C
Auger speed (rpm)	8	56.19	41.87	59.90	11.87	60.83
	12	57.53	42.75	62.16	13.32	62.01
Absolute difference	1.34		0.89	2.26	1.44	1.18
Feed rate (m^3/h)	4	59.64	47.82	65.66	13.94	64.79
	8	54.08	36.81	56.41	11.24	58.05
Absolute difference	5.56		11.01	9.25	2.70	6.73
Polymer addition	off	54.25	37.33	59.65	12.35	58.25
	on	59.47	47.30	62.41	12.84	64.59
Absolute difference	5.22		9.97	2.76	0.50	6.34
Bowl speed (rpm)	4020	56.20	41.22	59.03	12.90	60.25
	4320	57.52	43.41	63.03	12.29	62.58
Absolute difference	1.32		2.19	4.01	0.62	2.33

Table 6
Combined effect of bowl speed and auger differential speed on separation efficiencies.

Parameter set	TS	N	P	K	C
50% bowl speed, 8 rpm auger speed	55.59	41.07	58.67	12.27	59.66
50% bowl speed, 12 rpm auger speed	45.46	33.09	47.51	10.83	48.68
80% bowl speed, 8 rpm auger speed	56.80	42.67	61.13	11.48	62.00
80% bowl speed, 12 rpm auger speed	58.25	44.15	64.94	13.09	63.17

solid fraction produced (Table 3). The least electricity intensive run had the same set of parameters but at 4020 rpm bowl speed. While the electricity usage for these runs was low in relation to the mass of solid fraction produced, the electricity usage per unit digestate separated was higher than for runs carried out at a feed rate of 8 m^3/h.

The separation efficiencies observed in the current study showed important differences than those observed by other studies in the literature. Chuda and Zieminski (2021) in their study on mechanical separation of sugar beet pulp derived digestate showed that use of a cationic polymer had a strong influence on separation efficiencies. Without polymer, the separation efficiencies were: TN – 18%; TP – 26%; TS – 32%, and with polymer the separation efficiencies were: TN – 31%; TP – 62%; TS – 71%. The current study showed similar trends (addition of polymer increased the separation efficiencies) but the increase was to a much smaller degree. The base separation efficiencies of TS, TN, and TP reported here were higher than that shown by Chuda and Zieminski (2021) without the use of a polymer. The TS content of the sugar beet pulp digestate was lower (3.8% TS) than the digestate used in this study (4.8% TS) which may have played a role in their behaviour during separation. Additionally, the different feedstocks may have produced a digestate with different physical qualities (fibre content, particle size distribution) which may also affect separation behaviour.

4.2. Fertiliser properties

The reduced TS content of separated liquid fraction makes it easier to spread by low emission slurry spreading equipment (LESSE) by reducing the chance of blockages. Spreading by LESSE is attractive due to a reduction in ammonia volatilisation compared to methods such as splash plate (Bourdin et al., 2014). Additionally, the lower TS content of separated liquid causes less blocking of soil pores during application, improving N infiltration into the soil (Bourdin et al., 2014). Movement toward LESSE has increased in recent years with Northern Ireland developing legislation to enforce its use in place of splash plate spreading of digestate (DAERA, 2019) while the Republic of Ireland has introduced monetary incentives to help farmers purchase LESSE (DAFM, 2020).

The liquid fraction produced through mechanical separation has a lower P content relative to the starting material, meaning it can be spread on agricultural land with reduced risk to water quality. Under the most efficient P separation conditions observed (high bowl speed, low feed rate, high auger speed with polymer addition), 71% of phosphorous present in digestate could be redirected from land spreading. This could be especially important in areas of intensive livestock production as surrounding soils generally have a high nutrient load from manure spreading and fertiliser application during grass cultivation. In addition, AD plants are often located in these livestock intensive areas, as cattle, pig, and poultry manure are suitable AD feedstocks. This means that there can be an over-supply of slurry/digestate relative to the land available.

With its particularly large livestock industry relative to land area, Northern Ireland has a problem with high soil Olsen P indices in much of its agricultural land. Dairy farms in Northern Ireland have an average of 50% of their fields over supplied with P (Olsen P index >2). Only 25% of soils on ruminant farms have a P index >2 however they make up 78% of total grassland platform, and 36% of all grassland pastures with an Olsen P index >2 are from dairy farms (DAERA, 2021). As part of the Nutrients Action Program, The Department for Agriculture, Environment and Rural Affairs (DAERA) has imposed restrictions on the spreading organic fertilisers with specific restrictions on anaerobic digestate. A nutrient content analysis of the digestate must be carried out prior to spreading to determine: dry matter; total N; total phosphate; total potash; and ammonia N, a fertiliser plan must also be maintained (DAERA, 2019).

Anaerobic digestate produced using only livestock manures and non-waste feedstocks generated on the holding, can be spread back onto land of the same holding without restriction. If the digestate is generated with external feedstock, the agronomic requirement for the phosphorus contained in the digestate must be proven. In addition to restrictions on the spreading of anaerobic digestate, there are restrictions on ‘organic manures with a high proportion of phosphorus’, defined as organic manures with a P content greater than 0.25 kg per 1 kg of total N. If digestate falls into this category the controller must demonstrate agronomic requirement taking into account soil P index, recommended P index for the crop, and other sources of P from other fertilisers that will be applied.

Separation by decanter centrifuge produced liquid fractions with a P:N ratio as low as 0.18 (run 12) bringing it out of the high P manure classification (DAERA, 2019) and indicating that it presents a lower risk to waterways when applied as fertiliser. As the current regulations stand it is possible to produce a liquid fraction of digestate with lower P and N content than typical slurry (given as 2.6 g/kg N, 0.52 g/kg P, with a P:N ratio of 0.20 (DAERA, 2019)) but it is still subject to more stringent regulations. This highlights the requirement for more nuanced regulations which are based on the nutrient profile of organic fertilisers, rather than solely on origin.

The observed N separation efficiency of the decanter centrifuge is higher than would be ideal for grassland farmers, who require as much N from organic sources as possible to reduce mineral N costs. In areas where P loading of soils is of less concern, use of a screw press for mechanical separation may be more suitable, as less than 10% of nitrogen is partitioned to the solid fraction. Volatility in the chemical fertiliser market, with ammonium nitrogen and granular urea prices increasing 48% and 24% respectively between September 2021 and September 2022 (AHDB, 2022), emphasises the importance of organic fertiliser to farmers and that removing up to 56% N from their digestate with a decanter centrifuge could prove costly if it needs to be replaced by chemical fertiliser.

The solid fraction produced from mechanical separation can be more easily transported away from areas with high nutrient risk, and potentially processed into higher value products. The high C content of the solids combined with the moderate N and P content mean the solids could have use as a soil amendment/fertiliser (Tambone et al., 2017) in arable farming, where regeneration of soils by adding back soil organic matter helps to drive nutrient recycling (Lal, 2023). An alternative use of the solids is in the production of pellets for combustion to provide renewable heat from a waste-derived fuel (Cathcart et al., 2021, Kratzeisen et al., 2010).

4.3. Impact on costs and income

Separation by screw press incurs approximately 15% of the electricity costs compared to the decanter centrifuge (mean 0.37 kW h/m^3 vs. 2.37 kW h/m^3) (Table 3) and the capital and other operational costs are lower than for separation by decanter centrifuge (Cathcart et al., 2021). TS, C and P separation efficiency correlated strongly with electricity usage for the screw press (Table 4) meaning the more electricity used, the greater the separation efficiency observed. For separation by decanter centrifuge, the correlations with electricity usage are not as strong, with negative correlation coefficients observed for C, TS and P separation efficiencies. This is likely due to sub-optimal separation parameters and the decanter centrifuge operating in an inefficient manner for this particular feedstock, e.g. over-loading or under-loading of bowl, incorrect auger speed differential causing inadequate retention time in the bowl.

As the majority of AD plants in NI generate electricity which qualifies for Renewable Obligation Certificates (ROCs), they receive a payment for all electricity generated, regardless of whether it enters the grid or not; this means that the composition of the separated fraction may be of more importance than the electricity consumed to process it. ROCs are issued to renewable energy producers, by the UK's energy regulator (Ofgem), for eligible renewable electricity generated. ROCs are issued per unit of electricity produced at different rates depending on the technology, overall capacity, and location, e.g. in Northern Ireland AD plants with a capacity $\leq$500 kW$_e$ earn 4 ROCs per MWh while AD plants with a capacity >500–1000 kW$_e$ earn 3 ROCs per MWh. The additional electricity consumption on AD plants with digestate separation will result in a loss of income rather than a cost due to less energy being available for export. A 500 kW$_e$ AD plant with 4 ROCs is paid 21.812 p/kWh (PowerNI, 2022) for all electricity generated, with an additional 17.66 p/kWh being paid for the power exported (PowerNI, 2022). This means that only the export price (17.66 p/kWh) will be lost when extra power is used to separate the digestate.

4.4. Trade-offs and recommendations

Based on the findings, mechanical separation of digestate could be carried out in different ways depending on the requirements of the operator. In areas where soil P levels are a concern, the decanter centrifuge can be utilised to remove up to 71.5% of P from the liquid fraction (run 18) and avoid its application to land. A downside to operating a decanter centrifuge in this manner is that it has a higher electricity demand and requires additional investments in cationic polymer. Without polymer, the operator can partition up to 66.8% of P to the solid fraction (run 10), while reducing operational cost by between £1.11 and £2.22 per tonne of digestate separated.

In areas where soil P concentration is of less concern, and where the high capital and operational cost of a decanter centrifuge may be a barrier, the operator could make use of a screw press separator. Screw press separators have lower capital and operational costs compared to decanter centrifuges, but the separation efficiencies observed are well below those seen for decanter centrifuges. The operational costs of screw presses are also lower with an electricity requirement of between 22.03 kW h/t and 39.29 kW h/t of dry solids recovered, compared to the decanter centrifuge requirement of 63.22 kW h/t to 127.28 kW h/t. An additional advantage of screw press separation is that a greater proportion of the N remains in the liquid fraction, which can be spread back on land to help meet crop N requirements. The screw press produced a liquid fraction containing between 90.6% and 92.2% of the N from the starting digestate, while the liquid from the decanter centrifuge contained only between 43.6% and 68.7%.

In some cases, the driver for separation may be for solids recovery and commercialisation, e.g. the production of pellets for fuel (Cathcart et al., 2021) or as a soil conditioner (Dahlin et al., 2017). The method of separation with maximum TS recovery was the same as that for P recovery (run 10). The P present in the fuel pellets will remain in the ash after combustion and could potentially be recovered chemically and recycled. A drawback of decanter centrifuge separation is the N content in the resulting solids and the low TS content, which would mean a higher requirement for heat energy for drying. The presence of N in the solids can lead to issues with fuel quality as fuel-N can be oxidised during combustion to NO$_x$ (Glarborg et al., 2003). In the case of a soil amendment, the presence of P and N in the separated solids may be an advantage, due to improved fertiliser value. While the screw press produces a smaller quantity of solids compared to the decanter centrifuge, the solids have a higher TS content meaning less heat energy would be required to dry them for pellet production; they would also have a lower N content which could make them more suitable as a fuel pellet, and less so as a soil amendment.

One of the major advantage of the screw press used in this study over the decanter centrifuge used is the throughput achievable. The screw press can process 12 m^3/h of digestate while the decanter centrifuge is limited to 8 m^3/h, with better solids and P separation efficiency at 4 m^3/h (Table 5). A typical farm-fed digester (slurry plus energy crop) rated at 500 kW$_e$ can produce up to 24,000 m^3 of digestate per annum (Cathcart et al., 2021; NNFCC, 2021) meaning a screw press of this size can separate the daily output of the digester (66 m^3) in just 5.5 h, whereas a decanter centrifuge would need to run for between 8.2 and 16.4 h per day. The increased runtime would require more frequent services which would also add to costs.

4.5. Limitations and further work

The current study looked only at the separation of digestate with a TS content of approximately 5%. As screw presses separate based on particle size, it is likely that substrates with different TS contents would behave differently when separated. The digestate in the study was produced from an AD plant procesing 89% dairy cattle slurry and 11% grass silage, which was macerated prior to being introduced to the digester. Maceration reduces particle size in order to increase surface area, with the aim of improving digestibility and biogas production. The solids in raw slurry may have larger particle sizes, as they have not passed through the additional maceration and anaerobic digestion stages, and may be more easily separated by screw press and partitioned in the solid fraction. As the decanter centrifuge separates based on density rather than particle size, it is unclear how digestates or slurries with different TS contents would behave and further research is recommended.

It would be advantageous to investigate a greater range of bowl speeds and auger differential speeds to determine the point at which the bowl becomes overloaded and separation efficiency drops due to poor solid fraction formation. The highest bowl speed investigated was 4320 rpm due to concerns that higher bowl speeds would interfere with floccules produced by the polymer. In cases where polymer is not being used due to cost or availability, a higher bowl speed may increase separation efficiency by recovering more lower density solids in the solid fraction.

Investigating a broader range of feed rates for the decanter centrifuge would also help to determine the rate at which the bowl becomes overloaded and unseparated digestate leaves the bowl through the liquid ejection port. The position of the liquid ejection ports can be adjusted through the use of weir plates to give the bowl a greater pond depth, which essentially increases the bowl capacity. A higher feed rate reduces the electricity requirement per tonne of digestate separated but also reduces separation efficiency of TS, P and C.

5. Conclusions

A decanter centrifuge has a greater P separation efficiency compared to a screw press with a maximum separation efficiency of 71.5% achieved for the decanter centrifuge in this study compared to 10.9% for a screw press. This makes the decanter centrifuge a more effective technology to help manage P surplus on farms. In contrast, the screw press produces a solid fraction with high TS and C content, and lower N content, making it potentially more suitable for fuel pellet production. The addition of cationic polymer had an impact on nutrient and TS separation, with the greatest effect on nitrogen separation efficiency which may be less attractive due to the cost of chemical nitrogen fertiliser. The screw press is a less expensive technology in both capital and operational costs, however an AD operator struggling to conform to nutrient-limit regulations may require the superior nutrient separation efficiency of the decanter centrifuge to reduce the P content of the liquid fraction.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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