


Review

Review of Two Mechanical Separation Technologies for the Sustainable Management of Agricultural Phosphorus in Nutrient-Vulnerable Zones

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Abstract: This work reviews two mechanical separation technologies (screw press and decanting centrifuge) which could be used in the dairy, beef, pig and anaerobic digestion sectors in nutrient-vulnerable zones in order to improve the sustainability of manure and anaerobic digestate management by decreasing agricultural phosphorus loss and reducing environmental impact on water quality. Capital and operating costs, separation efficiency and throughput, and management and processing of separated fractions, including transport costs, environmental impacts and the biosecurity of separated solids for export, were considered. Of the two technologies reviewed, screw press separation is a more cost-effective option (5-fold cheaper per tonne of feedstock) when lower amounts of export of phosphorus off farm are acceptable. For farms and those with anaerobic digesters managing larger volumes of manure/digestate, screw press separation is possible. However if higher levels of phosphorus removal are required, the use of decanting centrifugation is a viable option. Centralised processing facilities could also make use of decanting centrifuge technology to act as processing hubs for local farms within a distance that makes it economical for transport of manure/treated manure to/from the processor (the maximum distance for economical transport of raw manure and separated solids is approximately 70 km and 84 km, respectively). Both separation technologies could be integrated into agricultural manure and digestate management systems in order to provide a more sustainable approach to managing agricultural phosphorus loss and its associated impact on water quality. Screw press and decanting centrifuge separation could reduce phosphorous loss to water bodies by 34% and from 30 to 93%, respectively.

Keywords: manure; digestate; phosphorus; mechanical separation; water quality



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1. Introduction

Livestock manure or slurry (excreta produced by livestock whilst in a yard or building, usually consisting of faeces, urine, bedding material and spilt feed) and anaerobic digestate (a stable, sanitised material resulting from the decomposition of biodegradable matter under controlled anaerobic conditions) are useful and valuable sources of plant nutrients. Their uses on farms as fertilisers help close the nutrient cycling loop. However, in regions with intensive livestock farming systems, the quantities of nutrients available in livestock manures and anaerobic digestates on a particular farm can exceed the nutrient requirements of crops grown on that farm. Applications of nitrogen (N) and phosphorus (P) that are surplus to crop requirements can result in high nutrient losses to groundwater, surface water, and the atmosphere [1], where eutrophication can cause reduced functioning and biodiversity of aquatic ecosystems and a decline in surface water quality [2]. In intensively

farmed areas such as Northern Ireland, manure typically supplies approximately 40% of the total phosphate (P_2O_5) input, and almost 60% of the total potash (K_2O) input to farmland [3]. When the total input of P_2O_5 is compared with the crop requirement for this nutrient in Northern Ireland, there is an annual surplus input of 9000 t and the vast majority of grazed (fresh grass and grass silage) farmland (i.e., >70%) has soil Olsen P indices of 2 or greater, which reflects the on-going excessive usage of this nutrient for agricultural production [3]. Conversely, the global demand for minerals is high. Because a number of minerals used in artificial fertilisers are mined (e.g., P and potassium (K)), they are finite and are increasingly costly resources [4]. As a consequence, nutrient removal and recovery from livestock manures has become important in the circular bioeconomy, particularly in regions with the types of intensive livestock farming found in Europe and other parts of the world [5].

The European Nitrates Directive (91/676/EEC) [6] and European Union (EU) Water Framework Directive (2000/60/EC) [7] have been implemented to improve water quality, resulting in all member states having to identify and define an action plan for nitrate vulnerable zones (NVZs). Parts of Belgium, Denmark, The Netherlands and all of Northern Ireland for example, have been designated as NVZs and the action plans in place include livestock manure processing to remove N and P and export of excess nutrients to less nutrient dense areas. It could be argued that the term NVZ should refer to nutrient-vulnerable zones (not just nitrates) as both N and P excesses need to be managed and it is in this context that we use the term in this review. Nowadays, with the volatile prices of synthetic fertilisers and lower P and K reserves, nutrient recovery and recycling by processing of livestock manures are becoming more widespread [5]. Exporting manure off farm is a potential means of moving nutrients from areas where there is environmental risk due to over-application to other areas where there is less risk and there is a crop requirement for the nutrients [8]. To promote a more circular bioeconomy, the link between sustainable use of agricultural resources and improved water quality needs to be further explored. Recovery and recycling of surplus nutrients in manures and digestates, particularly in sensitive areas where over-application causes environmental damage, would go some way to promoting this circularisation, potentially leading to major savings on the import of costly and finite chemical fertilisers. The benefits for the environment and aquatic ecosystems would be important, particularly through less P loss to water bodies.

In the EU, individual member states have developed nutrient action plans based on relevant legislation and as an extension to this the Department of Agriculture, Environment and Rural Affairs (DAERA) for Northern Ireland commissioned the Sustainable Agricultural Land Management Strategy (SALMS, 2016) [9] which made several key recommendations to help lower environmental risks to water quality from livestock manure management practices. The recommendations included an option for nutrient export off farm. Some of the other key recommendations were:

1. Appropriate redistribution of slurries/derivatives between farms.
2. Slurry could be separated by mechanical means to concentrate P into a separated solid fraction for export off farm.
3. Research into whether lime treatment of dewatered slurry will allow safe and biosecure redistribution.
4. Capital support to separate P from slurries on farms which cannot sustainably spread their nutrient to land.
5. Increase the proportion of slurry which is applied on land by trailing-shoe, band spreader or shallow injector.

Many of the most productive and intensive farms across the pig, dairy and beef finishing sectors have high soil P levels throughout their farms and need to move to a more sustainable position, as they make a vital contribution to agricultural productivity [10]. Use of mechanical separation technologies to separate manures and digestates in to solid and liquid fractions as an option to partition nutrients, water and fibre, could be a cost-effective way to help lower environmental risks to water quality [11]. Mechanical separation pro-

duces a liquid fraction with a lower dry matter concentration than the input manure and a solid fraction with a higher dry matter concentration than the input manure. This partitioning would facilitate the onward utilisation or redistribution of these materials in order to enable better nutrient management for the farmer and reduced environmental impact and would align with environmental legislation [4]. Because of its lower moisture content, transport of the separated solids fraction, containing a proportion of the total P, is more cost-effective than transporting whole manures or digestates with higher water content [12]. The liquid fraction with its lowered P content, is still a valuable biofertiliser. Technologies to further treat the liquid such as membrane filtration, N-stripping, and struvite crystallisation for example, could reduce its nutrient content and evapo-concentration could be used to reduce volume and concentrate nutrients [13]. Such treatment technologies, allied with nutrient export, would improve the sustainability of farm nutrient management.

However, despite the benefits that could be realised through mechanical separation of manures and anaerobic digestates, there has been limited implementation of the technologies in the agricultural sector. This is likely due to both financial barriers for farms and the lack of a comprehensive evidence base on the topic, particularly in relation to technology cost and effectiveness. **The aim of this review paper is therefore to compile, compare and contrast existing literature on two of the main mechanical separating techniques, the screw press and decanting centrifuge, so as to inform the development of the sector.**

2. Solid–Liquid Separation

Different techniques for separating manure/digestate into a dry matter (DM)-rich solid with a lowered moisture content and a liquid fraction have been developed and are used on farms. Separation of manures and digestates creates two products, a liquid fraction with higher moisture content and a fibrous material with a lowered moisture content, both of which need to be stored and handled separately. Solid–liquid separation may be carried out in settling tanks, where settled solids are removed from the bottom of the tank. Alternatively, settling can be forced using mechanical screen separators or centrifuges [14]. Solids may also be removed mechanically by pressurised filtration using screw presses or drainage through fabric belts or screens [15]. For mechanical separators, the solid phase generally contains approximately 14–30% of the total feedstock fresh matter and has a moisture content typically between 850 and 700 g L⁻¹ [15]. The composition of separated solids can vary greatly. The relatively high mineral N content of solids indicates a high potential for N losses during handling and application [16,17], in particular NH₃ volatilisation, leaching and gaseous losses by denitrification after nitrification of the NH₄⁺ to NO₃⁻ during (partially) aerobic storage and handling [18]. Legislation involving nutrient action plans classify the solid fraction of separated cattle manure to be the same as farmyard manure and can be applied to land throughout the year, provided soil and weather conditions are suitable. However, the solid fraction from separated pig slurry is subject to the same restrictions as raw slurry in regard to when it can be land spread.

The liquid phase is characterised by lower DM and P contents and high N and K contents [18,19], with N and K partitioned according to the proportion of the solid and liquid phases [18,20]. The liquid fraction is typically 20–30% lower in volume and DM concentration than the original slurry [21] and may not require mixing before being applied to the land. In addition, it is better suited to a number of low-emission methods of application such as irrigation, injection or application by trailing-shoe tanker. This is because a mechanical separator removes the larger fibre particles from the liquid fraction that might otherwise block delivery pipes and pumps. The separated liquid will generally have a lower P:N compared to the raw slurry and may therefore be better matched to crop requirements. Due to the lower DM content of the separated liquid, the efficiency of use of the ammonia-N (NH₃-N) concentration in the supernatant should be improved, even if applied by inverted splash-plate spreading. The supernatant will percolate into the soil more readily than raw slurry, thus decreasing the amount of time exposed to the atmosphere and, as a consequence, volatilisation of ammonia (NH₃) should be reduced [22]. Work

by [23] indicated that NH_3 volatilisation from separated slurries decreased with decreasing mesh size.

2.1. Length of Storage Time and Temperature Pre-Separation

Length of manure/digestate storage time prior to separation is an important consideration in relation to efficiency of separation. After 10 days of storage, the total suspended solids in pig manure tended to decompose at an increased rate and separation should take place within 10 days of excretion, to maximise separator efficiency, as measured by the proportion of dry solids partitioned to the solid fraction [24]. The effect of storage time on manure constituents was evaluated using pig and cattle slurries [25]. Results showed that DM concentration for all types of manure decreased with length of storage time. For example, the DM concentration of beef manure decreased from 7.26% at 57 days of storage to 3.29% at 102 days and 2.53% at 129 days. A similar result was reported for stored pig manure [26], with DM concentration decreasing with length of storage time. This decrease was attributed to the biological degradation of organic matter (OM), which increased with length of storage time.

Temperature also influences the degradation rate of OM during storage. In a study on cattle manure [27], storage for up to 26 weeks was examined under anaerobic conditions at 9 °C (typical winter storage temperature for Northern Ireland) and 20 °C prior to anaerobic digestion. Storage of manure at 9 °C had no significant effect on subsequent biogas production. However, after 8 weeks of storage at 20 °C, there was an increasing negative impact on subsequent biogas production so that after 26 weeks of storage at 20 °C biogas production had decreased significantly. This reduction was strongly related to the decrease in the concentration of volatile solids in the stored manure. As the OM is broken down during storage, an increasing proportion of this component is transferred from the solid fraction to the liquid fraction. Hence, it is recommended that manure/digestate is separated as soon as possible after production in order to improve DM and nutrient removal to the separated solids fraction [22].

2.2. Separation Efficiency

The efficiency of mechanical separation is a measure of the distribution of DM and nutrients into the separated liquid and solid fractions. The most common methods for measuring efficiency that are cited in the literature are the simple separation efficiency index and the reduced separation efficiency index. The simple separation efficiency index is calculated by taking the mass recovery of nutrients or solids as a proportion of the input of solids or nutrients Equation (1) [21,28].

$$E_t = \frac{U \times M_c}{Q \times S_c} \quad (1)$$

E_t = Simple separation efficiency,

U = Quantity of solid fraction (kg),

M_c = Concentration of component in solid fraction (g kg^{-1}),

Q = Quantity of slurry treated (kg), and

S_c = Concentration of component in slurry (g kg^{-1}).

The simple separation efficiency index indicates the proportion of a compound present in the solid fraction. A simple separation efficiency index of 0.5 would mean 50% of the component was present in the solid fraction.

$$E'_t = \frac{E_t - R_f}{1 - R_f} \quad (2)$$

E'_t = Reduced separation efficiency,

E_t = Simple separation efficiency, and

R_f = U/Q (solid fraction to total digestate ratio).

The reduced separation efficiency index takes into account the difference in the masses of the two fractions. It is used to show the increase (or decrease) in concentration in the solid fraction relative to the starting material Equation (2). The reduced separation efficiency index can be positive or negative; a positive index indicates that the concentration is greater in the solid fraction than the starting material and vice versa [21,28].

2.3. Separation Throughput

Separation throughput is the rate at which feedstock can be separated. Screw presses can separate on average $18 \text{ m}^3 \text{ h}^{-1}$, ranging from 6 to $25 \text{ m}^3 \text{ h}^{-1}$, while decanting centrifuges average at a rate of $12 \text{ m}^3 \text{ h}^{-1}$, ranging from 3 to $25 \text{ m}^3 \text{ h}^{-1}$ [29]. A decanting centrifuge separating at an average of $12 \text{ m}^3 \text{ h}^{-1}$, running for eight hours per day, five days per week and for forty weeks per year could process over $19,000 \text{ m}^3 \text{ yr}^{-1}$ of manure or digestate. The actual flow rate will be dependent on input DM content. High-DM manure would have a lower flow rate than lower-DM digestate and this will determine actual productivity. $19,000 \text{ m}^3 \text{ yr}^{-1}$ of manure would be equivalent to the volume produced by approximately 1300 dairy cows during 180 days of winter housing. The volume of feedstock, its DM content and the number of hours that the separator can operate will determine the separator throughput required and hence the choice of technology and the number of separators required.

3. Separation Methods

The two mechanical separation technologies which this review focuses on are the screw press and the decanting centrifuge, due to the large volume of peer reviewed literature on their use and their ability to achieve greater solids and therefore P removal efficiencies [8,13,15,21,22]. Both of these separation methods are verified as important environmental technologies in line with the Verification of Environmental Technologies for Agricultural Production (VERA) [30]. VERA offer independent validation of environmental performance and operational stability of environmental technologies determined by applying specific test protocols. The screw press separates by particle size, whilst the centrifuge separates by particle density. Efficiency and cost-effectiveness of separation are important factors to consider when choosing which separator technology to adopt.

3.1. Screw Press Separator

The screw press (Figure 1a) is a mechanical screen separator that uses a rotating screw to force feedstock against a cylindrical screen under pressure. The screen traps a proportion of the solid matter while allowing the liquid and smaller solids to pass through. The solid fraction is brought to the end of the separator by the rotating screw and is pressed against a scraper or plate as it exits. The liquid effluent collects in the outer cylinder and drains through an outlet. Dry matter content of the input feedstock determines the proportion of the solid fraction after separation [31]. There are several variables that may be adjusted to alter the separation profile of a screw press, namely mesh size of the screen, feed speed and scraper tension.

According to filtration theory, specific filter cake resistance (SRF) is constant during constant pressure filtration; however, for a complex organic suspension such as manure/digestate, SRF often increases during the process [15]. The increasing SRF has been ascribed to sedimentation [32], small particles blocking the pores in the cake [33], and a time-dependent compression of the cake [34]. The slurry filter cake is compressed during pressurised filtration, so the SRF is several orders of magnitude higher for pressurised filtration than for gravity separation [35]. The cake compression ensures that the screw press can produce a solid fraction with a high DM content. Increasing the applied pressure will increase the DM content of the solid fraction. Screw press separators cannot separate all the small sludge particles (0.5 – 1.0 mm) from the feedstock [36]. Although aggregation of particles on the filter may, to some degree, contribute to the retention of small particles in

the screw press, this has no substantial effect, as the applied pressure forces small particles through the filter pores.

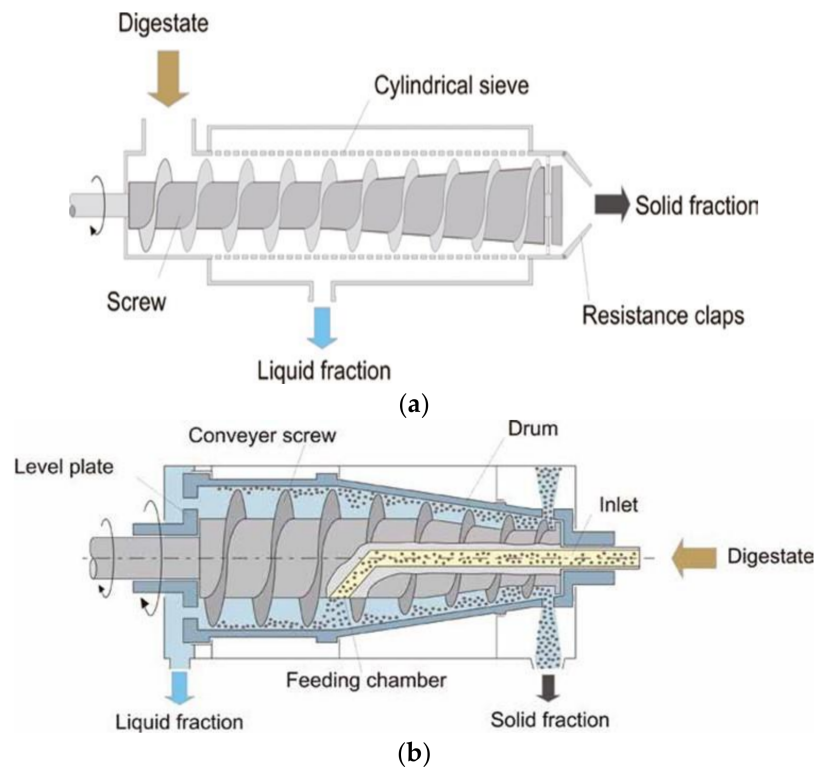


Figure 1. Simplified diagrams with digestate as a feedstock of (a) a screw press separator and (b) a decanting centrifuge separator, showing feedstock input, mode of action, separation chamber, and solid and liquid fraction outlets (reproduced by permission from Fuchs and Drosig, 2010 [37]).

Most of the small particles (<1.0 mm) are therefore found in the liquid fraction after separation. The amount of solid fraction that will accumulate is dependent on the DM content and [31] found a correlation between DM concentration in feedstock (digestate) and the proportion separated into the liquid phase (Figure 2).

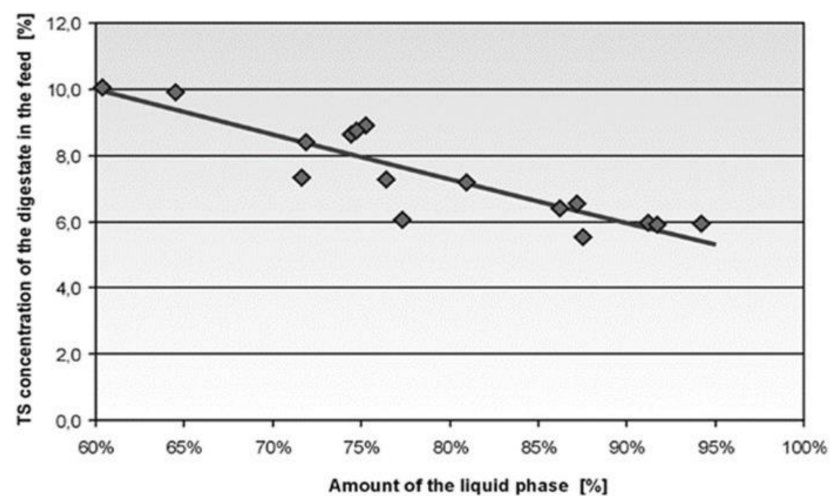


Figure 2. Relationship between the dry matter content in the inflow and the proportion of the liquid phase (pooled data from screw extractor and rotary screen separator experiments reproduced by permission from Bauer et al. 2009 [31]).

At a DM concentration of 10%, 60% of the feedstock was separated liquid. At a lower dry matter concentration of approximately 5%, 95% of the feedstock was separated to the liquid fraction. Several other separation technologies rely on the same principle of forcing the feedstock against a screen under pressure and these include a tilted plane screen-2-stage separator, a brushed screen, and the belt press separator [22,31].

3.2. Decanting Centrifuge Separator

Increasing the gravitational force can reduce the settling time needed to achieve a given separation efficiency. Decanting centrifuges work on this principle, where a centrifugal force is generated to cause the separation. Decanting centrifuges have higher capital and operating costs than screw presses and fewer references to them are found in the literature. There are vertical and horizontal types of decanting centrifuge. The horizontal decanting centrifuge (Figure 1b) uses a closed cylinder with a continuous turning motion. The resulting centrifugal force separates solids and liquids at the wall into an inner layer with a high DM concentration and an outer layer consisting of a liquid containing a suspension of colloids, organic components, and salts. The solid and liquid phases are transported to either end of the centrifuge by rotating the entire unit at high speed and by simultaneously rotating the conveyor (or screw) at a speed that differs slightly from the speed of the bowl (outer conical shell). The solid particles are conveyed towards the conical end and let out through the solid discharge openings, whereas the supernatant flows towards the larger end of the cylinder formed by the bowl and the flights of the conveyor. During the transport of the feedstock, the particles are separated from the liquid and the liquid phase is discharged through liquid-discharge openings at the wide end of the centrifuge [15]. A paring disc pumps the liquid fraction out. The separation performance depends on the particle size and shape, the difference in density between particles and fluid, as well as the fluid viscosity [38]. Differential speed between bowl and screw, retention time, and acceleration determine the separation efficiency of a decanting centrifuge. Typical operational parameters for a centrifuge capable of separating agricultural wastes at a feed rate of $11 \text{ m}^3 \text{ h}^{-1}$ are bowl diameter of 425 mm, a bowl speed of 3400 rpm, conveyor differential of 12 rpm, and a conveyor torque of 1.5 kNm [39]. Decanting centrifuges are very effective in separating small particles and colloids from the feedstock. In addition, they can be used to separate most of the P to the solid fraction [38].

4. Economics/Costs of Separation

The capital expenses (CAPEX) and operational expenses (OPEX) determine the cost of separation. Separation methods requiring high energy input (e.g., centrifugation) will have a high OPEX due to the electricity and maintenance costs. Typically, high energy systems will also have a high CAPEX as the manufacturing technology to produce them will also be costlier.

4.1. Capital Costs

Farm-scale screw presses suitable for slurry and digestate separation are likely to have combined capital and installation costs of approximately £15,000–65,000. Decanting centrifuges at the farm or larger processor scales are likely to have capital and installation costs of £50,000–250,000. Costs will be dependent on maximum output processing capability for feedstock, provision of feed pumps and flow meters, complexity of control and the addition of ancillary technologies to improve solid and/or nutrient removal. Examples of such ancillary technologies are automated separator shutdown at plug breakthrough, oscillation devices for improved solids offtake, noise reduction, and polymer flocculation systems, to name but a few.

4.2. Running Costs

The vast majority of mechanical separation techniques require the input of electrical energy to separate the feedstock in to solid and liquid fractions. The amount of energy

required per unit volume of feedstock separated is linked closely to separation efficiency. Generally speaking, the greater the energy input per unit volume the greater the separation efficiency and the higher the capital cost. For cost-effectiveness it is important that a balance is struck between CAPEX and OPEX. The energy requirements for separation of feedstock using screw presses are typically reported in the range of 0.4–1.2 kWh t⁻¹ and decanting centrifuges typically require 2.2–5.1 kWh t⁻¹ [21,40]. The energy cost of screw presses varies depending on operating parameters such as feed speed, clamp pressure, and mesh size of the screen. These parameters will vary the load on the motor—changing the power needed to turn the screw.

Screw presses have few moving parts and require little routine specialist maintenance or care [31] as cleaning, changing seals and screen sets can be undertaken by the operator. The centrifuge requires more maintenance than a screw press as it is comprised of more moving parts. The cost of running both types of separator varies with speed and retention time. The high rotation speeds of centrifuges produce vibrations that must be accounted for (mounting and slab depth) as well as the wearing of bushings and bearings. It is generally accepted that an annual service contract is essential for the maintenance and running of a decanting centrifuge. Assumed maintenance costs of separating machinery were suggested as being 2.5% of the investment cost per annum [21], but this figure is likely to be higher for centrifuges. Annual costs will vary depending on feedstock type, the presence of coarse matter (sand or grit for example) in the influent feedstock (causing greater wear) and the annual volumes separated.

The fixed and variable costs of separation include capital, depreciation, interest, electricity, chemicals, labour, and maintenance. In addition, there may be other costs associated with separation that are not necessarily apparent. Additional equipment and facilities are needed for handling/storage of the separated solid and liquid fractions, as well as the un-separated manure/digestate [22]. The economics of separating pig manure by screw press and decanting centrifuge have been calculated for a farm with an annual production of 4000 t of manure, corresponding to the yearly production from approximately 8000 pigs [21]. Table 1 shows the yearly running costs for screw press and decanting centrifuge separators along with the respective treatment costs of £0.44 and £2.21 t⁻¹ of feedstock manure. Thus, the cost per unit volume of feedstock manure separated with a decanting centrifuge is 5-fold more expensive than that using a screw press.

Table 1. Annual costs (£) for treatment of 4000 t of pig slurry by screw press and by decanting centrifuge (£/4000 t and £ t⁻¹)^a (reproduced by permission from Møller et al. 2000 [21]).

Variable	Screw Press	Decanting Centrifuge
Maintenance and repair	250	1250
Electricity (0.04 £/kWh)	80	480
Capital costs	1424	7119
Total yearly costs	1754	8849
Total costs £/tonne	0.44	2.21
Total costs £/kg of TP in solid fraction ^b	1.6	2.0

^a Yearly maintenance is calculated as 2.5% of the investment (I). Electricity consumption was set at 3.0 kWh t⁻¹ for decanting centrifugation and 0.5 kWh t⁻¹ for a screw press. ^b Assuming 20% and 80% removal of TP in a screw press and a decanting centrifuge, respectively (pig slurry with 1.4 g TP per litre).

Decanting centrifuges are more efficient at separating total phosphorus (TP) than screw presses (screw press 4–34%, decanting centrifuge without chemical addition 30–91%, Table 2). As a consequence, the cost per kg of TP transferred to the solid fraction is only 25% higher for the decanting centrifuge than for the screw press (Table 1). Another way to measure cost of separation is to calculate the cost per tonne of nutrient partitioned to the separated solid fraction. At an annual throughput of 4000 m³ without chemical addition, the estimated costs for partitioning nutrients into the separated solids from pig slurry could be in the order of £2000–6000 t⁻¹ of TP and £5000 t⁻¹ TN for a decanting centrifuge [21,22].

The lower cost for TP partitioning quoted by [21] may be due to the very low maintenance costs and unit price of electricity applied.

Table 2. Screw press (SP) and decanting centrifuge (DC) separation efficiencies for dry matter (DM), total nitrogen (TN), and total phosphorous (TP) reported in a number of studies. Separation efficiency is quoted as the percentage of the analyte from the input feedstock that was partitioned to the solid fraction. One of the studies did not report data for TP (ND).

Source	Feedstock/Separator Type	Separation Efficiencies		
		DM (%)	TN (%)	TP (%)
Hjorth et al. 2010 [15] (mean values from 16 studies)	Pig + cattle slurries SP	37	15	17
	Pig + cattle slurries DC	61	28	71
Gilkinson and Frost, 2007 [22]	Cattle slurry DC no polymer	51	25	64
	Cattle slurry DC with polymer	65	41	82
	Pig slurry DC no polymer	53	21	79
	Pig slurry DC with polymer	71	34	93
Møller et al. 2002 [26]	Pig digestate SP	18	7	10
	Cattle digestate SP	23	6	9
	Pig digestate DC	69	24	91
	Cattle digestate DC	54	24	54
Tambone et al. 2017 [41] (11 different AD plants studied)	Pig + energy crops digestate SP	17–36	6–10	8–14
	Cattle + energy crops digestate SP	21–49	8–24	4–17
Burton and Turner, 2003 [42]	Pig + cattle slurry SP	20–65	5–28	7–33
	Pig + cattle slurry DC	54–68	20–40	52–78
Danetv 2010 [43]	Digestate DC	63	25	72
	Cattle slurry DC	36–49	13–18	40–55
Perazzolo et al. 2015 [44]	Pig + cattle digestate SP	23	6	ND
	Cattle digestate SP	15	5	ND
Bolzonella et al. 2018 [45]	Cattle digestate SP	30	9	23
	Pig digestate SP			
	Cattle digestate SP + DC	488496	135029	348475
	Pig digestate SP + DC			
Fournel et al. 2018 [46]	Cattle slurry SP	28–43	9–17	14–24
	Cattle slurry DC	36–49	13–18	40–55
Finzi et al. 2020 [47]	Pig, cattle and poultry manures SP	13	3	6
	Pig, cattle and poultry manures DC	35	13	30
Pantelopoulos et al. 2021 [48]	Pig slurry SP + DC	56	18	73

Both types of separator have a much higher annual capacity than 4000 t yr⁻¹. Increasing the annual volume of feedstock separated will lower the annual costs per tonne separated (Figure 3). Increased annual feedstock availability can be achieved either by increasing the number of livestock on the farm or by treating manure from several farms at a centralised separation plant. 4000 t of slurry equates to the annual production from approximately 200 sows plus finishers, or 300 dairy cows over 6 months, allowing for some slurry dilution [22]. The average dairy farm in Northern Ireland has a herd size of 95 cows producing approximately 1200 t of slurry over 6 months [49]. Therefore, the capital and running costs of separation are major considerations, especially for the decanting centrifuge.

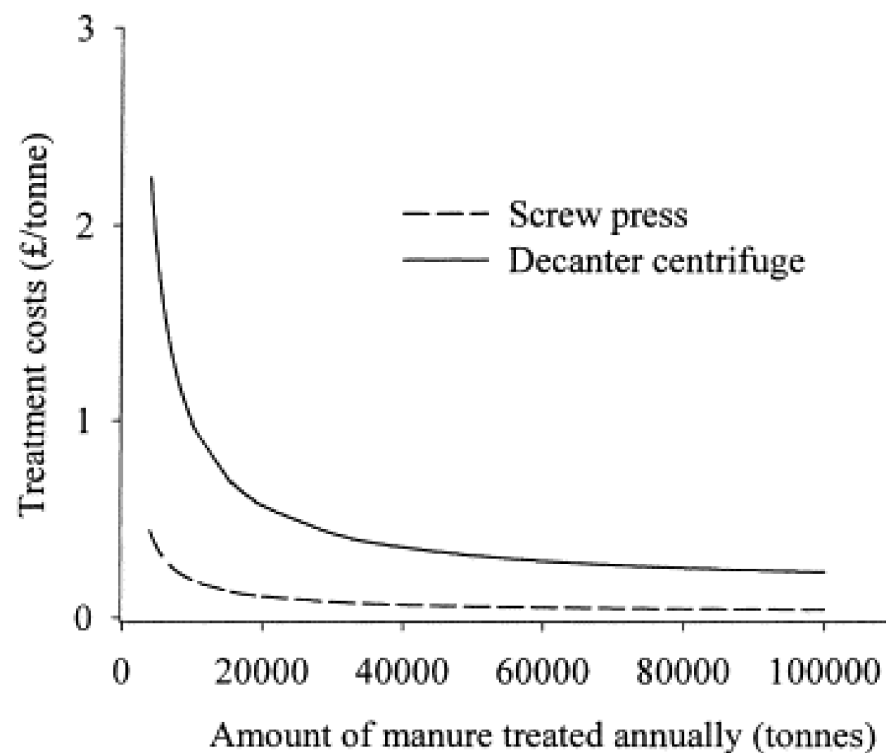


Figure 3. Costs in £ t^{-1} for slurry separation using a screw press and a decanting centrifuge influenced by the amount of animal manure treated annually (reproduced by permission from Møller et al. 2000 [21]).

To lower the cost per unit volume of feedstock separated, it may be possible to use a mobile separator that could service a number of farms. Alternatively, a separator could be set up in a central location, maybe as part of a centralised treatment system, to separate feedstock from a number of farms. Biosecurity and end use of separated fractions then become major considerations which must be assessed [22].

4.3. Chemical Addition

Evidence in the literature indicates that the use of chemicals (coagulants and flocculants) improves separation efficiency of manures and digestates [13,35,50]. Flocculation, coagulation, and precipitation are chemical pre-treatments that improve the mechanical solid–liquid separation of many suspensions [51–53]. In most suspensions, colloidal particles will not aggregate because the particles are negatively charged and repel each other [49]. However, aggregation will be facilitated by adding (i) multivalent cations that cause coagulation and/or (ii) polymers, whereby flocculation occurs. The addition of multivalent cations will also enhance the precipitation of P [15] along with particle coagulation. An optimum dose exists, and overdosing occurs when the adsorbed ions reverse the surface charge, thus counteracting aggregation [54].

The addition of polyelectrolyte polymers to manures induces flocculation (Figure 4). Most studies indicate that a cationic polymer is superior to anionic and neutral polymers which correlates well with the fact that the particles in animal manures are mainly negatively charged [15]. Polymer bridging is the main reaction mechanism (Figure 4c), whereas patch flocculation is of limited significance (Figure 4b), and charge neutralisation is not important [35].

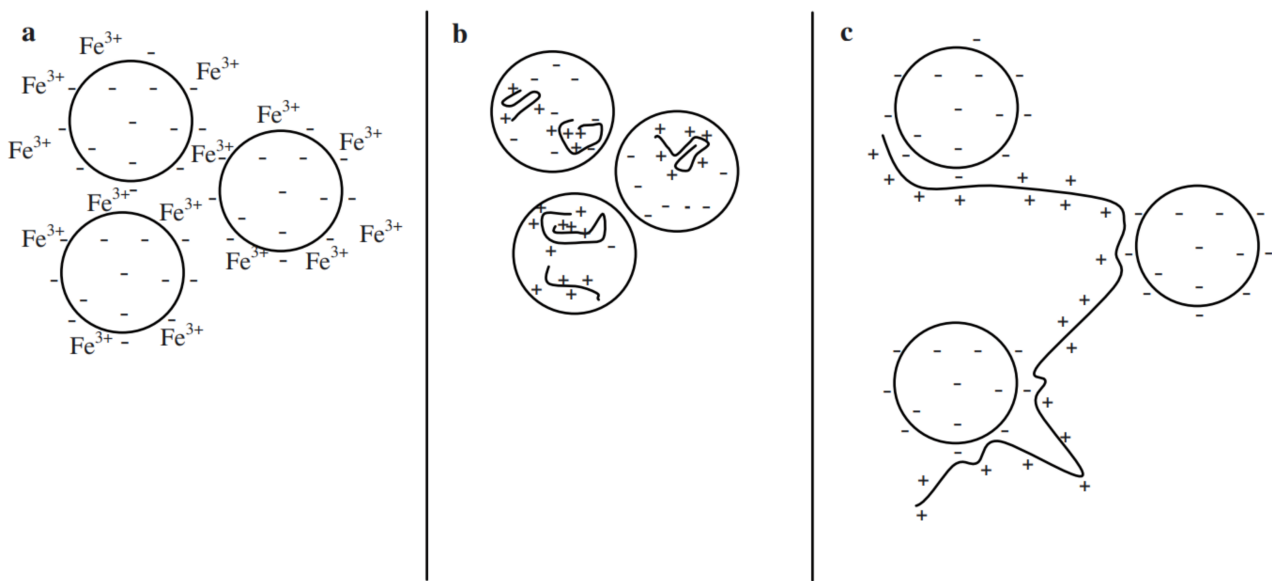


Figure 4. Diagrammatic representations of (a) coagulation, (b) patch flocculation and (c) polymer bridging (reproduced by permission from Hjorth et al. 2008 [35]).

The addition of polymers will cause flocculation of particles and of existing but smaller aggregates that have been produced due to coagulation, for example, induced by the addition of Fe³⁺ to the feedstock (Figure 4a). Patch flocculation is the adsorption to particles of oppositely charged polyelectrolytes with a charge density much higher than the charge density of the particles. Thus, local positively and negatively charged areas are formed on the surface of the particles (Figure 4b; [51]). This results in a strong electrical attraction between the particles, especially when the electrical attraction extends far into the solution, i.e., at low conductivity [51]. Polymer bridging occurs when long-chain polymers adsorb to the surface of more than one particle, causing the formation of strong aggregates of large flocs (Figure 4c; [54]). At high conductivity of the feedstock or at high doses of added polymer, the polymer coils up and forms loops and tails. Due to steric hindrance between the particles, the loop and tail formation leads to deflocculation [51]. The cost and implications of chemical addition must also be considered. Using a decanting centrifuge with a polymer cost of approximately £1.80 L⁻¹ undiluted and a conditioner at £0.18 L⁻¹, the costs per tonne of pig manure separated, using a range of dosages were shown to be £1.50–3.74 t⁻¹ of slurry, and along with increased volume of liquid separated that had to be stored and handled, these are substantial additional costs [22].

In the last 30 years, pH adjustment by acidification of manures and digestates has become more prevalent to reduce NH₃ emissions during storage, processing, and field application. The use of inorganic acids such as sulphuric acid has been researched and applied commercially as a chemical amendment where reduction of the pH to 5.5 minimises the concentration of NH₃ relative to NH₄ [55]. Acidified manure contains fewer particles <0.05 mm than untreated manure, which can be explained by particle aggregation because of lower electrostatic repulsion between particles under the conditions of higher conductivity and less negative surface charge [56]. This particle aggregation is likely to benefit solids removal during mechanical separation as the larger particles will be more easily partitioned to the separated solid fraction. It should also be noted that acidification of manure/digestate might induce higher losses by leaching, due to solubilisation of mineral elements such as P which are increased in the liquid fraction [55]. This would be undesirable if maximising P removal to the separated solids was the main objective of mechanical separation.

5. Dry Matter and Nutrient Partitioning

5.1. Screw Press vs. Decanting Centrifuge

Screw presses, along with other mesh screen separation technologies have a lower efficiency of solids separation compared to decanting centrifuges. With a screw press, solid fractions are obtained containing approximately 20% of the total solids from the original feedstock. In addition, the solid fraction contains approximately 10–20% of the total mass of the original feedstock [13,31]. The addition of flocculants, such as chitosan (a linear polysaccharide polymer produced by treating chitin from crustacean shells with alkali), has been shown to increase solids separation efficiencies to as high as 95% [20]. Typically, a decanting centrifuge will achieve a solids separation efficiency of 60% or greater without the use of flocculants or coagulants [21]. The mass separation is broadly the same as with a screw press at 10–20% [13].

Review of published literature indicates that a high degree of variation exists in reported separation efficiencies for DM, N and P (Table 2) and that the variation is due to feedstock DM content, separator setup and running conditions (screen size, clamp pressure, centrifugation velocity, centrifugation time, chemical addition). Screw press separators remove a proportion of the DM, and have some success in removing TP and TN. In contrast, centrifuges have a high separation efficiency for TP and have some effect in removing TN. Mechanical screen separators with a screen pore diameter of 0.5 mm or greater will not retain the dry matter particles that contain high concentrations of plant nutrients [21]. In contrast, the decanting centrifuge can retain particles <0.5 mm. It has been reported that in the liquid fraction of centrifuged pig manure [57], only 2% of the particles were >0.02 mm, compared with 53% in the raw manure. The centrifuge had removed almost all the particles >0.02 mm. Some of the TN is retained in the solid fraction, because as much as 50% of the nitrogen in the manure is in the form of dissolved $\text{NH}_3\text{-N}$ in the liquid fraction, and the quantity in the solid fraction is dependent on DM content [58].

The differential partitioning of more nutrients into the solid fraction of separated pig or cattle manure by a decanting centrifuge, except for $\text{NH}_3\text{-N}$ and K, compared to a brushed screen separator has been described [22]. Data presented in Table 2 indicate that the decanting centrifuge is also more efficient at partitioning DM and nutrients to the solid fraction than a screw press, with increasing efficiency if chemicals are included. The solubility of the $\text{NH}_3\text{-N}$ and K components means that they do not differentially partition into the separated solid fraction [21]. It is likely that most of the N transferred into the separated solid fraction is from the organic N fraction, i.e., in the suspended solids. The concentrations of TN and $\text{NH}_3\text{-N}$ in the supernatants from pig manure separated through the decanting centrifuge with chemical additions, were found to be almost identical, thus the organic N fraction had been almost completely partitioned to the separated solid fraction [22].

The solubility of $\text{NH}_3\text{-N}$, and its preferential separation into the liquid fraction, leads to an increase in the Total Ammonia Nitrogen/Total Kjeldahl Nitrogen (TAN/TKN) ratio in the separated liquid fraction. Published work [41] showed that separation by screw press increased TAN/TKN ratio by 9% on average from 13 different digestates. Similar findings have been reported by [15,59] suggesting that the increased TAN/TKN ratio makes the liquid fraction a good, fast acting, fertiliser for plants as the N is readily available.

5.2. Solid vs. Liquid Fractions and Their Fertilising Potential

Plant uptake of N in liquid separated from digestate is improved due to its high NH_4^+ :TN share, lower organic carbon contents and therefore lower N immobilisation after field spreading, faster soil infiltration, and higher short-term N-manuring effects, resulting in better control of the applied N [60]. Field application of digestate and separated digestate liquids resulted in similar grass yields and N uptake in comparison to plots treated with commercially available N fertilisers [61,62]. A considerable share of N organic fractions, in separated liquid digestates, is rapidly mineralised in soil and such separated fractions are characterised as N–K fertilisers comparable to mineral N–K fertilisers or

animal urine [14]. Limited information exists on the agronomic response of temperate grassland systems to separated liquid manures in terms of herbage quality and yield, although some evidence suggests that there is potential for separated liquid manure to cause increased yield relative to untreated slurry, due to higher bioavailable N [63]. Less N volatilisation occurs from field application of separated liquid due to quicker soil infiltration when using finer mesh sizes for separation [23]. Slurry acidification to pH 5.5 inhibited the degradation of organic materials during storage and led to an increase in slurry fertiliser value (NH_4^+ -N and sulphur concentration) whilst mitigating its environmental impacts through a reduction in NH_3 losses during storage and after soil application. The losses in the acidified separated liquid fraction were reduced by 92% relative to the non-acidified separated liquid fraction [64].

Application of the solids from separated pig manure and thermophilic anaerobically digested poultry waste resulted in significantly lower crop yields (corn/vegetable, fruit and grass plots, respectively) compared to the liquids and to plots with mineral fertiliser [61,65]. Incubation experiments indicated a net N immobilisation after application of separated dairy manure digestate solids [66]. Evidence suggests that considerable N losses during storage reduce the plant available N from the separated solid fraction [16]. After a solid-liquid separation the solid fraction should ideally be applied to fields immediately, as the main N emissions take place in the first weeks of storage [67,68] especially during warmer weather due to the temperature dependency of the emission rates [67]. If storage is unavoidable, anaerobic conditions should be maintained. In summary, the solid phase may be characterised as an organic fertiliser comparable with solid animal manure, but, with highly available N and P contents having potential for gaseous N losses, best suited to application on arable land in order to increase soil humus reproduction and to mitigate P removal via harvested P-rich biomass such as cereal crops. Application of acidified and composted solid fraction separated by a screw press instead of the whole slurry [64], mitigated NH_3 losses during storage and after field application. The NH_3 loss reduction in the composted solid fraction was mainly related to its negligible concentration of NH_4^+ -N before application.

6. Logistics of Handling and Transport Options

Handling and transport options for unseparated manures and digestates are well established and costs for these activities are readily calculated. One option for better P management in nutrient-rich areas is the export of these feedstock from farms which have high soil P levels to land which has a P deficit. However, the associated handling and transport costs become uneconomical as the distance from source to sink increases, with unit costs for spreading increasing 2–4 fold over a distance of 0–10 km from manure store to field, dependent on spreading method [3]. This type of export would also lead to N, K and other plant nutrients which are required for crop growth leaving the farm and these may have to be supplemented through the use of chemical fertilisers with associated environmental and monetary costs. This option is not currently favoured as a solution for most farms. Separation on farm using mechanical separation technologies is a possible solution to export P effectively and at a lower cost than exporting whole manures/digestates.

6.1. The Separated Liquid Fraction

The liquid fraction of separated manure and digestate can be managed using tankers in the same way as whole manure or digestate is normally transported and land spread. Compared with whole manure and digestate, the separated liquid fraction has a lower DM concentration and is therefore less viscous and is easier to pump. In addition, because many of the large and heavy particles have been removed there is little settlement during storage. As a result, there is much less requirement for mixing separated liquid prior to removal from store. A further benefit of the lowered fibre concentration in separated liquid is that there is less risk of pump and pipe blockages and therefore no requirement for maceration

prior to using land spreading equipment such as trailing hose/shoe/dribble bar and liquid manure injection [63]. When used as a biofertiliser, separated liquid fraction with its lower P concentration will be more closely matched to crop nutrient requirements [18]. The lower P content than the input feedstock also means that there is lower risk to waterways when field spread. The volume of separated liquid is approximately 20% less than the unseparated feedstock meaning that less storage capacity is required for the liquid phase [18]. However, in many cases, separated liquid storage may be additional to existing on-farm storage as the feedstock may need to be stored prior to separation. The transportation costs of the liquid fraction will be broadly the same cost per unit weight as raw manure or digestate (Table 3). Approximate transport costs are likely to be £60–80/h for a hauled load or £3–4 t⁻¹ or m³ for a 16 km delivery if paying by volume [69]. The 10–20% reduction in mass compared to raw digestate (if no chemicals have been applied) should lower transport cost by a similar factor.

Table 3. Annual costs associated with raw pig manure transport and spreading by tractor and vacuum tanker and by truck for a 500-sow integrated pig farm (reproduced by permission from Nolan et al. 2012 [70]).

Distance Travelled (km)	Tractor Outward Speed (km h ⁻¹)	Tractor Annual Costs (€)	Tractor (€ m ⁻³)	Truck Outward Speed (km h ⁻¹)	Truck Annual Costs (€)	Truck (€ m ⁻³)
1	20.00	13,877	1.3	45.0	36,048	3.4
2	20.50	16,936	1.6	45.0	37,220	3.5
5	21.25	25,824	2.5	45.0	40,736	3.9
10	22.50	39,427	3.8	47.5	46,006	4.4
14	23.50	49,350	4.7	48.5	50,151	4.8
15	23.75	51,711	4.9	48.8	51,161	4.9
20	25.00	62,860	6.0	50.0	56,070	5.3
30	27.50	82,334	7.8	52.5	65,216	6.2
50				60.0	81,213	7.7
75				60.0	101,591	9.7
100				60.0	123,830	11.8
125				60.0	146,068	13.9
150				60.0	168,306	16.0
200				60.0	212,782	20.3
250				60.0	479,641	45.7

6.2. The Separated Solid Fraction

At a DM content of 15% and above (typically this is higher for both separator types studied in this review), the separated solid fraction is a stackable material which can be transported by tractor and trailer or by truck, in a manner similar to grain, silage and farmyard manure (FYM) and can be applied using conventional FYM spreading technology. It is rich in OM and nutrients (mainly P) meaning transport costs are lower on a nutrient content basis than those for whole manure/digestate [21]. Transportation of less water means that the cost of moving nutrients will depend on concentrations of N, P and K. In addition, manure and digestate have a specific gravity of approximately 1 t m⁻³. Separated solids density will depend on DM content and is likely to be considerably lower than 1 t m⁻³ which will impact on transport efficiency.

6.2.1. Solid Fraction Transportability

Annual costs for transporting and spreading raw pig manure by tractor and vacuum tanker (11.8 m³ capacity) or by truck (27 m³ capacity) in Ireland were calculated by [70] (Table 3). For a distance of up to 14 km from the pig farm to the customer's farm, the most cost-effective way of transporting and spreading was shown to be by tractor and vacuum tanker. To transport and spread the slurry a distance of 14 km from the pig farm, the cost per m³ of slurry was €4.7 if transported by tractor and €4.8 if transported by truck. For distances longer than 15 km (30 km return journey), transporting by truck becomes more

cost-effective. To transport and spread the slurry a distance of 30 km from the pig farm, for example, the cost per m³ was €7.8 if transported by tractor and €6.2 if transported by truck. In a 2001 study of costs of field application of manure in Europe [71], the cost per m³ of manure applied in Ireland (0.5 and 2 km distance from customers' farm) was estimated to be €3.6–6.3. The authors attributed the higher costs to the lower quantities of manure applied (between 946 and 2247 m³ yr⁻¹). For the data presented in Table 3, the cost of application was based on a yearly manure production of 10,500 m³. For comparable yearly production of 2200 m³ and distance to a hypothetical customer's farm of 2 km, the cost for the manure application would be €7.7 m⁻³ [71]. In a study on the transportability of the screw pressed solid fraction compared to raw slurry for a German dairy farm [72], the assumption was made that the farmer wanted to export 1000 kg of N off the farm.

Based on average values of N content of raw slurry at 7% DM, this would involve export of 500 t of raw slurry off farm with a P₂O₅ content of 300 kg. To export the same amount of N in separated slurry solids, 189 t of solids would have to be exported containing 378 kg of P₂O₅. To generate 189 t of solids, 1048 t of raw dairy slurry would have to be screw press separated. The monetary value of the raw slurry and solids are offset by the costs of separation and transportation. This study assumed a separation cost of €0.7 t⁻¹ raw slurry (slightly higher than the figure of £0.44 t⁻¹ suggested by [21] allowing for exchange rate adjustment). Transport by truck was deemed the most flexible and best solution. Transport costs are mainly influenced by distance and calculated costs were €10 t⁻¹ for approximately 50 km, €16 t⁻¹ for approximately 100 km and €21 t⁻¹ for approximately 150 km. The costs apply for raw slurry and separated solids because they are based on weight rather than volume [72]. The results of the study are illustrated in Table 4.

Table 4. Results for transportation costs of raw and separated manure solids over a range of distances (reproduced by permission from Kroger and Theuvsen, 2013 [72]).

Transport Distance	Raw Slurry			Separated Solids		
	50 km	100 km	150 km	50 km	100 km	150 km
Nutrient value €/t	7.2	7.2	7.2	8.5	8.5	8.5
Energy Value €/t	4.0	4.0	4.0	8.7	8.7	8.7
Total Value €/t	11.2	11.2	11.2	17.2	17.2	17.2
Separation Costs €/t	0	0	0	3.9	3.9	3.9
Transportation Costs €/t	10.0	16.0	21.0	10.0	16.0	21.0
Total Costs €/t	10.0	16.0	21.0	13.9	19.9	24.9
Total €/t	1.2	−4.8	−9.8	3.3	−2.7	−7.7
Total per kg N €/t	0.3	−1.2	−2.4	0.6	−0.5	−1.4

The total costs for transporting raw slurry were between €10.0 and €21.0 t⁻¹ of fresh matter (FM) depending on the distance travelled. The total costs for transporting the separated solids were €13.9–€24.9 t⁻¹ FM. The data presented in Table 4 indicate that transportation of raw slurry and separated solids is not profitable over a distance of 100 km or more, with transport costs higher than the combined nutrient and energy values of both products. Exact calculations revealed that the maximum distance for economical transport of raw slurry is approximately 70 km and 84 km for separated solids. If separation costs were to increase to €1.1 t⁻¹ FM then transporting raw slurry would be less costly than separated solids [72]. A report on transportability [69] indicated that approximate transport costs for separated solids are likely to be £40–60 h⁻¹ for a hauled load or £2–3 t⁻¹ or m³ for a 16 km delivery if paying by volume. The data provided from the various studies cited suggests that transport costs are lower for separated solids than whole slurry or digestate.

In Northern Ireland, the costs for contracted field application of farmyard manure using a manure spreader and tractor are £50–55 per hour [48]. For a farmer using their own tractor, hire of a rear discharge manure spreader would cost £120–150 per day and fuels costs would have to be factored in [73]. These costs would also be the same for land

application of separated manure or digestate solids, but higher fertiliser value than FYM per tonne applied due to concentration of nutrients (mainly P and some N) is also an important financial consideration.

6.2.2. Further Processing of the Solid Fraction

As an alternative to exporting separated solids straight from the separator, the solid fraction could be processed on site, as a means of improving the economic feasibility of export distances, or potentially to create a product that could be used locally or exported. Processes that increase the concentration of nutrients in the separated fibre increase the value per unit weight, thus decreasing transport costs per unit weight of nutrient.

In general, processed products are easier to handle with less odour. Drying separated solids to obtain a less dense biomass (10–20% moisture content with a higher concentration of nutrients per unit of fresh weight) could be a possibility on sites where excess or cheap heat is available, for example AD plants with unused heat from combined heat and power (CHP) engines [74]. Belt dryers are commonly used (Figure 5a) in which the solids are placed on a conveyor belt and dried at temperatures of 60–150 °C for approximately 2 h. Multiple belts can also be arranged one above the other. A similar principle applies to push-turn, fluidised bed, and drum dryers, in which the material is transported through the hot air by movement of vanes, air injection, or a rotating drum. With trailer or container dryers, hot air is blown through a motionless pile. Depending on the technology used, the heat requirement is 750–1200 kWh of thermally evaporated water per cubic metre [74].

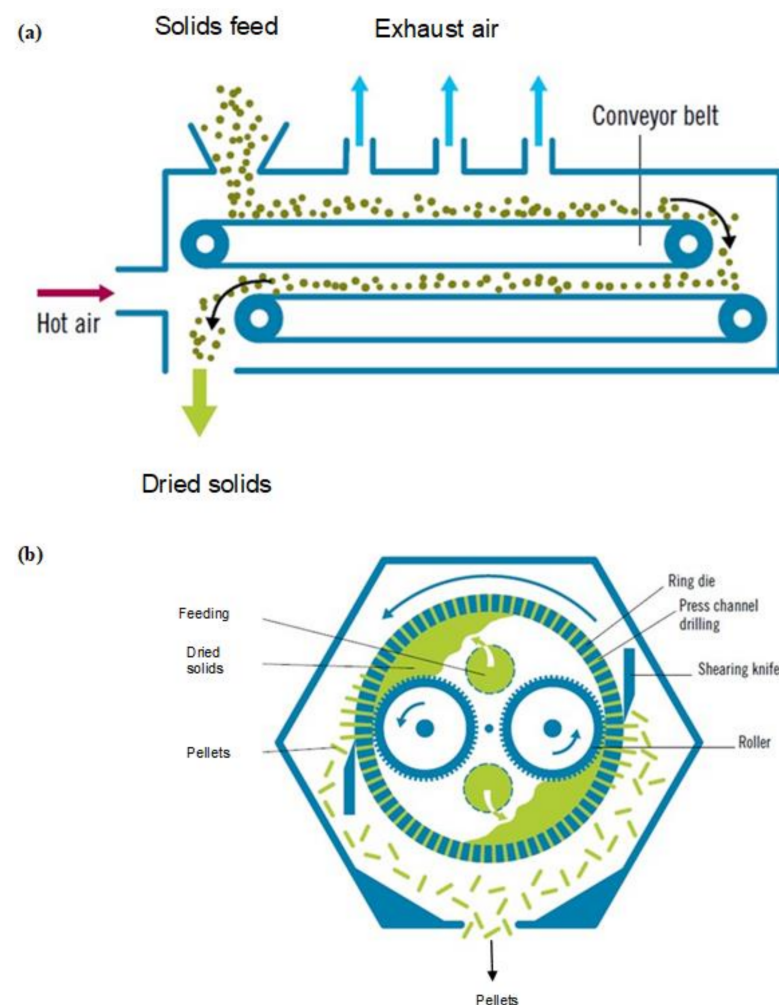


Figure 5. Diagrammatic representation of (a) a belt dryer and (b) pelletisation for processing separated manure or digestate solids (reproduced by permission from Wilken et al. 2018 [74]).

Dried solids can be processed to form pellets [19,41,75]. The goal of pelletising is to compact the dried solids into pellets to improve the density as well as handling and appearance. This requires a DM content of the dried solids of 85–90%. The solids are pressed through dies under high pressure. This results in very high temperatures on the surfaces, which means that the pellets melt on the outside and have a glassy shine. In the ring die, the solids are pressed from inside to outside through the annular die from inside rollers (Figure 5b). The power consumption for pelletising dried solids is approximately 30–50 kWh t⁻¹. Loose dried solids have a bulk density of 250–350 kg m⁻³. Pelletising produces pellets with a bulk density of 700–750 kg m⁻³ and thus considerably decreases transport costs and increases storage suitability [74].

The dried and/or pelleted solids could undergo thermal conversion as a biofuel either in raw form or mixed with other biomass sources, by using technologies such as combustion [19,76], gasification [77,78] or pyrolysis [79], leading to the production of energy (heat and/or electricity), carbon/nutrient-rich chars/biochars and bio-oils [80] or P-rich ash fractions, depending on the technology used. Chars and biochars could then have value for carbon sequestration and soil amendment [81]. Dried separated solids in pellet form would also have potential as renewable fertilisers or soil conditioners. However, previously published work [14] reported that no data were found on the agronomical implications of pelletising manures or digestates (nutrient composition, nutrient availability, effects of used field spreading technology, e.g., broadcast application versus application near crop rows). In recent years, a number of EU funded projects have been investigating the organic fertiliser potential of processed manures and digestates (EU-FP7- ReUseWaste—www.reusewaste.eu accessed 04/01/21; H2020 SYSTEMIC—<https://systemicproject.eu/> accessed 04/01/21) to improve agricultural sustainability in the future circular bioeconomy. Drying of separated solids is related to N losses as NH₃ [82], so it is likely that any drying process should include relevant technology for NH₃ capture which may add cost. Belt dryers can be fitted with scrubbing technologies where the NH₃-rich vapour phase passes through sulphuric acid to recover ammonia in the form of ammonium sulphate, which can be used as a fertiliser [45]. Acidification of manures/digestates followed by mechanical separation is another option to minimise N loss on drying, as the concentration of NH₄⁺-N in the acidified solids is negligible compared to the liquid fraction, resulting in much lower NH₃ losses [64,83].

Another potential option for the treatment of separated solids is composting [84,85]. However, outdoor composting is related to strong losses of N [16,17]. In addition to direct NH₃ losses, this is due to denitrification producing nitrous oxide (N₂O) and nitrogen (N₂) gases, following nitrification of the NH₄⁺ component to NO₃⁻ during aerobic turnover. In-vessel compost systems using a continuously turned rotating drum may provide an alternative to windrow or static pile outdoor composting. However, there are still associated losses of GHGs and NH₃ which must be taken into account. In a study looking at in-vessel composting of dairy manure [86], the total GHG emissions (CH₄ + N₂O) from solid separation, composting, compost storage, and separated liquid storage were reduced substantially on a CO₂-equivalent basis compared to traditional liquid storage. The results of this study also noted that an environmental trade off was that NH₃ was emitted at higher rates from the continuously turned composter than reported values for traditional storage. From application of fresh and composted solid animal manures, it is known that the effect on N availability and on soil humus reproduction of fresh manures directly applied to the soil is comparable to composts derived from the same amounts of fresh manures [87]. Therefore, composting reduces the fertiliser value of separated solids in terms of direct nutrient availability and probably also the effect on long-term preservation of soil fertility and is also related to strong emissions of GHGs (N₂O and CO₂). Consequently, from both an environmental and a plant nutrition point of view, composting may not be an effective nutrient management option [14].

6.3. Emissions from Separated Fractions

Gaseous emissions of NH_3 are of major concern, both in terms of monetary N losses to the farmer and unwanted environmental effects such as damage of sensitive terrestrial and aquatic habitats. Stored separated manure fractions have potential for increased NH_3 emissions relative to untreated manure [88], especially from the liquid fraction which has a higher concentration of NH_4^+ -N [89]. The effects of mechanical separation on NH_3 and GHG emissions from the storage of different fractions obtained from separation of co-digested pig and cattle manures were studied at laboratory the scale [44]. Results from the study indicated that relative to whole digestate, mechanical separation of digested manures increased N losses during storage when both separated fractions were taken into account, by 35% and 86% for pig and cattle manures, respectively. However, the flux measurements from the agitated samples showed that there was a lower potential for NH_3 emissions during storage for the separated fractions than the unseparated digestate (9% and 23% reductions for the pig and cattle manures, respectively), probably due to the lower TAN concentration of the liquid fraction. The separation treatment resulted in a significant reduction (40%) of GHG emissions for cattle manures but had no consistent effect for pig effluents.

A number of studies involving solid–liquid separation systems have produced inconsistent results for their effects on emissions. One publication found that separation increased total NH_3 and N_2O emissions during composting/storage and application by 77% and 19%, respectively, with most emissions from the composting of the solid fraction [1]. Conversely, another study observed no significant difference in N_2O emissions between separated liquids from unprocessed manure and reported that the separated solids showed lower N_2O emissions than unprocessed manure in terms of percentage of N applied [90]. A third publication also found no significant difference in NH_3 emissions between raw manure and separated liquids [91]. Results from work on separation following anaerobic digestion [92], found reduced N losses during storage and the first growing season following land application. Incorporation of separation following digestion can reduce the NH_3 losses during storage, but the losses from storage of the digested and separated manure are still greater than the raw manure alone. Separation alone did show a trend in reduction but was not statistically significant in this study. Other land application methods which do not immediately incorporate manure may further increase NH_3 losses [93,94].

A study by [64] investigated the effect of acidifying whole slurry and separated slurry fractions to pH 5.5 using sulphuric acid. Treatment of whole slurry with sulphuric acid reduced NH_3 volatilisation by 69% relative to the untreated slurry but had no effect on emissions of CH_4 , CO_2 and N_2O during storage. Application of acidified slurry fractions (separated liquid and composted solid fraction separated by a screw press) instead of the whole slurry mitigated NH_3 losses after field application. The effect in the separated liquid was related to the higher infiltration of NH_4^+ -N in the topsoil (0–5 cm layer) relative to the whole slurry whereas the reduction in the composted solid fraction was mainly related to its negligible concentration of NH_4^+ -N before application. Slurry acidification inhibited the degradation of organic materials during storage and led to an increase in slurry fertiliser value (NH_4^+ -N and sulphur concentration) whilst mitigating its environmental impacts through a reduction in NH_3 losses during storage and after soil application. After field application, the cumulative NH_3 lost in the separated liquid fraction was almost 50% lower than the whole slurry. The losses in the acidified separated liquid fraction were reduced by 92% relative to the non-acidified separated liquid fraction.

Work by [95] compared NH_3 and GHG emissions plus crop yield when employing slurry injection in soil (reference technique) and a combined approach of slurry treatment (by centrifuge separation and/or acidification to pH 5.5 with sulphuric acid) followed by surface application. Soil injection reduced NH_3 emissions to insignificant levels and did not increase N_2O emissions, while maintaining oat yields similar to those for the surface application of whole slurry. Surface application of acidified slurry or acidified separated liquid fraction led to NH_3 emissions <7% of applied NH_4^+ -N, with no increase of N_2O

emissions relative to surface application of whole slurry. Furthermore, a stronger decrease of N losses was achieved by surface application of acidified slurry followed by soil incorporation. However, surface application of separated liquid fraction without incorporation led to significant NH₃ emissions and therefore is not recommended. Significantly lower ($p < 0.05$) CH₄ emissions were observed with application of acidified slurry and separated liquid fraction, relative to the respective non-acidified treatments.

6.4. Biosecurity of Exported Separated Fractions

Animal manures and slurries may contain a wide range of pathogenic microorganisms such as *Salmonella* spp., *Listeria* spp., *Campylobacter* spp., enterohaemorrhagic *Escherichia coli* (EHEC), *Cryptosporidium* oocysts, *Giardia* cysts and enteric viruses [96]. If whole or separated manure fractions are to be transferred to other receiving lands, precautions should be taken to reduce the risks of cross infections. Treatment by “Lime Stabilisation” has been a methodology used by the biosolids/wastewater treatment sector for over a century (<http://www.britishlime.org>) to treat the sludge so it can be used safely on agricultural land with reduced risk of pathogen transfer. Sludge treatment became a necessity for agricultural reuse in the UK with the introduction of the ADAS “Safe Sludge Matrix” (<http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=94737>). Lime treatment is achieved by applying a controlled dose of hydrated lime or quicklime to the organic material (in a homogeneous mixture, lime reacts with the moisture present in the material) to both increase the temperature via an exothermic reaction (70 °C+) and the pH (12) for a certain length of time in order to produce a valuable end product for safe land-based recycling, both simply and efficiently.

Specifically, the Department for Environment, Food and Rural Affairs (DEFRA) UK guidelines for sewage sludge on farmland: Code of practice for England, Wales, and Northern Ireland outlines a requirement for pH above 12 for a minimum of 2h. At these high pH values, cell membranes of harmful pathogens are destroyed while the presence of the lime in the material prevents regrowth of harmful or unhygienic organisms, facilitating longer-term storage and stability of the material [97]. The liberation of NH₃, over pH 10, is also inhibitory to many enteric bacteria [98]. However, NH₃ emissions causing monetary N losses to the farmer and the unwanted environmental effects highlighted in Section 6.3 must be taken into account if lime stabilisation is proposed as a sanitation treatment procedure for biosecure export of separated fractions.

The thermal conversion technologies and composting of the solids fraction highlighted in Section 6.2.2 may also be considered as potential treatments for biosecure solids export. Treatment via high temperature is widely reported as one of the most effective techniques for disinfection [99,100]. Anaerobic digestion both mesophilic and thermophilic can also play a significant role in pathogen reduction in whole and separated feedstock. A recent study showed that pelletisation of digestate solids eliminates the presence of *Clostridium* spp [101]. Once again, loss of volatile N through emissions of NH₃, N₂O and N₂ plus GHG emissions must be considered and potentially mitigated against if environmental sustainability criteria are to be met. Work on livestock manure [102] showed that the viable numbers of *Escherichia coli*, *Salmonella typhimurium*, *Yersinia enterocolitica*, *Listeria monocytogenes* and *Campylobacter jejuni* were reduced during mesophilic anaerobic digestion. Investigation of the survival of *Listeria monocytogenes*, *Salmonella enterica*, *Escherichia coli*, and *Campylobacter jejuni* found that none of these species was capable of survival under the thermophilic anaerobic conditions of a biogas reactor for more than 24h, indicating that the temperature and physicochemical properties of the process were effective in inhibiting their survival [103].

Further investigation into the biosecurity issues around the processing and redistribution of farm manures is required, for example to prevent the spread of bovine tuberculosis (bTB) and other livestock pathogens [9]. There are potential benefits of facilitating increased redistribution of manures, should our understanding and application of biosecurity measures be improved, but there is also a need to produce guidelines for safe

slurry redistribution. Pathogens introduced through the land spreading of animal manures can be transmitted to soils, waterways, crops, livestock and finally to the human food chain [104–106]. There is the potential to develop biosecurity guidelines using a risk assessment approach, addressing the implications of different separation methods and the biosecurity impact arising from the potential uses of resulting separated fractions [107]. This type of approach should investigate the impact of the spread and survival of pathogens to the natural environment, livestock, and humans, and would provide a comprehensive assessment of a number of manure/digestate processing methods, delivering critical processing parameters for bacterial pathogens of concern and selected animal diseases such as bTB and bovine viral diarrhoea (BVD) from manures/digestates and their separated fractions. The synthesised outputs of best practice methods and critical processing parameters for manure and digestate treatment would support farmers in minimising safety risks and in contingency planning.

7. Conclusions

Increases in agricultural productivity and production efficiencies must be coupled to reduced impacts if they are to be truly compliant with environmental sustainability in the circular economy. The idea of “climate-smart” agriculture with in-built environmental safeguards is of paramount importance. Mitigation of environmental risks to water quality through adoption of new manure and digestate management practices, including options for nutrient export off farm, are key to achieving environmentally sustainable farming systems. In NVZs, screw press and decanting centrifuge separation of manures and digestates could play a major role in facilitating the more cost-effective export of separated solids fractions for P redistribution between farms, with the added benefit of the ability to adopt low emission spreading technologies through reductions in feedstock solids content. The separated liquid fraction may be better matched to crop requirements.

Purchase and operational costs presented in this report suggest that for NVZs, screw presses offer a cost-effective technology which could be of benefit for farmers who need to employ new management practices for better P management of manures and digestates. Screw press separators remove a proportion of the DM and have some success in removing TP and TN but most of these nutrients remain in the separated liquid fraction. In comparison, decanting centrifuges have much higher separation efficiencies, effectively removing TP and have some effect in removing TN, but at considerably higher purchase and operating costs. It is likely that large dairy/beef farms or those incorporating a biogas plant with greater manure/digestate volumes to manage on P-rich land, or for example intensive pig farms with little or no land bank for nutrient spreading, should consider using a decanting centrifuge to reduce P application to farm-land. Centralised processing facilities could also make use of decanting centrifuge technology to act as processing hubs for a number of local farms within a distance that makes it economical for transport of manure/treated manure to/from the processor. Manure (or digestate) type and volumes to be managed must also be considered, as increasing volumes tend to result in a reduction in the separation cost per tonne of feedstock. Using the annual agricultural phosphate surplus from manures of 9000 t (containing 3928 t of TP) for Northern Ireland with the assumption that the remainder is taken up by crops as an example [3], data from Table 2 indicate that screw press separation could remove between 275 and 1336 t of TP and decanting centrifugation between 2043 and 3653 t of TP to the separated solid fraction. High-efficiency screw press separation could reduce P loss to water bodies by 34% and depending on separation efficiency, decanting centrifugation could achieve a reduction of between 30 and 93%. It is therefore plausible that both separation technologies could have an important impact on agricultural P loss and resultant improvement in water quality.

The management of the separated fractions is also important and ideally should be easily incorporated into standard farming practices. The two separation technologies reported produce a separated liquid fraction that can be managed using slurry tankers for land spreading. Reduced DM content means that low emission spreading technologies

can be employed resulting in improved percolation into the soil and better control of the applied N with potential for increased yield relative to untreated manure, due to higher bioavailable N content and less N loss to the atmosphere. Lower P content means that lower risk is posed to waterways when separated liquids are spread. The separated solid fraction is a stackable material which can be transported by tractor and trailer or by truck, in a manner similar to FYM and can be applied using conventional FYM spreading technology. It is rich in OM and nutrients (mainly P) meaning transport costs are lower on a nutrient content basis than those for raw manure/digestate. It is well suited to application on arable land to increase soil humus reproduction and to substitute P losses. The solid fraction could be further processed (composting, drying, pelleting, soil amendment, fuel source) improving the economic feasibility of export distances, or potentially to create a product that could be used locally. However, such processing is associated with high volatile N losses and GHG emissions which may involve the use of abatement technologies to avoid pollution swapping. N losses can also be significantly reduced by acidification of manures/digestates to pH 5.5. The export of separated solids for better P management is a possible biosecurity issue and precautions may need to be taken to reduce the risks of cross infections caused by pathogenic microorganisms. Liming is a potential sanitisation measure along with thermal processing and composting. However, loss of volatile N and GHGs must be considered and potentially mitigated against if environmental sustainability criteria are to be met.

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