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An economic analysis of anaerobic digestate fuel pellet production: can digestate fuel pellets add value to existing operations?

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ABSTRACT

Anaerobic digestion provides renewable energy through waste valorisation, but the digestate by-product is underutilised and presents a risk to water quality. Mechanical separation partitions phosphorous into the solid fraction and further processing into a fuel pellet can provide an additional source of energy and revenue. Previous economic analyses looked only at aspects of the system (e.g. operational costs solely) and the system requires further investigation to determine viability. In this paper, an economic assessment of digestate fuel pellet production at farm-scale anaerobic digestion plants was carried out. The significance of this work is to provide a comprehensive assessment of the energy, phosphorous, and economic balances involved in digestate fuel pellet production at existing anaerobic digestion plants. The aim of this paper is to determine the financial viability of digestate fuel pellet production with objectives to compare two mechanical separation technologies: screw press, and decanting centrifuge. Economies of scale hold true for digestate pellet production and the available digestate in typical UK farm-based anaerobic digestion plants ($\leq$500 kW$_e$) is insufficient for profitability, with pellet production costing from £176/t (decanting centrifuge) to £215/t (screw press), compared to a typical wood pellet sale price of £185/t. Increasing digestate quantity by collaboration of plant operators can reduce the cost of pellet production to between £95/t and £121/t, improving financial viability and increasing the profit per head of cattle by 9–20% on a typical dairy farm utilising anaerobic digestion. The system has potential to aid rural development while also protecting the environment and contributing to the diversification of energy supply.

1. Introduction

The EU's *Renewable Energy Directive* (European Commission, 2018) sets out targets for each member state to achieve 32% of gross energy from renewable sources by 2030. Renewable energy sources such as wind, solar, and marine play an important role in reducing fossil fuel dependence, however, they have drawbacks when it comes to energy storage and reliability in meeting peak demand (Connolly et al., 2016). Bio-energy does not suffer from these issues, as the products are essentially chemical energy stores. Anaerobic digestion (AD) is important as an energy conversion method as it can take an underutilised resource (e.g. agricultural slurry) and generate a gaseous combustible fuel (biogas) (Huttunen et al., 2014).

While AD has been identified as an important instrument in the transition of agriculture to a circular economy (Stanchev et al., 2020) there are drawbacks associated with its use, such as the underutilisation of the digestate by-product. Digestate is spread on agricultural land as fertiliser, but this can contribute to pollution of waterways, especially when applied to nutrient-saturated land typically found within intensive livestock farms (Gourley et al., 2015), which are often the areas in which AD plants are located. While both phosphorous (P) and nitrogen (N) lead to environmental problems, over-application of P is of particular concern, as P is often the limiting factor for eutrophication of inland waterways (Carpenter, 2008; Schindler et al., 2008). There is also an economic incentive to properly manage nutrients from livestock excreta. P loss to waterways is a waste of a valuable and finite resource. It is estimated that global P reserves will be depleted by between 20% and 100% by 2100

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Abbreviations

AD	Anaerobic Digestion
P	Phosphorous
N	Nitrogen
kW_e	Kilowatts of electricity
kW_{th}	Kilowatts of heat
AFBI	Agri-Food and Biosciences Institute
CSTR	Continuously Stirred Tank Reactor
TS	Total Solids
TP	Total Phosphorous
TN	Total Nitrogen
DM	Dry Matter

(Cordell et al., 2009; Vuuren et al., 2010). There is currently no financially viable means of chemically stripping P (Herbes et al., 2020), highlighting the need to explore alternative methods of P recovery.

As P is not incorporated in the gaseous products of AD (Vasco-Correa et al., 2018), digestate contains the same amount of P as the input feedstock. Digestate's high water content (typically >90%) means that it is economically challenging to transport it outside the locality (Herbes et al., 2020) but nutrient demand is generally not co-located with agricultural AD plants, which tend to be in intensive livestock areas with soil P levels above the agronomic optimum. The partitioning of P from digestate into a reduced-mass solid fraction has the potential to produce a transportable commodity and increase the financial viability of AD, which struggles in the absence of subsidies, particularly at farm scale (Cucchiella et al., 2019) and where there is high reliance on non-gate fee feedstock such as slurry (Smyth et al., 2010).

Waste heat from biogas combustion can be utilised to dry the solid fraction to further reduce its moisture content to ~10%, so that it can then be pelletized and thermochemically treated (combustion/pyrolysis/gasification) to generate heat, biochar, and/or syngas, and produce P-rich ash with the potential for further processing into nutrient-dense fertiliser (Nagy et al., 2018). While previous studies investigated improving the economics of AD through new sources of feedstock and feedstock pre-treatments (Zou et al., 2020), bioaugmentation (Sharmila et al., 2020), digestate processing (Herbes et al., 2020) and alternative biogas uses (Hakawati et al., 2017), to the authors' knowledge there has been limited investigation into digestate fuel pellets.

Nagy et al. (2018) showed that use of digestate for combustible pellets was more economically viable than for its use as fertiliser and that the excess heat from a biogas combined heat and power (CHP) plant was sufficient to dry the separated solids (when separated by screw press). However, the fixed annual costs were approximated to 10% of the capital investment cost (based on an equipment lifetime of 10 years), costs were not annualised, and loan interest and depreciation were not considered. Czekała et al. (2018) compared the production of digestate pellets with production of briquettes, determining that pellets were less costly to manufacture due to lower capital costs, depreciation, and electricity demand. Czekała et al. (2018) found the production cost of pellets to be £18.09/t, but the cost of digestate separation and equipment for drying was not included, and the analysis assumed that heat from cogeneration was free and did not take into account the capital cost of the digestate drying and pelletising equipment. The capital cost of a separator and belt dryer can account for >80% of total costs (Nagy et al., 2018).

Kratzeisen et al. (2010) showed that production of a pellet was possible using two different high-maize silage digestates (50% and 81% maize feedstock), resulting in pellets with a calorific value similar to softwood pellets and that the process was net positive in terms of energy. The digestates did not contain cattle slurry with only one of the samples containing 7% poultry manure, and the authors highlighted the need for further investigation into different digestate compositions.

Based on information in the literature, three areas of concern have been identified: (i) digestate is an underutilised resource that presents an environmental risk and therefore requires better management, (ii) production of a fuel pellet has been shown to be promising however, information on the economic viability of the system is limited, and (iii) operators are looking for ways to make AD more profitable, particularly for farm-based plants without significant gate-fee income. To address these issues, the novel contribution of this paper is the exploration of the energy, P, and economic balances involved in digestate fuel pellet production at a typical farm-based AD plant. The significance of this work is that it could contribute to improving the long-term economic sustainability of the sector, through providing a route for the financial viability of AD without incentives.

The analysis was based on the Northern Ireland perspective, focussing on agricultural AD and utilising data from Northern Ireland and UK AD plants. Mismanagement of P is a major factor in environmental degradation caused by agriculture (Rothwell et al., 2020) and Northern Ireland has a disproportionately large livestock agriculture industry, producing slurry and digestate with P content exceeding agronomic requirements by 20% (Rothwell et al., 2020). While the P surplus in Northern Ireland is particularly prominent, other countries with significant livestock industries will face the same issues with P surplus. New methods of management must be explored to both reduce impacts on the environment and conserve a finite natural resource that is essential for modern agriculture.

2. Materials and methods

2.1. Boundaries of analysis

A simple economic analysis was carried out to determine the potential value of the solid fraction of digestate using the annual expenditures and incomes of the pellet production phase, which was assumed to be a standalone operation on an existing AD facility (Fig. 1).

The system under investigation comprises mechanical separation of digestate into solid and liquid fractions, followed by drying of the solid fraction before pelletising into fuel pellets. The potential value of the resulting pellets was compared with commercially available softwood pellets. Although fuel pellets can be utilised via a range of technologies (such as gasification and pyrolysis), conventional combustion was assumed, as it is the typical end use for fuel pellets.

2.2. Digestate and anaerobic digestion plant parameters

A theoretical 483 kW_e (kilowatts of electricity) farm-based AD plant, requiring 16,007 t/y of feedstock (a mixture of animal slurries and energy crops), was selected for the analysis, based on typical operational plants in the UK (Table A1). Data published by NNFCC (2019) indicates that the mean capacity of farm-fed AD plants in the UK is 572 kW_e, while the majority are ≤500 kW_e (284 of 338 total). This is of the same order of magnitude of average plant sizes in France (387 kW_e) and Germany (255 kW_e). Ratings of 500 kW_e and under are popular in the UK due to incentives available, e.g. 4.27 p/kWh_e is paid in England for plants <500 kWe vs 1.54 p/kWh_e for larger installations (ofgem, 2020). In Northern Ireland plants ≤500 kW_e receive four Renewable Obligation Certificates (ROCs) per MWh_e, compared to three for 500 kW_e-5 MW_e plants and 1.8 for plants >5MW_e if registered before the scheme was closed to new entrants on March 31, 2017 (ofgem, 2019). NNFCC data shows that plants rated from 450 to 500 kW_e (the most popular size range for farm-fed plants) process between 11,200 t/y and 24,000 t/y of feedstock, with a mean value of 16,007 t/y (Table A1).

The dry matter and nutrient profiles of digestate are required to determine potential pellet yield and ash P content. The present study estimated pellet yield from digestate with a dry matter content of 6.3%, based on comprehensive monitoring data from a farm-based AD research plant in Northern Ireland (Agri-Food and Biosciences Institute (AFBI),

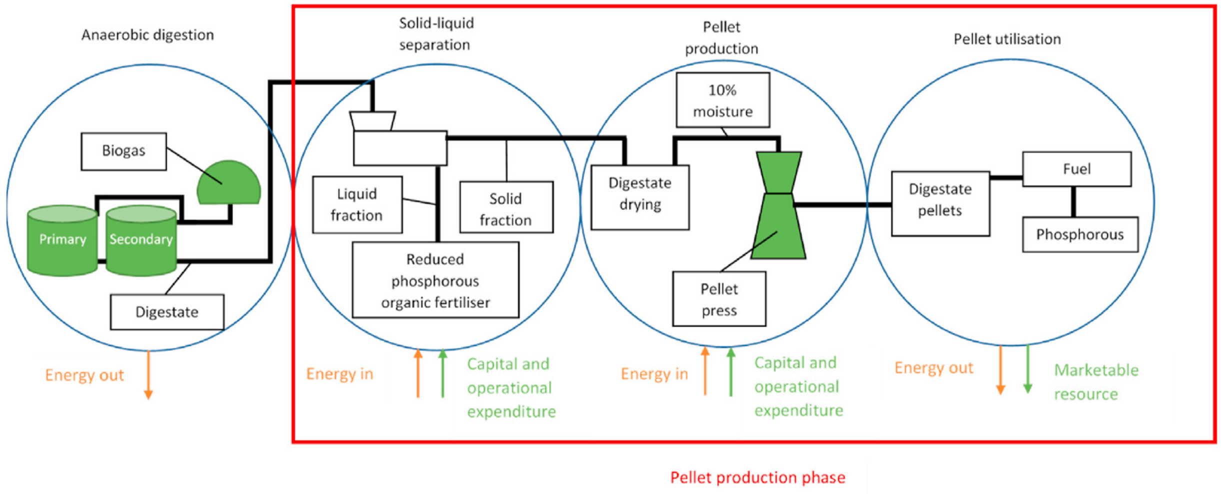

Fig. 1. Overview of pellet making process.

Hillsborough) (a 660 m^3 continuously stirred tank reactor (CSTR) operating at 39 °C with a 660 m^3 continuously stirred, non-heated and non-insulated secondary tank).

The feedstock (grass silage and cattle slurry) and plant set-up are typical for farm-based systems, although the feedstock contains a higher than average proportion of slurry. The AD process converts solid lignocellulosic biomass into biogas and water resulting in a lower dry matter content of the digestate, while pH changes result in conversion of organic nitrogen compounds to ammonia-N (Fig. 2).

The anaerobic digester at AFBI, Hillsborough, produces 600 m^3 biogas per day, consisting of 45% CO_2 and 55% CH_4. Using the ideal gas law (Equation (1)),

$$PV = nRT \tag{1}$$

Where P = Pressure (atm).

V = Volume (litres)
n = Moles of substance
R = Ideal gas constant (0.0821 L atm/(mol·K))
T = Temperature (Kelvin)

600 m^3 of biogas is equivalent to 714 kg, which is 3.17% of the daily feedstock mass. Therefore, a 483 kW$_e$ rated plant with an annual feedstock of 16,007 t/y, produces 15,499 t/y digestate. Calculation of the mass of biogas produced assumes a temperature of 20 °C when leaving the digester. While the above calculation provides a good approximation for the quantity of digestate produced, it should be noted that anaerobic digesters fed with a higher proportion of energy crops will produce a greater volume of biogas, reducing the amount of digestate available.

2.3. *Solid-liquid separation of digestate*

Screw presses and decanting centrifuges are the most common types of equipment reported in the literature for mechanical separation of digestate and slurry (Table 1). The two technologies separate based on different principles: filtration, and centrifugation respectively. Screw presses have been more widely studied, with 11 of the 12 articles on separation identified in the literature search investigating their use (Table 1). Decanting centrifuges are a more complex technology with higher capital and operational costs but achieve better efficiency in solids and P partitioning to the solid fraction (Guilayn et al., 2019). The greater efficiency results in a higher potential pellet yield and increased diversion of P from land spreading, thus offering an interesting comparison with the conventional screw press technology. Both technologies have therefore been assessed in this paper.

Data on the separation efficiency of each technology (Table 2) was

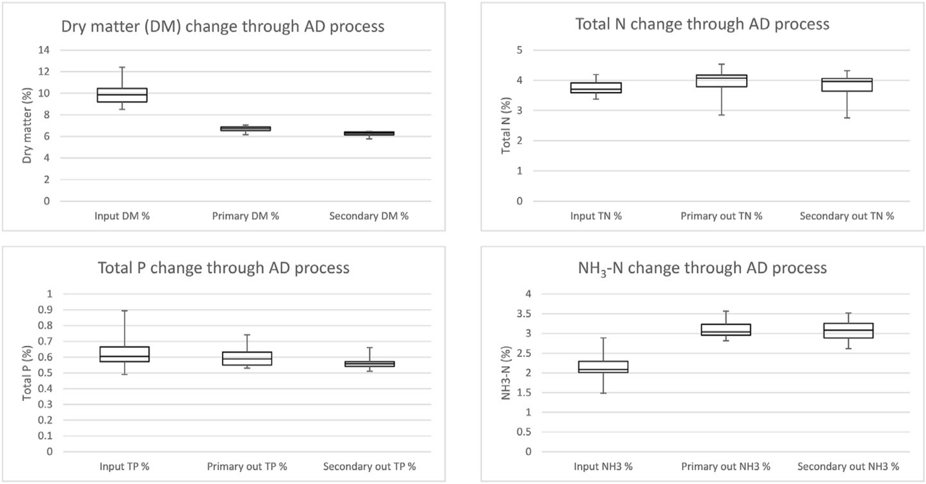

Fig. 2. Dry matter and nutrient content change throughout the anaerobic digestion process for the AFBI AD plant over a period of 19 weeks (February 13, 2018–June 29, 2018).

Table 1
Literature sources involving mechanical separation of digestate and cattle slurry.

Country	Summary of findings	Feedstock(s) investigated	Separation equipment	Citation
France	A literature study was carried out comparing various separation techniques. Two mass separation profiles were defined based on efficiencies; high-performance and low-performance. Screw press was defined as low performance while decanting centrifuge was defined as high-performance.	Digestates from cattle slurry, pig slurry, agro-industrial wastes, and sewage sludge	Screw press, plane screen, rotary drum, filter press, vibrating screen, decanting centrifuge	Guilayn et al. (2019)
USA	Screw press and centrifuge both achieve higher separation efficiencies for total solids than for phosphorous and nitrogen. Centrifuge performs better than screw press.	Dairy manure and digestate	Screw press, decanting centrifuge	(Aguirre-Villegas et al., 2019)
Canada	Comparison of the ammonia emissions from the liquid fractions of slurry and digestate. Digestate has higher ammonia content and therefore emissions but correcting for ammonia content when spreading can reduce impact. Separated liquid from AD has higher total nitrogen content than separated liquid slurry due to ammonia formation in AD process	Dairy manure and dairy manure based digestate	Screw press	(Evans et al., 2018)
Italy	Separated liquid fractions of digestate have a higher ammonium content and provide more readily available nitrogen to crops when used as fertiliser. The majority of ammonium-N is partitioned to liquid fraction.	Digestate from a cattle slurry and maize mixture	Screw press	(Cavalli et al., 2017)
Italy	Majority of TAN partitioned to liquid fraction. Roller press produced a solid fraction of 15.82–17.02% dry matter	Digestate from dairy farm (90% slurry, 10% corn silage)	Roller press	(Perazzolo et al., 2017)
Italy	While separation produces a high solids fraction (21.2% dry matter) the majority of the total solids are still present in the liquid fraction (67% of solids present in unseparated digestate)	Digestate from 13 different full-scale digesters including: pig slurry + energy crops, cow slurry + energy crops, and energy crops + milk whey.	Screw press	Tambone et al. (2017)
France	Solid liquid separation digestate from co-digestion plants. Liquid fraction contains high proportion of nitrogen. Nitrogen is mainly present in suspended particles and dissolved matter with just 0.4–8.5%, and 0–13% present in fine colloids and course colloids respectively. Separation method determines physical and chemical characteristics of resulting fractions. Decanting centrifuge is more efficient than screw press and vibrating screen.	Digestates from 11 different full-scale digesters including: sludge, cow manure, crop residues, fruits and vegetables, pig manure.	Screw press, centrifugation, vibrating screen	(Akhiar et al., 2017)
USA	Screw press separation of digestate resulted in solid	Cattle slurry Digestated cattle slurry	Screw press	(Holly et al., 2017)

(continued on next page)

Table 1 (*continued*)

Country	Summary of findings	Feedstock(s) investigated	Separation equipment	Citation
	fraction of 38.1% dry matter			
Italy	Screw press produced a drier solid fraction than roller press (22.68% vs 14.9% dry matter), even when acting on a lower dry matter digestate (5.09% vs 6.26%). Results are not directly comparable due to different feedstocks.	'Digestate C' = 90% cattle slurry, 10% corn silage 'Digestate P' = 35% pig slurry, 50% cattle slurry, 5% poultry and cattle manure, 10% other biomass	Screw press (digestate P), roller press (digestate C)	(Perazzolo et al., 2015)
Austria	Screw press requires less maintenance and care than rotary screen. Rotary screen must regularly be cleaned. Rotary screen not appropriate for high fibre energy feedstock. The authors state the screw press achieved a higher degree of separation however data from both pieces of equipment was pooled in their analysis.	Two different digestates. Digestate 1 composed of cattle and pig slurry with energy crops and digestate 2 composed of cattle slurry, poultry manure and waste with energy crops.	Screw press, rotary screen	(Bauer et al., 2009)
UK	Separation of slurry resulted in 15% of the total mass partitioned to the solid fraction. The resulting solid fraction comprised 24.8% dry matter. The solid fraction had a total ammonia content of 85 mg kg^{-1} while the liquid fraction had a content of 552.5 mg kg^{-1}	Cattle slurry	Screw press	(Fangueiro et al., 2008; Payscale.com, 2020)
Denmark	Centrifugation is more efficient than mechanical screen separation in removal of phosphorous and dry matter. Decanting centrifuge is more expensive with a cost of £2.21 t^{-1} vs £0.44 t^{-1} for mechanical screen separators.	Pig slurry and cattle slurry	Tilted plane screen, two-stage separator, screw press, flat-belt separator, decanting centrifuge	Moller et al. (2000)

Table 2
Separation efficiencies of decanting centrifuge and screw press.

	Screw press		*Decanting centrifuge*	
Separation efficiencies	Solid	Liquid	Solid	Liquid
Mass separation efficiency (%)	10.0	90.0	12.6	87.4
Dry matter separation efficiency (%)	32.5	68.5	50.9	49.1
Nitrogen separation efficiency (%)	13.1	86.9	24.6	75.4
Phosphorous separation efficiency (%)	28.4	71.6	63.9	36.1
Reference	Tambone et al. (2017)		Gilkinson and Frost (2007)	

obtained from published reports (Gilkinson and Frost, 2007; Tambone et al., 2017). These efficiencies were combined with dry matter and nutrient data (Fig. 2) to estimate the proportion of digestate separated into the solid fraction. Reporting of digestate separation by decanting centrifuge is limited; slurry separation efficiencies are therefore used (Table 2) due to similarities in material physical properties and origin.

2.4. Drying of solid fraction

The belt dryer system was chosen as it is continuous and separated solids can be fed directly, reducing requirement for the wet solids storage needed in a batch drying system. A 483 kW_e rated AD plant with a 75.9% efficient CHP engine (30.8%/45.1% electricity/heat efficiency) (DECC, 2008) will produce approximately 707 kW_{th} of heat or 6.2 GWh_{th}/yr. Mesophillic AD plants have a parasitic heat demand of 14% (Smyth et al., 2009) leaving 5.3 GWh_{th} of useable heat. Belt drying requires approximately 1 MWh_{th} per tonne of water removed (Turley et al., 2016), meaning that the CHP engine at a 483 kW_e plant can remove 5328 t/yr of water from the separated solids. For the plant analysed, a 400 kW_{th} belt dryer is sufficient (this size of dryer has an electrical demand of 7 kW_e and the capacity to remove 9600 kg of water per day (new-eco-tec.com, 2020)). In the UK and Ireland, heat from AD CHP plants is underutilised, so drying of digestate solids is not expected to displace other uses.

2.5. Pelletisation of solids

Pelletisation of solids was considered over briquetting as it has been shown to be less costly (Czekała et al., 2018). Pellet press technology is used in various applications from feed production to biomass fuel production and is an established technology. Previous studies showed pelletisation of digestate is possible (Czekała et al., 2018; Kratzeisen et al., 2010; Nagy et al., 2018) and ongoing research by the authors of this paper has produced digestate pellets without the requirement of additional binders. The pellets in our reported work were made from digestate produced at AFBI (Hillsborough, Northern Ireland) using a Farm Feed Systems Minipress (Farm Feed Systems Ltd., Cinderford, Gloustershire, United Kingdom) with a 6 mm pellet die. Calorific value was determined as 16.9 MJ/kg using a PARR6200 bomb calorimeter with 1108 oxygen bomb (Scientific & Medical Products, Stockport, UK).

2.6. Determining fuel pellet economic value

Pellets produced from digestate at AFBI have a similar energy content to wood pellets (16.9 MJ/kg for AFBI pellets vs 17.2 MJ/kg for softwood (Balcas Energy, 2020)). Commercial wood pellets retail for between £185/t and £206/t depending on the quantity purchased (Balcas Energy, 2020). In addition to the fuel value of the pellets, the ash contains P previously partitioned in the solid-liquid separation phase. Pellets produced from AFBI digestate have an ash content of 11.18% (O. De Priall, Ulster University, personal communication, 24 January 2020) with an expected P content of between 5.9% and 8.5%, for screw press and decanting centrifuge separated solids respectively, which is comparable to the P content of rock phosphate (Vuuren et al., 2010). Rock phosphate price varies over time, with a 10-year high of £130.48/t and low of £55.22/t (10-year average = £83.27/t); the cost used in this paper is the value as of July 2020, £59.90/t (IndexMundi, 2020).

2.7. Economic analysis

The economic analysis looked at all incomes and costs associated with the pellet production system. Income was determined by calculating the mass of pellets produced and by using the cost of commercially available softwood pellets (Balcas Energy, 2020). The quantity of P obtained in the ash from combustion was calculated and the price of rock phosphate (IndexMundi.com, 2020) used to determine its value.

Both capital and operational costs were taken into account. Operational costs were calculated from electrical energy requirements (separation, drying, and pelletising). Heat energy for drying of the solids was assumed to be provided by the biogas CHP engine and is not included in the cost calculation, in line with Czekala et al. (2018), as there is often not a high demand for heat in agricultural AD settings. Operational energy inputs were taken from experimental and monitoring data from the AD plant and trial pelletising facility in AFBI, supplemented by information in the literature (Table 1). Electricity from the CHP plant that would have otherwise been exported was assumed to be used to meet the parasitic demand; the lost revenue was taken as the electricity cost (assuming the English export tariff of 5.24 p/kWh$_e$ (ofgem, 2020)).

Capital costs were obtained from recent equipment purchases and quotes obtained by AFBI and were annualised using Equation (2) (SAC consulting, 2018).

$$R = \frac{\left[P(1+r)^N r\right]}{\left[(1+r)^N - 1\right]} \tag{2}$$

where R = annual capital cost (£/y); r = rate of return (5%); P = principal (£); and N = lifetime of equipment.

A median value of 5% (Purdue University, 2017; SAC consulting, 2018) was chosen for the rate of return, which is in line with market values and those cited in the literature (Bolzonella et al., 2018; Smyth et al., 2010). 10 years was chosen for the depreciation period, as this is the typical lifetime of agricultural equipment.

3. Results and discussion

3.1. Solid-liquid separation of digestate

Literature and specific reporting on separation of digestate by decanting centrifuge is lacking, therefore data on cattle slurry separation (with similar dry matter content) was presented in this case. Studies comparing both technologies separating cattle slurry show similar trends (Hjorth et al., 2009; Moller et al., 2000), therefore the same relationship was assumed for digestate. The decanting centrifuge is more effective at partitioning both total solids (TS) and total phosphorous (TP) compared to the screw press (50.9% TS and 63.9% TP compared to 32.5% TS and 28% TP respectively) (Fig. 3). Total nitrogen (TN) partitioned to the solid fraction is greater with the decanting centrifuge than the screw press: 24.6% vs. 13%. Moller et al. (2000) explained that the increased N separation efficiency was due to the centrifuge's ability to partition fine

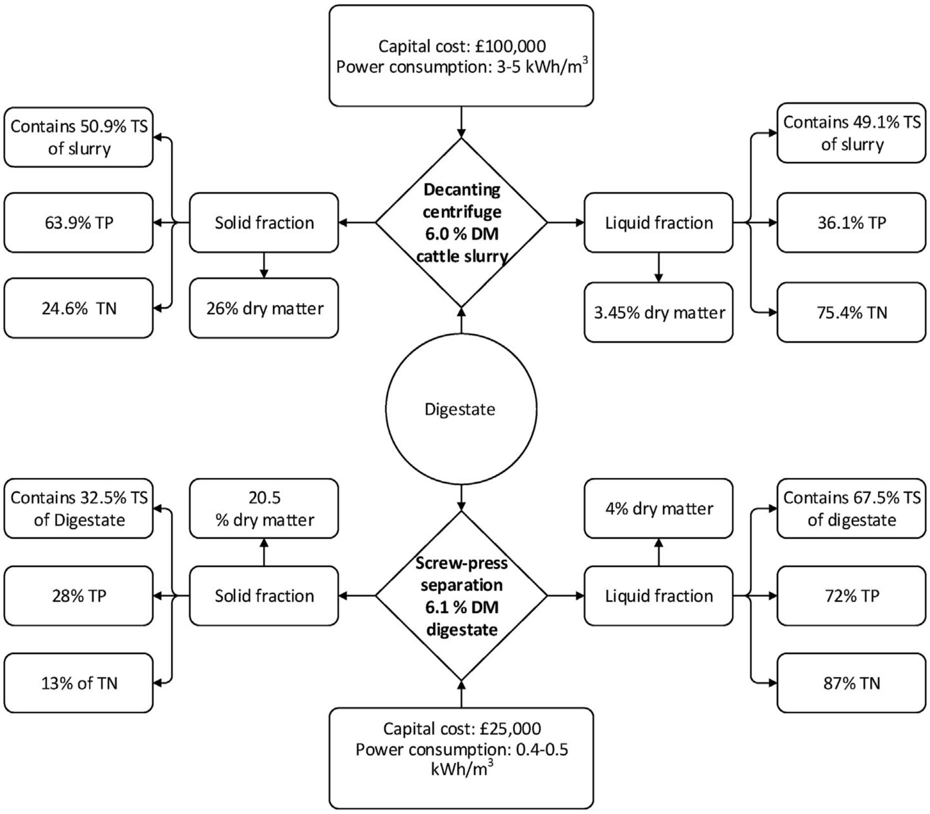

Fig. 3. Nutrient separation efficiency for digestate processing by screw press and decanting centrifuge.

solids in the solid phase. During separation by screw press, particles smaller than the screen size pass through to the liquid fraction. Screw press screen size varies (from 0.5 to 3 mm) depending on the particular separator, while a decanting centrifuge has been shown to partition particles as small as 0.02 mm into the solid fraction (Moller et al., 2000). These small particles contain organic nitrogen compounds, while the majority of the nitrogen in the liquid fraction is inorganic, dissolved, ammonia nitrogen (NH_3–N).

Dry matter content of the separated fractions also varies depending on separation technology. The decanting centrifuge produces a drier solid fraction (25.8% DM compared to 20.5% DM), which accounts for a greater proportion of the original material's mass: 10% (screw press) vs 12.6% (decanting centrifuge) (Table 2). The greater separation ability is reflected in the higher operational costs of the decanting centrifuge. A decanting centrifuge requires approximately 3.5 kWh_e of electricity to separate 1 m^3 of digestate while a screw press requires just 0.5 kWh_e. In the screw press scenario, approximately 1119 t of water needs to be removed annually, requiring 1119 MWh_{th}; using a belt dryer the energy requirement is 19,583 kWh_e. In the decanting centrifuge scenario 1400 t of water needs to be removed requiring 1400 MWh_{th} and 24,493 kWh_e annually.

3.2. Pellet energy balance and yield

Despite the higher operational costs of a decanting centrifuge, the net energy is greater than for the screw press (78.2 MJ/t vs. 51.7 MJ/t) owing to the higher TS obtained through this separation method (Fig. 4). Energy content of digestate pellets has previously been reported as 15 MJ/kg at 10% moisture (Kratzeisen et al., 2010); however, the authors' experimental research on digestate (89% slurry, 11% grass silage) shows an energy value of 16.9 MJ/kg at 10% moisture (Cathcart et al., 2020).

Utilising the separation efficiencies of each technology and the dry matter of the digestate feedstock, the annual pellet yield at 10% moisture content was determined. as 353.3 t/y for the screw press and 553.3 t/y for the decanting centrifuge.

3.3. Phosphorous content of pellets

A proportion of the P in digestate is partitioned into the solid fraction and subsequently the ash (Fig. 5). Fuel pellets from the digestate yield ash had 0.15 kg and 0.37 kg of P per tonne of digestate for the screw press and decanting centrifuge respectively. The concentration of P in the ash is equivalent to the P content of rock phosphate (4–20%) at 5.9% for screw press and 8.5% for decanting centrifuge. Rock phosphate was valued at ₤59.90/t in July 2020 (IndexMundi, 2020). For a 483 kW_e anaerobic digester producing 15,500 tonnes of digestate annually, the combustion of fuel pellets could result in between 41.7 t/y (screw press) and 65.3 t/y (decanting centrifuge) of ash with a potential market value of £2498 to £3911. This value could be integrated to the sale price of the pellets, with the assumption that the consumer would make use of the ash, or worked into a buy-back scheme where the ash is collected by the pellet producer and sold or processed separately.

3.4. Fuel pellet economic balance

In the screw press scenario, the cost of production outweighs the potential revenue from pellet sales (Table 3). Despite the higher capital cost of the decanting centrifuge, (approximately four times more

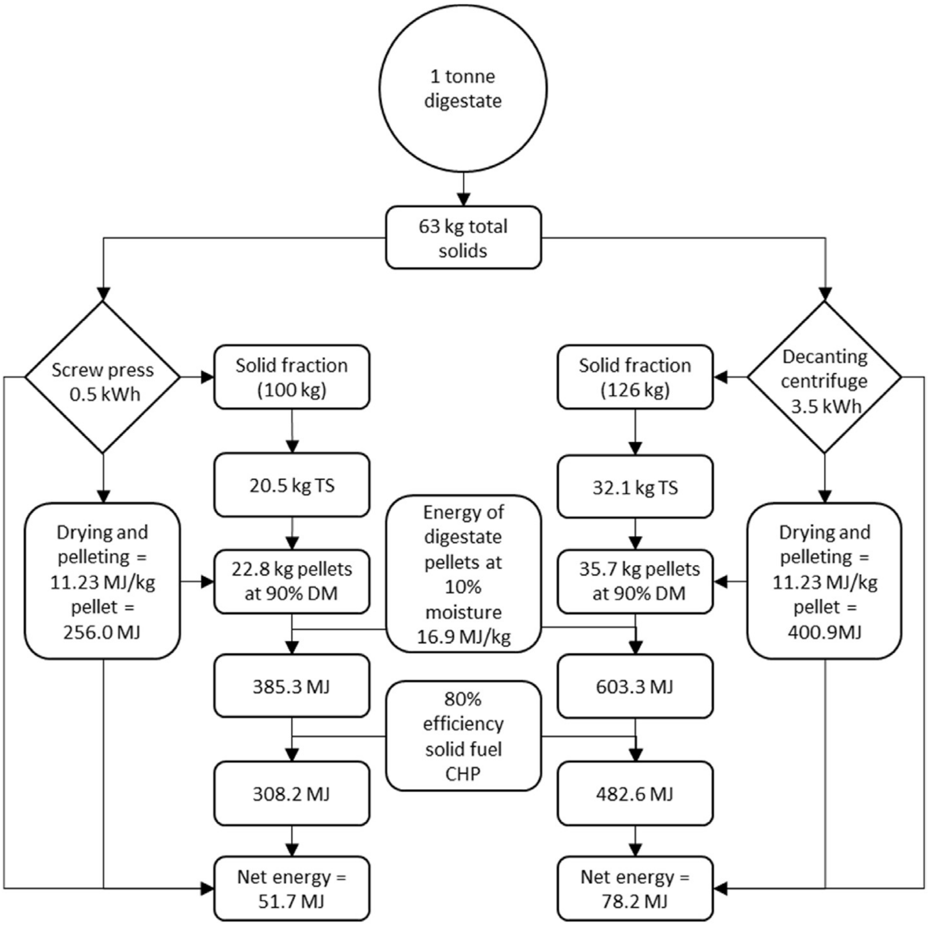

Fig. 4. Combustible pellet energy balance for processed digestate solids, comparing two separation methods followed by drying and pelletising.

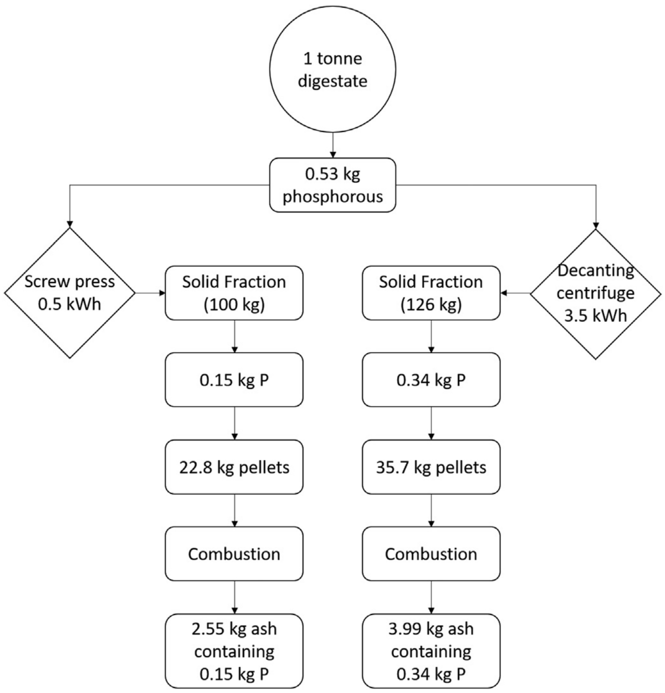

Fig. 5. Phosphorous content of digestate pellet ash derived from two different separation pathways.

Table 3
Digestate pellet formation economic analysis: comparison of screw press with decanting centrifuge.

Capital costs	**Total cost (£)**	***Screw press***	***Decanting Centrifuge***
		Annualised cost (£/y)	**Annualised cost (£/y)**
Screw press	25,000	3238	
Decanting centrifuge	100,000		12,950
Drying belt	258,000	33,412	33,412
Pellet press	29,000	3756	37,56
Total capital costs		40,405	50,118
Operating costs			
Depreciation		31,200	38,700
Separation energy (kWh$_e$)		7750	54,247
Separation cost (5.24 p/ kWh)		406	2843
Drying electrical energy (kWh$_e$)		19,583	24,493
Drying electrical cost		1026	1283
Pellet press energy (kWh$_e$)		53,007	82,999
Pellet press cost		2778	4349
Total operating costs		35,410	47,175
Total annual costs		75,815	97,293
Income †			
Pellet production cost (£/t)		215	176
Pellet sales £185/t		65,376	102,365
Pellet sales £206/t		72,797	113,985
Profit at £185 sale price		−10,439	5071
Profit at £206 sale price		−3018	16,691
Phosphorous value of ash (£)		2498	3911

expensive) there is the potential to make an annual profit of between £5071 and £16,691 (Table 3). This is due to the greater solids separating ability of the decanting centrifuge, which can lead to the production of 56% more pellets than the screw press (553 t/y vs 353 t/y). The greatest cost in each scenario comes from the drying belt at £258,000, annualised to £33,412. This equates to 35% of the total cost for the decanting centrifuge scenario vs. 45% for the screw press scenario.

While the system does not provide profit, the redirection of P from saturated land represents a non-market co-benefit which has the potential to reduce pressure on deteriorating water quality and abstracted water treatment. While not providing direct monetary gain to farmers and AD operators, there has been legislative action by European member states (Amery and Schoumans, 2014) to reduce water pollution by restricting the application of organic fertiliser in areas of concern. This system may assist farmers in meeting fertiliser limits by reducing the P:N ratio of digestate, allowing spreading to continue without risk of fines and/or prosecution and the continuation of intensive agriculture. It should be noted that the AD feedstock in the analysis is not typical (89% slurry and 11% grass silage). Commercial AD plants typically have a higher energy crop to slurry ratio and may in turn produce digestate with a higher dry matter content. A higher pellet yield would be expected in this case, potentially making the economics of the system more favourable.

3.5. *Reducing pellet production cost*

The cost of separation and pelletisation represents just 4.3% and 7.7% of the total annual cost for the screw press and decanting centrifuge scenarios respectively. The biggest contributor to cost in each scenario is the annualised capital cost and depreciation of the drying belt. This comprises 61% of the annual cost in the decanting centrifuge scenario and 78% in the screw press scenario. By increasing throughput, the cost per tonne of pellet can be reduced. Collaboration between several AD operators to increase feedstock availability was therefore explored to determine the effect on profitability.

3.5.1. *Increasing available feedstock*

Increasing the amount of available feedstock has the potential to raise the profitability of the system by increasing pellet quantities, and therefore potential income of the system. The capital costs remain the same but the rise in potential income accelerates more quickly than operational costs as feedstock quantity grows. Doubling the available feedstock from ~16 kt/y to ~32 kt/y reduces the pellet production price to £96/t and £113/t for the decanting centrifuge and screw press scenarios respectively (Fig. 6). Increasing available feedstock may be achieved by a centralised pellet production system in a collaboration involving several AD operators. The NNFCC database (NNFCC, 2019) was consulted and a cluster of three farm-fed AD plants within a 2 km radius in County Tyrone, Northern Ireland, was chosen. The on-road distance between plants 1 and 2 is 1.3 km and between plants 2 and 3 is 3.4 km, with plant 2 as the central plant where the pelletising facility was assumed to be situated.

Plants 1, 2 and, 3 have an annual feedstock of 18,000 t, 17,650 t and 16,000 t respectively for a combined total of 51,650 t/y (NNFCC, 2019). Based on Fig. 6, the cost of pellets would be approximately £75/t (screw press) or £65/t (decanting centrifuge). The costs associated with transport of digestate to the central plant were estimated using transport cost data adapted from Nolan et al. (2012). The costs in Nolan et al. (2012) are based on the assumption that a contractor handles the transport of digestate off-site and subsequent spreading as well as the return journey with an empty tank. The return journey is assumed to take less time as the tank is empty and less mass is being transported. The scenario in the current work is slightly different, in that the digestate is offloaded to a receiving tank by vacuum pump and replaced with the separated digestate liquid fraction for the return journey. Although the full load on the return journey would increase the time required, field spreading is avoided, and the Nolan et al. (2012) costs were therefore considered to be a reasonable approximation. This brings the pellet production cost for decanting centrifuge to £95/t and screw press to £121/t, with potential annual profits of £160 k-£198 k and £72 k-£96 k for the decanting

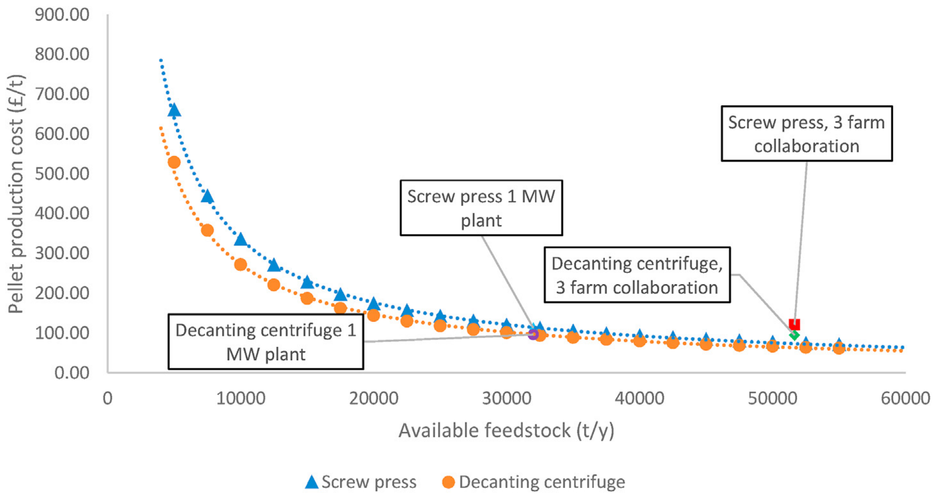

Fig. 6. Effect of feedstock availability on pellet production price.

centrifuge and screw press respectively (Table 4). Both methods to increase feedstock availability reduce the cost of pellets by approximately 45% (Fig. 6).

3.6. *Added value to farms – economic and ecosystem services*

In Northern Ireland farm-fed AD plants are typically operated by dairy farmers with cattle slurry comprising a significant proportion of the feedstock. Profitability of the system can be presented as added value per cow in such cases. Large dairy farms in Northern Ireland, where AD plants are likely to be located, have an average herd size of 175 cows (DAERA, 2019), giving a total of 525 for the above three-farm collaboration. Taking the conservative sale price of £185/t in the screw press scenario, this equates to an additional £137 profit per cow per year (£71,888/525 = £136.93). The decanting centrifuge scenario generates an additional £305 profit per cow per year (£160,265/525 = £305.26). The average annual profit generated by a dairy cow in Northern Ireland is £1514 (DAERA, 2019) therefore the screw press scenario adds 9% per cow while the decanting centrifuge scenario adds 20%.

In addition to economic benefits, digestate fuel pellet production removes P from the agricultural system leading to reduced stress on the environment and downstream activities such as water treatment plants, inland fisheries, and tourism. AD operators have a duty to protect their surrounding environments by reducing the potential for run-off of nutrients. To date, the means of controlling diffuse pollution associated with digestate and other wastes has consisted of government legislation and fines, with regulations detailing when and where digestate must not be applied (The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations, 2018, Nutrients Action Programme Regulations (Northern Ireland), 2019). Meanwhile, renewable energy advancements have been incentivised by governments through grants and tariff schemes. This leads to a situation where AD plants are incentivised for renewable energy generation and simultaneously discouraged due to the by-products produced. By moving away from linear thinking to sustainable use of resources in a circular economy, digestate fuel pellet production can provide a renewable energy source, alleviate water pollution, and bolster farm incomes.

Production of fuel pellets helps to diversify energy supply and reduce dependence on fossil fuels which can be especially important for countries with non-diversified energy mixes. The European Green Deal (European commission, 2019) provides an action plan to achieve net zero emissions of greenhouse gases by 2050 while decoupling economic growth from resource use. It has been proposed that the European Green Deal provides the opportunity to strengthen energy security across Europe by encouraging alternative fuel uses and moving away from monolithic suppliers of fossil fuels (Morningstar et al., 2020). A movement towards increased biogas production, to bolster natural gas reserves and reduce reliance on imports, would see an increase in digestate quantities and potential for fuel pellet production.

Table 4
Economics of three-plant collaboration (three AD plants serving one pelletising facility) for the production of digestate fuel pellets using two different separation technologies.

Technology	*Screw press*	*Decanting centrifuge*
Available digestate (t/y)	50,012	50,012
Pellet output (t/y)	1140	1785
Transport cost plant 1 to plant 2 (1.3 km distance, 18,000 t/y)	19,872	19,872
Transport cost plant 3 to plant 2 (3.4 km distance, 16,000 t/y)	34,000	34,000
Total annual cost	139,061	170,037
Pellet production cost (£/t)	122	95
Pellet sales (£185/t)	210,949	330,302
Pellet sales (£206/t)	234,895	367,796
Profit at £185/t sale price	71,888	160,265
Profit at £206/t sale price	95,833	197,759

The United Nations 2030 Agenda for Sustainable Development (United Nations, 2021) sets out 17 goals with the aim of tackling climate change and preserving the environment while improving economic growth and opportunities around the world. The current work addresses directly, and indirectly, 7 of the 17 goals: ‘Affordable and Clean Energy’, ‘Clean Water and Sanitation’, ‘Decent Work and Economic Growth’, ‘Industry, Innovation and Infrastructure’, ‘Responsible Consumption and Production’, ‘Climate Action’, and ‘Life on Land’.

3.7. *Comparisons with previous research and limitations*

Previous research determined the cost to produce pellets at between £76.32/t and £77.78/t (Nagy et al., 2018; Shirani and Evans, 2012), which is considerably lower than the current findings. Another research group found the cost to be as low as £18.09/t (Czekała et al., 2018). The current research goes beyond previous published material by carrying out a comprehensive analysis which takes into account the annualization of capital costs, a factor omitted from other articles. Only three articles were found which investigated the economic feasibility of pellet production: Nagy et al. (2018), Shirani and Evans (2012), and Czekala et al. (2018).

Nagy et al. (2012) based their study on a plant producing 66,000 t/y of digestate, which means their expected costs should be lower than the current study. However, their economic analysis did not take into account the annual capital costs of purchasing the equipment necessary for pellet production (separator, drying belt, pellet press) and instead only used a linear depreciation of 10%. The present study accounts for the need for a loan to purchase the equipment.

Shirani and Evans (2012) explored pellet production at a food waste AD plant with a feedstock of 4000 t/y producing 500 t of separated solids and 156 t of pellets annually. The capital expenditure was estimated at just £129,600 and the total operational cost was £12,345/yr. They estimated pellet production cost at £79.08/t but did not account for the annualization of capital costs in their calculation.

Czekała et al. (2018) based their study on a <2 MW rated plant producing 16 t of separated solids each day. Similar to the present study, Czekała et al. (2018) did not account for the cost of heat to dry the solid faction, as the heat from CHP operation was used for this purpose. The authors of the paper indicate that drying is carried out in a drying hall, rather than by using specific drying equipment (such as the belt drying in the present study). This may represent a bottle-neck in the process, as drying of solids is likely to need mechanical aid. Commercial wood pellet production sites require belt dryers and the water removal requirement for wood is less than that of separated digestate solids.

Czekała et al. (2018) included the cost of bagging the pellets, to 15 kg capacity bags, in their analysis which may be unnecessary. The additional step is likely to be included on the assumption that the pellets would be sold in a similar manner to wood pellets for domestic use. The authors would question this assumption based on the source of the pellet feedstock, its high nitrogen content (Fig. 2), and the likely poor emissions performance which would rule out their use in a domestic setting. Preliminary data from ongoing combustion trials at AFBI show that the NO_x emissions produced by digestate pellets is 6–7 times that of wood pellets, meaning emission scrubbing is likely to be required.

While the economic analysis carried out establishes that fuel pellet creation from digestate has potential to add value to anaerobic digestion, there are unknown factors that require investigation. The P left in the ash must be analysed to determine bioavailability as further processing is likely to be needed to facilitate its use as a fertiliser. Research is also needed to confirm the ash content of fuel pellets produced by decanting centrifuge, and to explore the impact of digestate dry matter variability on fuel pellet quality.

4. Conclusions

This paper is the first in the literature to provide a comprehensive analysis of the energy, P and economic balances associated with production of fuel pellets from anaerobic digestate. The process energy balance is positive and is economically viable provided there is enough feedstock available to make sufficient use of the equipment. With the cost of current technology, pellet production at small scale (≤500 kWe AD plant) appears too expensive, but in certain areas where AD operators are clustered together, the increased quantity of digestate available can make the process viable, with profits up to ~£200,000/yr achievable in the best case scenario. The process can effectively improve the profitability of dairy cows by 9–20% depending on the technology used. In addition to potentially providing an income stream, processing of digestate can help to disrupt the flow of P to agricultural land, and therefore waterways, by locking it in a nutrient dense form (ash) which is more easily removed from the specific agri-land base on which it is contributing environmental damage. The benefits of the system extend beyond financial gains to the operator, as downstream processes such as water treatment plants benefit from reduced strain. A whole-system approach is required when tackling energy generation and waste management in agriculture, and utilisation of digestate as a fuel can help to bridge the gap between these currently disparate issues. Additionally, a new form of solid biomass can help to improve energy security and promote rural development through diversification of farmers' businesses.

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Declarations of competing interest

None.

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Appendix

Table A.1
Anaerobic digestion generation capacities and associated feedstock (450–500 kWe) (NNFCC, 2019)

County	Name	Capacity KW_E	Feedstock	Total feedstock (T/Y)
Lancashire	Hillam Lane Farm	461	Cattle slurry, poultry manure, grass silage	12,000
East Wales	Pancross Farm	482	cattle slurry, waste cattle feed, maize silage	12,000
Cambridgeshire	Somerset farm	475	Cattle manure and vegetable outgrades	20,000
West & South of Northern Ireland	Holly Park Farm	500	Grass silage and cattle slurry	16,875
West & South of Northern Ireland	IB Energy	500	Grass silage and cattle slurry	15,000
West & South of Northern Ireland	Riverview Farms	500	Cattle slurry and energy crops	18,000
West & South of Northern Ireland	Crossnenagh road AD	500	Grass silage and cattle slurry	11,750
West & South of Northern Ireland	Deerpark Road AD	500	Grass silage and cattle slurry	17,650
Cheshire	Aston Lowe Hall Farm	475	Cattle slurry and waste cattle feed	17,000
Highlands and Islands	Wester Kerrowgair Farm	450	Cattle manure, grass silage, wholecrop rye	20,650
Durham	Hope House Farm	500	Cattle manure and grass silage	16,000
Shropshire	Warthill Farm	475	Cattle manure and grass silage	13,000
Cumbria	Kirkbride House Farm	470	Energy crops and animal slurries	16,000

(*continued on next column*)

Table A.1 (*continued*)

County	Name	Capacity KW$_E$	Feedstock	Total feedstock (T/Y)
Wiltshire	Sharcott Pennings Farm	482	Animal Slurry and energy crops	15,000
Lancashire	Wilcross Farm	499	Grass silage, wholecrop silage and cattle slurry	18,000
Devon	Hogsbrook Farm	465	Energy crops and animal manure	24,000
Southwestern Scotland	Charlesfield Farm	475	Grass silage, maize silage and animal manure	11,200
Devon	Hartnoll Farm	483	Energy crops and animal manures	14,000
Average		483		16,007

References

Amery, F., Schoumans, O.F., 2014. Agricultural Phosphorus Legislation in Europe. Merelbeke, Flanders Research Institute for Agriculture, Fisheries and Food, ISBN 9789040303531, p. 45.

Balcas Energy, 2020. Balcas energy [WWW document]. https://balcasenergy.com/online-shop/bulk-wood-pellets/. (Accessed 14 February 2021).

Carpenter, S.R., 2008. Phosphorus control is critical to mitigating eutrophication. Proc. Natl. Acad. Sci. U. S. A. 105, 11039–11040. https://doi.org/10.1073/pnas.0806112105.

Cathcart, A., Smyth, B.M., Lyons, G., Murray, S.T., Rooney, D., Johnston, C.R., 2020. Adding value to anaerobic digestion through by-product valorisation. Engineering the Energy Transition Conference, Belfast. 26th-28th February 2020.

Connolly, D., Lund, H., Mathiesen, B.v., 2016. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew. Sustain. Energy Rev. 60, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025.

consulting, S.A.C., 2018. Farm Management Handbook 2018/2019, Farm Management Handbook, 23/02/2021. https://www.fas.scot/downloads/farm-management-handbook-2018-19/.

Cordell, D., Drangert, J.O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19, 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2019. An economic analysis of biogas-biomethane chain from animal residues in Italy. J. Clean. Prod. 230, 888–897. https://doi.org/10.1016/j.jclepro.2019.05.116.

Czekała, W., Bartnikowska, S., Dach, J., Janczak, D., Smurzyńska, A., Kozłowski, K., Bugała, A., Lewicki, A., Cieślik, M., Typańska, D., Mazurkiewicz, J., 2018. The energy value and economic efficiency of solid biofuels produced from digestate and sawdust. Energy 159, 1118–1122. https://doi.org/10.1016/j.energy.2018.06.090.

DAERA, 2019. Statistical Review of Northern Ireland Agriculture 2019. DAERA. https://www.gov.uk/government/statistics/statistical-review-of-northern-ireland-agriculture-2019. (Accessed 5 February 2021).

DECC, 2008. CHP technology. Department of energy & climate change [WWW document]. https://www.gov.uk/government/publications/combined-heat-and-power-chp-technology. (Accessed 14 February 2021).

European commission, 2019. A European green deal [WWW document]. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. (Accessed 27 February 2021).

Gilkinson, S., Frost, P., 2007. Evaluation of mechanical separation of pig and cattle slurries by a decanting centrifuge and a brushed screen separator 1. Agri-Food and Biosciences Institute [WWW document] 28–29. https://www.afbini.gov.uk/publications/reports-evaluation-mechanical-separation-pig-and-cattle-slurries. (Accessed 14 February 2021).

Gourley, C.J.P., Aarons, S.R., Hannah, M.C., Awty, I.M., Dougherty, W.J., Burkitt, L.L., 2015. Soil phosphorus, potassium and sulphur excesses, regularities and heterogeneity in grazing-based dairy farms. Agric. Ecosyst. Environ. 201, 70–82. https://doi.org/10.1016/j.agee.2014.12.010.

Guilayn, F., Jimenez, J., Rouez, M., Crest, M., Patureau, D., 2019. Digestate mechanical separation: efficiency profiles based on anaerobic digestion feedstock and equipment choice. Bioresour. Technol. 274, 180–189. https://doi.org/10.1016/j.biortech.2018.11.090.

Hakawati, R., Smyth, B.M., McCullough, G., de Rosa, F., Rooney, D., 2017. What is the most energy efficient route for biogas utilization: heat, electricity or transport? Appl. Energy 206, 1076–1087. https://doi.org/10.1016/j.apenergy.2017.08.068.

Herbes, C., Roth, U., Wulf, S., Dahlin, J., 2020. Economic assessment of different biogas digestate processing technologies: a scenario based analysis. J. Clean. Prod. 255 https://doi.org/10.1016/j.jclepro.2020.120282.

Hjorth, M., Christensen, K.V., Christensen, M.L., Sommer, S.G., 2009. Review article Solid – liquid separation of animal slurry in theory and practice. Agron. Sustain. Dev. 30, 153–180. https://doi.org/10.1051/agro/2009010.

Huttenen, S., Manninen, K., Leskinen, P., 2014. Combining biogas LCA reviews with stakeholder interviews to analyse life cycle impacts at a practical level. J. Clean. Prod. 80, 5–16. https://doi.org/10.1016/j.jclepro.2014.05.081.

IndexMundi, 2020. Rock phosphate monthly price [WWW document], 8/6/2020. https://www.indexmundi.com/commodities/?commodity=rock-phosphate&currency=gbp.

Kratzeisen, M., Starcevic, N., Martinov, M., Maurer, C., Müller, J., 2010. Applicability of biogas digestate as solid fuel. Fuel 89, 2544–2548. https://doi.org/10.1016/j.fuel.2010.02.008.

Moller, H.B., Lund, I., Sommer, S.B., 2000. Solid-liquid separation of livestock slurry: efficiency and cost. Bioresour. Technol. 74, 223–229. https://doi.org/10.1007/s00595-015-1112-8.

Morningstar, R.L., Simonyi, A., Khakova, O., Markina, I., 2020. European energy diversification: how alternative sources, routes, and clean technologies can bolster energy security and decarbonisation. Atlantic Council [WWW document] (January), 2–6. https://www.atlanticcouncil.org/wp-content/uploads/2020/01/Khakova-Energy-Diversity-IB-A4.pdf. (Accessed 22 February 2021).

Nagy, D., Balogh, P., Gabnai, Z., Popp, J., Oláh, J., Bai, A., 2018. Economic analysis of pellet production in Co-digestion biogas plants. Energies 11, 1135. https://doi.org/10.3390/en11051135.

new-eco-teccom, 2020. BELT DRYER SERIES ALLinDRYer® [WWW document]. https://www.new-eco-tec.com/compact-belt-dryer-allindryer. (Accessed 14 February 2021).

Nnfcc, 2019. AD portal map site list external May 2019 [WWW Document]. http://www.biogas-info.co.uk/resources/biogas-map/attachment/ad-portal-map_site-list_external_may-_2019/. (Accessed 14 February 2021).

Nolan, T., Troy, S.M., Gilkinson, S., Frost, P., Xie, S., Zhan, X., Harrington, C., Healy, M.G., Lawlor, P.G., 2012. Economic analyses of pig manure treatment options in Ireland. Bioresour. Technol. 105, 15–23. https://doi.org/10.1016/j.biortech.2011.11.043.

ofgem, 2019. Guidance for Generators that Receive or Would like to Receive Support under the Renewables Obligation (RO) Scheme. https://www.ofgem.gov.uk/system/files/docs/2019/04/ro_generator_guidance_apr19.pdf. (Accessed 5 February 2021).

ofgem, 2020. Feed-in tariff (FIT) rates [WWW document]. https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates. (Accessed 5 February 2021).

Schindler, D.W., Hecky, R.E., Findlay, D.L., Stainton, M.P., Parker, B.R., Paterson, M.J., Beaty, K.G., Lyng, M., Kasian, S.E.M., 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37-year whole-ecosystem experiment. Proc. Natl. Acad. Sci. U. S. A. 105, 11254–11258. https://doi.org/10.1073/pnas.0805108105.

Sharmila, V.G., Angappane, S., Gunasekaran, M., Kumar, G., Banu, J.R., 2020. Immobilized ZnO nano film impelled bacterial disintegration of dairy sludge to enrich anaerobic digestion for profitable bioenergy production: energetic and economic analysis. Bioresour. Technol. 308, 123276. https://doi.org/10.1016/j.biortech.2020.123276.

Shirani, A., Evans, M., 2012. Driving Innovation in AD Optimisation – Uses for Digestate. WRAP Feasibility Report. https://www.wrap.org.uk/sites/files/wrap/DIAD%20I%20AWS%20Burdens%20feasibility%20report.pdf. (Accessed 15 May 2021).

Smyth, B.M., Murphy, J.D., O'Brien, C.M., 2009. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renew. Sustain. Energy Rev. 13, 2349–2360. https://doi.org/10.1016/j.rser.2009.04.003.

Smyth, B.M., Smyth, H., Murphy, J.D., 2010. Can grass biomethane be an economically viable biofuel for the farmer and the consumer? Biofuels, Bioproducts and Biorefining 4 (5), 519–537. https://doi.org/10.1002/bbb.238.

Stanchev, P., Vasilaki, V., Egas, D., Colon, J., Ponsá, S., Katsou, E., 2020. Multilevel environmental assessment of the anaerobic treatment of dairy processing effluents in the context of circular economy. J. Clean. Prod. 261, 121139. https://doi.org/10.1016/j.jclepro.2020.121139.

Tambone, F., Orzi, V., D'Imporzano, G., Adani, F., 2017. Solid and liquid fractionation of digestate: mass balance, chemical characterization, and agronomic and environmental value. Bioresour. Technol. 243, 1251–1256. https://doi.org/10.1016/j.biortech.2017.07.130.

The Nutrient Action Programme Regulations (Northern Ireland) 2019 (NISR 2019/81). Available at: https://www.legislation.gov.uk/nisr/2019/81/made (accessed 04/03/2021).

The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 (SI 2018/151). Available at: https://www.legislation.gov.uk/uksi/2018/151/made (accessed 04/03/2021).

Turley, D., Hopwood, L., Burns, C., di Maio, D., 2016. Assessment of Digestate Drying as an Eligible Heat Use in the Renewable Heat Incentive, vol. 28. NNFCC, York, UK.

United Nations, 2021. Sustainable Development Goals [WWW Document]. https://sdgs.un.org/goals. (Accessed 22 February 2021).

University, Purdue, 2017. Farm Machinery Costs and Custom Rates [WWW Document], 05/2/2021. https://ag.purdue.edu/commercialag/home/resource/2017/08/farm-machinery-costs-and-custom-rates/.

Vasco-Correa, J., Khanal, S., Manandhar, A., Shah, A., 2018. Anaerobic digestion for bioenergy production: global status, environmental and techno-economic implications, and government policies. Bioresour. Technol. 247, 1015–1026. https://doi.org/10.1016/j.biortech.2017.09.004.

Vuuren, D.P. van, Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970 – 2100 period : a scenario analysis of resource depletion. Global Environ. Change 20, 428–439. https://doi.org/10.1016/j.gloenvcha.2010.04.004.

Zou, X., Yang, R., Zhou, X., Cao, G., Zhu, R., Ouyang, F., 2020. Effects of mixed alkali-thermal pretreatment on anaerobic digestion performance of waste activated sludge. J. Clean. Prod. 259, 120940. https://doi.org/10.1016/j.jclepro.2020.120940.