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Regional assessment of bioeconomy options using the anaerobic biorefinery concept

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One of the outputs on an ongoing programme of research into the bioeconomy concept in Northern Ireland was the publication of a 'Biogas Research Action Plan' in 2014, which included a 'Quantification of Feedstocks for Anaerobic Digestion' research project. This research quantified the feedstocks available for biogas production on a regional basis. The present research builds on and extends that previous work by applying the anaerobic biorefinery concept to the data for feedstocks for anaerobic digestion to include both biogas and digestate utilisation options. The assessment aims at evaluating the potential significance of anaerobic biorefineries on a regional basis, including types of feedstocks and uses for both biogas and digestate outputs. The use of the anaerobic biorefinery concept allows the evaluation of both biogas and digestate management pathways in an integrated way and can contribute to the development of a road map for a regional bioeconomy. The usefulness of the anaerobic biorefinery concept in informing regional and/or national policy and decision-making for the circular economy and the bioeconomy is evaluated, and recommendations made for future research priorities in this important research and policy area.

1. Introduction

A programme of research has been underway in Northern Ireland (NI) for a number of years with the aim of defining priorities for support to regional development, co-operation and knowledge transfer within the region in the field of production and use of biogas. One of the outputs of this research was the publication of a 'Quantification of Feedstocks for Anaerobic Digestion' report (Groom and Orozco, 2014: Appendix 3.1; see also 'Quantification of bioresource feedstocks for the development of a regional bioeconomy' by Curry *et al.*, submitted to *Waste and Resource Management*). This research report quantified the feedstocks available for biogas production on a regional basis and provided estimates for potential biogas production, electrical and heat energy generation, and potential reductions in greenhouse gas (GHG) emissions from biogas utilisation. However, the research did not make any attempt to quantify the digestate outputs from the anaerobic digestion (AD) of these feedstocks or identify potential utilisation pathways. The present research builds on and extends this research by applying the anaerobic biorefinery concept to the data on feedstocks for AD to include both biogas and digestate utilisation options.

1.1 Background

AD is an established technology that involves the breakdown of organic materials by microorganisms under controlled conditions in the absence of oxygen. The products of AD are biogas and digestate. Biogas typically consists of 55–70% methane (CH_4), 45–30% carbon dioxide (CO_2) and some minor constituents, such as hydrogen sulfide (H_2S) and water (Smyth *et al.*, 2010). Methane energy in the biogas can be combusted as a fuel and is commonly used for electricity generation and combined heat and power (CHP) generation. Digestate, which consists of a suspended solid fraction and the other liquid fraction containing soluble nutrients, is the material that remains at the end of the AD process. Digestate can be used as an organic fertiliser and is reported to be more suitable than raw agricultural wastes (e.g. slurry, manure) for fertiliser use (Monson *et al.*, 2007). A particularly active area for research is approaches to optimise the process to increase biogas yield and to look for economical uses for the digestate outputs (Smyth *et al.*, 2009).

One interesting approach is to place AD within the context of the anaerobic biorefinery, to allow an integrated approach that maximises synergies between technologies and processes (Sawatdeenarunat *et al.*, 2016). The use of the anaerobic biorefinery concept allows the evaluation of both energy (electricity and heat) and chemical/material/nutrient management pathways in an integrated way and can contribute to the development of a road map for a regional bioeconomy (Vazquez-Rowe *et al.*, 2015). A schematic diagram of the anaerobic biorefinery is shown in Figure 1 (adapted from Sawatdeenarunat *et al.* (2016)).

1.2 Aims and objectives

The overall aim of this research is to build on and extend the outputs of the regional 'Quantification of Feedstocks for Anaerobic Digestion' report through the application of the anaerobic biorefinery concept to both biogas and digestate

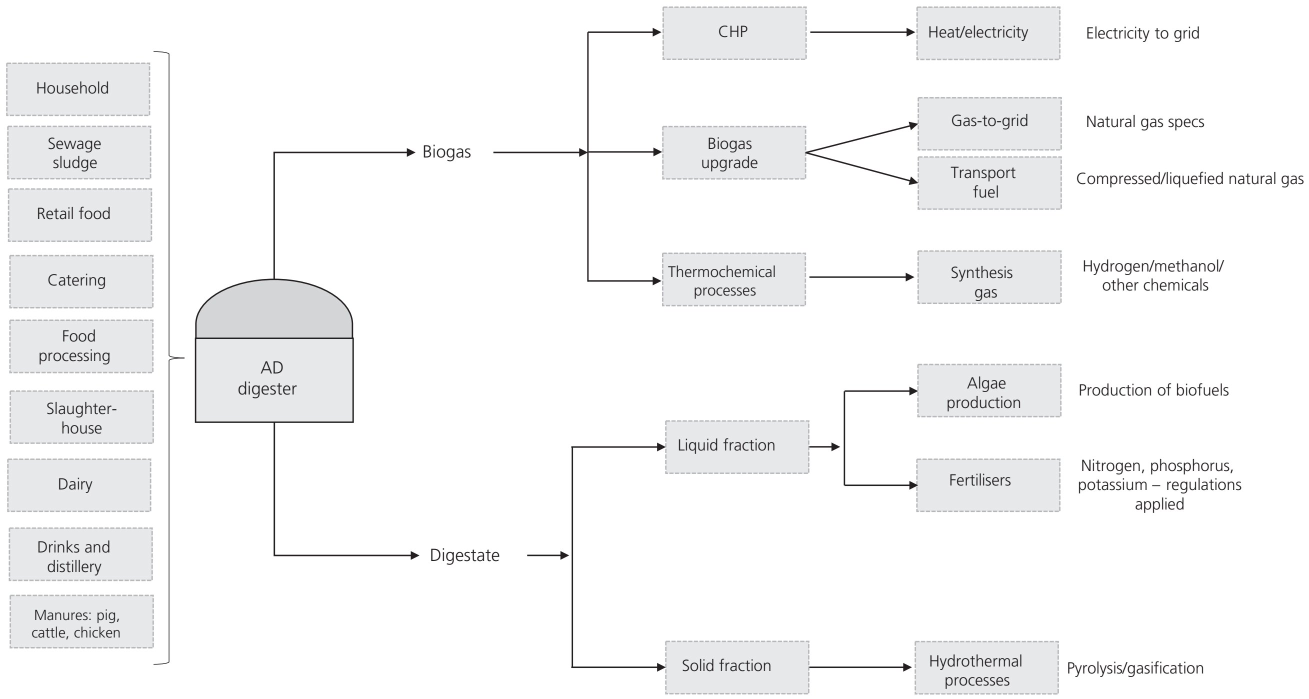

Figure 1. Schematic diagram of large-scale anaerobic biorefinery for production of biofuels and bio-based products (adapted from Sawatdeenarunat *et al.* (2016))

outputs from the AD process. The following underlying objectives underpin this aim

- to identify potential biogas and digestate production and utilisation pathways using the anaerobic biorefinery concept
- to contribute to the development of a road map for a regional bioeconomy
- to gain an understanding of the usefulness of the anaerobic biorefinery concept in informing regional and/or national policy and decision-making for the circular economy and the bioeconomy
- to make recommendations for future research priorities in this important research and policy area.

2. Methodology

Data from the 'Quantification of Feedstocks for Anaerobic Digestion' research were used to evaluate the potential amounts of biogas and digestate that can be produced from organic wastes on a regional basis. This was followed by an evaluation of a selection of utilisation pathways for both biogas and digestate. Biogas and digestate were explored using the anaerobic biorefinery concept, for the following utilisation options

- biogas (non-CHP)
- digestate as fertiliser
- digestate use for algae production
- digestate use in hydrothermal processes (gasification/pyrolysis).

This study focused on the uses of digestate after dewatering for both the liquid and solid components. The liquid fraction of the digestate, which is the primary component, can be used as a fertiliser and for algae production (Xia and Murphy, 2016), while the solid fraction can be used in hydrothermal processes such as pyrolysis and gasification (Monlau *et al.*, 2016).

It is acknowledged that a wide range of products can be manufactured in a biorefinery that are not included in this analysis (e.g. high-value products such as volatile fatty acids, polyhydroxyalkanoates/polyhydroxybutyrate polymers and surfactants (Sawatdeenarunat *et al.*, 2016)). As such, this analysis represents a 'snap-shot' of the many potential production and utilisation pathways and this limitation is addressed in the conclusions and recommendations for future research priorities.

3. Potential feedstocks for AD: initial data

The 'Quantification of Feedstocks for Anaerobic Digestion' research estimated the potential feedstocks for AD as organic biodegradable materials from three main sectors: agriculture,

Table 1. Summary of NI organic waste produced

Waste origin	Waste amount produced: t/year
Municipal and commercial waste	484 000
Manures	10·8 million
Crops (grass silage)	1·94 million
Total	13·2 million

municipal, and commercial and industrial. The agriculture sector comprises the production of crops, grass silage and sugar beet; with residues such as wheat straw. The most commonly available source in NI is the production of manures from cattle, pig and poultry farms. The municipal sector comprises household, canteen and sewage sludge wastes, while the commercial and industrial sector comprises wastes produced from fruit and vegetable companies, industrial factories, supermarkets, tanneries, food processing companies, catering, dairy, fish processing, slaughterhouses and food scraps factories. The research estimated an average of 484 000 t of municipal and commercial and industrial waste produced, while manure production is 10·8 Mt/year. Crops, basically grass silage, is reported to be 1·94 Mt/year. Thus, the total estimated potential feedstocks for AD is 13·2 Mt/year in NI (Curry *et al.*, submitted; Groom and Orozco, 2014). It should be noted that estimates of feedstock quantities are derived from the regional quantification of feedstocks research project, which used a methodology set out by Slade *et al.* (2011), who described how biomass potential estimates are most often discussed in terms of a 'hierarchy of opportunity': theoretical, technical, economic and realistic. This research used the theoretical estimates of the organic resources generated and potentially available, and these quantities were used to enable alignment of the regional biorefinery evaluation with the regional feedstocks project. It is acknowledged that technical and economic issues may impose limitations on the total quantities of feedstocks that can realistically be made available for AD. The main figures from the 'Quantification of Feedstocks for Anaerobic Digestion' research (Curry *et al.*, submitted; Groom and Orozco, 2014) are summarised in Table 1.

4. Potential utilisation pathways for AD outputs: the anaerobic biorefinery

4.1 Biogas (non-CHP)

Biogas has traditionally been considered to be the main product in the AD of organic residues (AEBIOM, 2009). Its most common use is in a biogas engine for the production of electricity and heat (Holm-Nielsen *et al.*, 2009). Usually, industrial plants producing biogas are able to use part of the produced electricity for self-consumption and feed the rest of the production into the national electricity grid. However, the biogas can also be upgraded to natural gas quality and be used as biomethane as part of a wider bioenergy system (Murphy *et al.*, 2014), or utilised for producing energy and chemicals within the anaerobic biorefinery concept (Cherubini, 2010).

If the aim is the production of biomethane, the biogas from AD must first be upgraded and further purified after the initial hydrogen sulfide removal stage. A range of technologies exists to do this, including water scrubbing, pressure swing adsorption and amine scrubbing. The most extensively used process for large-scale systems (>100 Nm^3 biogas per hour) is water scrubbing (Yliopisto, 2013).

Standards have been developed for the upgrading of biogas to allow it to be used as a substitute for natural gas (Bright *et al.*, 2011). This option is gaining the interest of policymakers in traditional gas markets such as the UK, the Netherlands and Germany. Targets for its production are being included in some national renewable plans; furthermore, biomethane is also attractive to gas companies as a low-carbon dioxide energy source (AEBIOM, 2009).

Other uses of biogas include the production of synthesis gas (syngas), which is a mixture containing varying amounts of carbon oxide and hydrogen. It can be produced by reforming hydrocarbon-containing streams such as methane or biogas, or through gasification of coal. The main processes for the production of syngas from methane are steam reforming, dry reforming (DRM) and partial oxidation of methane, or a combination of these. These processes are based on one or more chemical reactions that are either endothermic or exothermic. Achieving an appropriate balance of these reactions can result in processes that require little added energy (Pérez-Camacho *et al.*, 2015). Synthesis gas can be used as a fuel in similar ways to methane, such as combustion in a gas turbine or an internal combustion engine. In DRM, two of the most abundant carbon-containing GHGs, methane and carbon dioxide, react to form more valuable products – that is, carbon monoxide (CO) and hydrogen (H_2) ($CH_4 + CO_2 \leftrightarrow 2\ CO + 2\ H_2$). From an industrial point of view, DRM also satisfies the requirements of many synthesis processes generating oxygenated compounds and liquid hydrocarbons (Fischer–Tropsch synthesis) from syngas – that is, a syngas with a ratio of hydrogen/carbon monoxide close to 1 (Choudhary *et al.*, 2006).

The estimation of biogas production by Curry *et al.* (submitted) quantified ca. 491 million m^3 of biogas produced per year from AD in NI. It has been assumed that half of this amount is used for the upgrading of biogas to biomethane and half for synthesis gas production. Based on this assumption, the amount of biomethane produced would potentially be 120·3 million m^3 per year, which corresponds to 132 million litres of diesel (IEA, 2015), while the syngas to be produced would be 390 million m^3 per year, based on a conversion

Table 2. Biogas non-CHP utilisation options

Biogas as a feedstock = 491 million m^3 per year	
Biomethane production (million m^3 per year) as 98% v/v purity	120·3
Synthesis gas production (million m^3 per year)	390·1[a]

[a]For a conversion factor of biogas to syngas of 70% (Pérez-Camacho *et al.*, 2014)

factor of biogas to syngas of 70% (Pérez-Camacho *et al.*, 2014). These data are summarised in Table 2.

4.2 Digestate

Digestate is the general term used to designate the material left after the production of biogas from the AD process. It is composed of undigested solids and the liquid fraction of the digested feedstock. Between 90 and 95% of the feed to the digester will remain as digestate (Tampio *et al.*, 2016; WRAP, 2012). Depending on the feedstock, the percentage of dry matter will vary. The reported values of dry solids can vary from 4·33% for food-based digestate to 8·22% for manure-based digestate (WRAP, 2011), while the assumed value for grass silage digestate was 6·6% (Drosg *et al.*, 2015).

Research has shown that the AD process consumes relatively few nutrients and enhances the availability of nutrients such as nitrogen, phosphorous and potassium (Ayala-Parra *et al.*, 2017; Svehla *et al.*, 2017). Results from work carried out at AFBI Research Centre in NI (Frost and Gilkinson, 2011) demonstrated that the fertiliser value of digested cattle slurry was increased by about 15%, and this is supported by other researchers who have demonstrated similar improvements (Matsunaka *et al.*, 2006; Tani *et al.*, 2006).

The further refining of the digestate through different treatments and technologies is called digestate processing. The most usual process, due to its simplicity and low cost, is the separation of the digestate into liquid and solid fractions. For the separation, decanter centrifuges and screw press separators are the most commonly used technology although there is a range of other processes/technologies available (at varying levels of technology readiness), all having the same broad aims: volume reduction and separation of the nutrient and fibres with the higher value from the water contained in the digestate (Al Seadi *et al.*, 2013; Flotats *et al.*, 2011).

Table 3 provides estimates for the regional production of digestate per year in NI. Assuming 12 different streams for the waste produced in NI – household, sewage sludge, retail food, catering, food processing, slaughterhouse, dairy, drinks and distillery, dairy manure, pig manure, chicken manure and crops (Curry *et al.*, submitted; Groom and Orozco, 2014) – the amount of digestate produced per stream is calculated assuming that all the waste produced is anaerobically digested, with the resulting digestate being 90% of the initial fed to the reactors (Tampio *et al.*, 2016; WRAP, 2012). Then, the percentage of dry solids has been applied to each stream. This percentage will vary depending on the origin of the feedstock: from 4·33% for food-based digestate to 8·22% for manure-based digestate (WRAP, 2011) and 6·6% for grass silage digestate (Drosg *et al.*, 2015), obtaining the values of solid and liquid fractions for each stream and the total as a sum of them.

Using this methodology, estimation results are 0·9 Mt/year for the solid fraction and 11 Mt/year for the liquid fraction of the digestate. These figures are set out in Table 3.

The separation of liquid and solid fractions of the digestate can be done utilising a decanter centrifuge-type equipment (Flotats *et al.*, 2011; Tampio *et al.*, 2016), while the liquid fraction can be further treated to produce fertiliser products.

4.2.1 Digestate as a fertiliser

The liquid fraction of the digestate can be upgraded to enhance its use as a fertiliser. A range of processes/technologies is available to do this, including ammonia stripping, evaporation, struvite precipitation, membrane separation or a combination of them (Antonini *et al.*, 2011; Boehler *et al.*, 2015; Bonmatí and Flotats, 2003a, 2003b; Chiumenti *et al.*, 2013).

Tampio *et al.* (2016) compared the potential of four digestate liquid treatment processes in a theoretical AD plant using food waste to produce fertilisers with low water content and high nutrient value, and provided estimates of the conversion efficiency of each.

The four options for producing fertilisers are described below together with their production efficiencies (Tampio *et al.*, 2016).

- S1, consisting of the stripping of the ammonia contained in the liquid digestate with sulfuric acid producing ammonium sulfate and stripping residue. Efficiency of fertiliser production: 79 wt%.
- S2, consisting of the combination of ammonia stripping with reverse osmosis (RO) to produce ammonium sulfate. Efficiency of fertiliser production: 26 wt %.
- S3, combining evaporation with RO where the liquid digestate is concentrated in the evaporation and then undergoes an RO process to concentrate the product further. Efficiency of fertiliser production: 16 wt%.
- S4, combining stripping, evaporation and RO. Efficiency of fertiliser production: 20 wt%.

Utilising these efficiency values, the potential production of fertiliser from the liquid fraction of the digestate has been

Table 3. Production of digestate per year in NI

Waste category	Waste amount: t/year	Digestate from each source of waste: tyear	Dry solids: %	Solid fraction: t/year	Liquid fraction: t/year
Household	244 043·67	219 639·30	4·33	9510·38	210 128·92
Sewage sludge	38 566·667	34 710	4·33	1502·94	33 207·06
Retail food	35 700	32 130	4·33	1391·23	30 738·77
Catering	4140	3726	4·33	161·34	3564·66
Food processing	26 000	23 400	4·33	1013·22	22 386·78
Slaughterhouse	17 823	160 407	4·33	6945·62	153 461·38
Dairy	13 200	11 880	4·33	514·40	11 365·60
Drinks and distillery	12 000	10 800	4·33	467·64	10 332·36
Dairy cattle manure	10 000 000	9 000 000	8·22	739 800	8 260 200
Pig manure	500 000	450 000	8·22	36 990	413 010
Chicken manure	300 000	270 000	8·22	22 194	247 806
Crops (grass silage)	1 937 170·12	1 743 453·10	6·6	115 067·90	1 628 385·20
Total				935 558·68	11 024 586·72
Millions				0·936	11·02

Table 4. Fertiliser production potential from the liquid fraction of the digestate

Feedstock for fertilisers (liquid fraction of the digestate) = 5·5 Mt/year		Estimation	
Fertiliser production technology	wt% of fertiliser[a]	Fertiliser produced: t/year	Fertiliser produced: Mt/year
S1 (stripping)	79	4 354 711·76	4·35
S2 (stripping + RO)	26	1 433 196·27	1·43
S3 (evaporation + RO	16	881 966·94	0·88
S4 (evaporation + stripping + RO)	20	1 102 458·67	1·10

[a]Using efficiencies from Tampio *et al*. (2016)

estimated based on the assumption that 50% of the total liquid digestate (5·5 Mt/year) produced will be used in this process. The results are set out in Table 4.

In order to be no longer classified as a waste, fertilisers produced from digestate must comply with the biofertiliser certification scheme, which provides assurance to consumers, farmers, food producers and other retailers about the safety of fertilisers from digestate to human, animal and plant health (EA and WRAP, 2009). Digestate that meets the criteria set out by the quality protocol and standard PAS 110 or any other approved standard is then known as biofertiliser (EA and WRAP, 2009; WRAP, 2014).

4.2.2 Digestate use for algae production

There is a wide range of technologies and processes for the recycling of nutrients from waste water using algae (Markou and Georgakakis, 2011; Prajapati *et al*., 2014; Rawat *et al*., 2011). Algae have the ability to grow and extract nutrients from waste, which increases the feasibility and economic viability of biofuel based on algae streams. There are studies on AD of manure and industrial liquid effluents for the production of biomass algae where the algae production is enhanced by adding the liquid fraction of the digestate to them. One example is research performed by Wang *et al*. (2010) whose cultivation of *Chlorella* sp. was carried out in diluted dairy manure by way of AD. The liquid fraction of the digestate from AD is rich in nutrients, which can be used for cultivation of algae. It is also possible to use the algal digestion for biogas production with subsequent utilisation of the liquid digestate as a nutrient source for more algae cultivation. There are studies where a process using liquid digestate from algae cultivation was used as a medium for the growth of more algae (Prajapati *et al*., 2014).

Another promising area of research is bioproducts derived from microalgae; however, commercial applications have yet to be developed due to the current cultivation costs. If liquid digestate treatment and microalgae cultivation are combined, a significant reduction in the nutrient cost could be achieved (Xia and Murphy, 2016). Research done by Xia and Murphy (2016) has demonstrated how 1 m^3 of liquid digestate could be used as the nutrient source of microalgae cultivation, producing 14·6 kg volatile solids (VS) of microalgae (Xia and Murphy, 2016). This value has been used in the authors'

Table 5. Algae and biodiesel production from liquid digestate

Liquid digestate as a feedstock = 5·5 Mt/year	
Algae production (Mt of VS of microalgae per year)[a]	80·3
Biodiesel production (million m^3 per year)[b]	53·6

[a]Using microalgae yield from Xia and Murphy (2016)
[b]Using yield from the literature (Gnansounou and Kenthorai Raman, 2016)

calculation for the estimation of algae that could be produced from liquid digestate within the anaerobic biorefinery. This would potentially yield around 80 Mt of VS of microalgae produced per year based on the use of 5·5 Mt of liquid digestate for this, as set out in Table 5.

The biofuel produced from algae is classified as a third generation biofuel and is promoted as a renewable biofuel with the potential to displace petroleum-derived transport fuels without adversely affecting the supply of food and other crop products (Piloto-Rodríguez *et al*., 2017). In addition, algae are a source for not only biofuels but also other bioproducts (Sawatdeenarunat *et al*., 2016; Xia and Murphy, 2016). For the purposes of this study, the estimation of how much biodiesel could be produced from the microalgae previously produced using liquid digestate as a nutrient source was based on yields from Gnansounou and Kenthorai Raman (2016) and Xia and Murphy (2016). These results are set out in Table 5.

4.2.3 Digestate for hydrothermal processes (gasification/pyrolysis)

The solid fraction of the digestate is estimated to be between 4 and 8% of the total digestate produced (Drosg *et al*., 2015; WRAP, 2011) and although a smaller proportion than the liquid, it is a potentially valuable product. One example of this is its use in gasification/pyrolysis to manufacture a wide range of products such as synthesis gas (a mixture of hydrogen and carbon monoxide), bio-oils and biochar (Monlau *et al*., 2016).

Monlau *et al*. (2015, 2016) coupled pyrolysis with AD in an anaerobic biorefinery, and provided estimates of the quantities of biochar, bio-oil and syngas that could be produced. The estimates used in this research are based on their yield factors.

Pyrolysis is the direct thermal decomposition of biomass in the absence of oxygen and at 400–800°C (Gold and Seuring, 2011). The products, syngas, bio-oil and biochar and their relative proportions will depend on the pyrolysis method utilised and the type of biomass and the reaction parameters. In general, the yields are 40–65 wt% of bio-oil, 10–20% of biochar and 10–30% of syngas (Uslu *et al*., 2008). The data used for the calculations (Monlau *et al*., 2016) are covered by these ranges (Table 6).

Additionally, the solid fraction of the digestate can, at a further stage, also be used as a fertiliser (Deal *et al*., 2012). Through the pyrolysis process, biochar is produced. Biochar is a mixture of organic compounds also called ‘black carbon’ biomass with soil amendment properties. This converts the biochar into a carbon-sequestration product, contributing to global warming mitigation (Dias *et al*., 2010; Gold and Seuring, 2011; He *et al*., 2017).

Biochar can be used as an alternative to liquid digestate as a soil amendment, and its importance is related to its potential carbon-sequestration ability coupled with the provision of valuable nutrients (nitrogen, phosphorus). Some studies have focused on the combination of AD and pyrolysis (Monlau *et al*., 2015), while others (Monlau *et al*., 2016) have focused on the replacement of solid digestate for soils by biochar due to the similar or even better effects on soil quality. Similar biochar yields to the ones used for the authors’ calculation (Table 6) have been found by Inyang *et al*., (2010), Stefaniuk and Oleszczuk (2015) and Yao *et al*. (2011). Recent publications (Monlau *et al*., 2016) have shown a 34% yield of biochar from solid digestate and this is the yield factor used to estimate the production from the NI feedstock data.

It is also possible to combine AD with gasification. Gasification is the thermochemical conversion process where carbon-based materials at high temperature (800–1200°C) react in an environment with a limited amount of oxygen, air

Table 6. Product estimation potential from the pyrolysis of the solid fraction of the digestate

Feedstock for pyrolysis (solid fraction of the digestate) = 820 000 t/year		Estimation	
wt% averages for each product[a]		Products: t/year	Products: Mt/year
Biochar	34%	318 089·95	0·318
Bio-oil	53·50%	500 523·89	0·500
Syngas	12·50%	116 944·84	0·116

[a]Monlau *et al*. (2016)

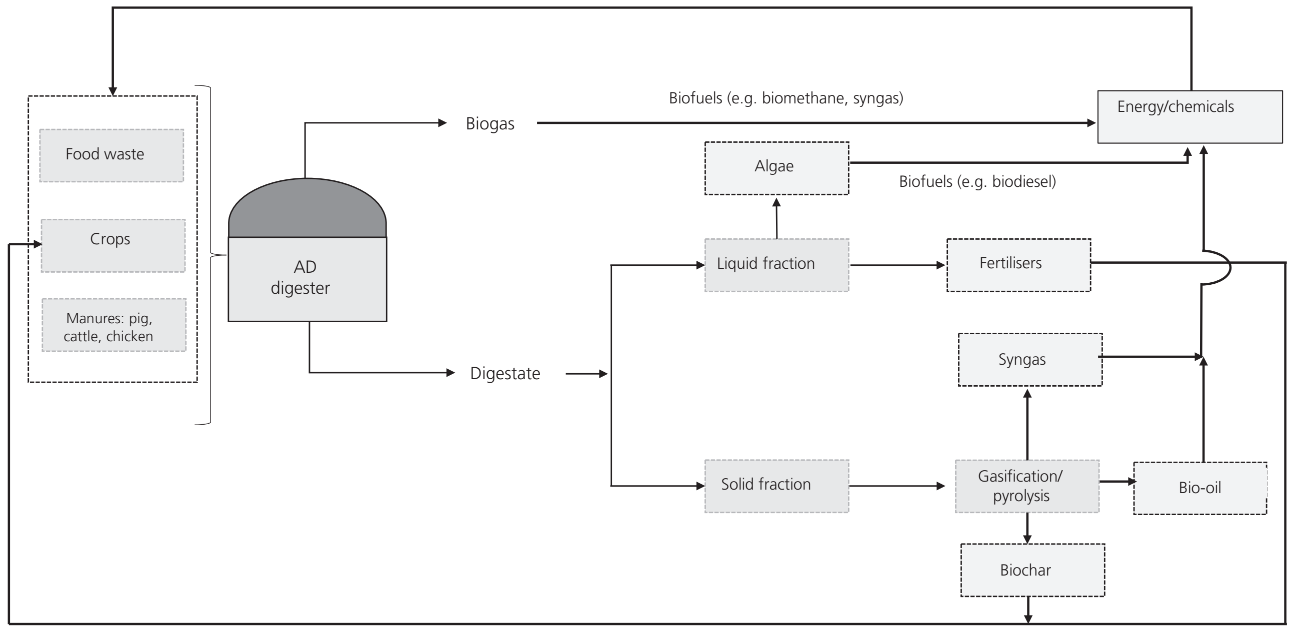

Figure 2. Schematic diagram of the proposed anaerobic biorefinery

and/or steam. The product is synthesis gas and a solid carbon-rich material also called biochar. AD and gasification processes have the capacity to adapt their feedstocks and operational characteristics, which can lead to the manufacture of by-products with a wide range of physicochemical characteristics (Kataki *et al*., 2017).

Based on the above review of potential processing options and products, the following product options were selected for the estimation of product quantities from hydrothermal processes

- biochar
- bio-oil
- syngas.

The results for the estimation of the products from the pyrolysis of the solid fraction of the digestate are presented in Table 6. The authors' results give an estimation of production as 0·318 Mt/year of biochar, 0·500 Mt/year of bio-oil and 0·116 Mt/year of syngas.

5. Conclusions

Using the data from the 'Quantification of Feedstocks for Anaerobic Digestion' research, the estimation of biogas and digestate production was explored using the concept of anaerobic biorefinery. The overall aim of this research was to apply the anaerobic biorefinery concept to the outputs of the regional 'Quantification of Feedstocks for Anaerobic Digestion' research estimates, with the following underlying objectives

- to identify potential biogas and digestate production and utilisation pathways using the anaerobic biorefinery concept
- to contribute to the development of a road map for a regional bioeconomy
- to gain an understanding of the usefulness of the anaerobic biorefinery concept in informing regional and/or national policy and decision-making for the circular economy and the bioeconomy
- to make recommendations for future research priorities in this important policy area.

The use of the anaerobic biorefinery concept has facilitated the identification of potential biogas and digestate production and utilisation pathways that have the potential to provide synergies and optimise the use of all of the outputs of AD. The use of yield factors from the literature has enabled estimates to be made of the potential quantities of product/material from each option; and although it must be emphasised that these are early estimates, they do provide a starting point for the development of a road map for a regional bioeconomy. As such, the authors conclude that the application of the anaerobic biorefinery concept is a useful model for informing regional and/or national policy and decision-making in the circular economy and the bioeconomy. In this research paper, the authors presented a possible application of the anaerobic biorefinery concept for NI that had potential organic material feedstocks for AD previously estimated. Figure 2 presents a schematic diagram of the proposed application of the anaerobic biorefinery for NI. The authors believe that this identifies a number of interesting and important priorities for an ongoing research to contribute to the further development and implementation of the bioeconomy concept. They would identify as a limitation of the research that it provides only a 'snap-shot' of the many potential production and utilisation pathways and this is addressed in future research priorities below.

6. Recommendations for further research

The authors would highlight the following areas as priorities for future research

- further development of the anaerobic biorefinery concept
- further analysis using as full a range of potential production and utilisation pathways as possible
- identification of potential synergies with other input processes for the bioeconomy, including gasification, fermentation and hydrodeoxygenation.

The authors hope that the issues identified and discussed in this paper can provide insights for other researchers and help set out the priorities for research to support this important policy area.

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