Cite this article

Curry R, Pérez-Camacho MN, Brennan R *et al.* (2018)
Quantification of anaerobic digestion feedstocks for a regional bioeconomy.
Proceedings of the Institution of Civil Engineers – Waste and Resource Management **171**(4):
94–103, <https://doi.org/10.1680/jwarm.17.00014>

Research Article

Paper 1700014

Received 10/04/2017;
Accepted 05/10/2018;
Published online 16/11/2018

Keywords: environment/renewable
energy/sustainability

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Quantification of anaerobic digestion feedstocks for a regional bioeconomy

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Anaerobic digestion (AD) for biogas production forms one of the fundamental building blocks of the bioeconomy, and a research programme has been under way in Northern Ireland, which culminated in the publication of a Biogas Research Action Plan 2020 in 2014. One important element of this programme was the identification of the need for an evidence base for the potential bioresource feedstocks. This paper reports the outputs of the quantification of feedstocks for AD research, which has identified the organic feedstocks available for biogas production on a regional basis and categorised these as: organic (biodegradable) fraction of municipal solid waste, sewage sludge, organic industrial and commercial wastes, manure from livestock, food wastes and energy crops. The research study further quantified the biogas and energy potential of these feedstocks and possible reductions in greenhouse gas emissions. The limitations of the research study are acknowledged and opportunities to address these and build on and extend the study are identified, including feedstocks for other bioeconomy processes and the application and further development of the biorefinery concept.

1. Introduction

The increasing interest in the circular economy and the growing evidence for its benefits in terms of material savings, emissions reduction and job creation (Mitchell and Doherty, 2015; Mitchell and Morgan, 2015), has led to a commensurate focus on the bioeconomy, particularly in those countries and regions with large agri-food sectors (Blades *et al.*, 2017). The agri-food sector in Northern Ireland accounts for a higher

proportion of the economy than the UK average, is the region's largest employer (Department for the Economy, 2017) and accounts for a much higher proportion of region's total greenhouse gas (GHG) emissions, at 29% as opposed to 9% in the rest of the UK (CCC, 2015). In addition, the sector has set ambitious growth targets to 2020 (growth of sales by 60% to £7 billion and sales outside Northern Ireland by 75%), which will result in a commensurate growth in wastes from this sector

(AFSB, 2013). Anaerobic digestion (AD) has been proposed by several researchers and policymakers as central to reducing emissions of GHGs from agriculture and food production (Bacenetti *et al.*, 2016; Kaparaju and Rintala, 2011), waste management (Davidsson *et al.*, 2007) and as a source of renewable energy (Curry and Pillay, 2012) and/or biofuels (Börjesson and Mattiasson, 2008; Singh *et al.*, 2010).

In response to these drivers and challenges, a programme of research has been ongoing in Northern Ireland 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, in order to realise the following objectives (Groom and Orozco, 2014).

- Development of new cost-effective, energy-efficient and sustainable technologies for biogas production and use within energy supply chains.
- Development of technologies and services optimising the benefits of biogas for Northern Ireland agriculture, infrastructure and communities.
- Provision of research expertise and facilities for manufacturers to commercialise ideas from research and development activities.

The authors report one of the main outputs of this research, namely the quantification of feedstocks for AD. The need for classification and quantification of feedstocks is widely recognised by researchers and policymakers as essential to planning and implementation in all areas of waste and resource management (Thomas, 2004), and particularly for the information needs of the bioeconomy (HLEUC, 2014). This research study has identified the organic feedstocks available for biogas production on a regional basis and categorised them.

AD offers significant benefits in the context of bioeconomy, including (Monson *et al.*, 2007)

- recycling nutrients and organic matter (digestate) back to land (subject to legislative constraints) and reducing the consumption of chemical fertilisers
- reduction of GHG emissions
- diverting biodegradable municipal waste away from landfill
- generation of renewable energy
- creation of jobs in the supply chain
- heat capture and use in heating schemes – for example, commercial operations and district heating schemes
- upgrading biogas (biomethane) to be used as a biofuel for vehicles – for example, road freight, agricultural and similar plant and machinery
- upgrading biogas (biomethane) to natural gas quality for injection into the gas grid.

2. Methodology

The research focused on the theoretical estimates of the organic resources generated and potentially available, based on the 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 – as illustrated in Figure 1.

The scope of this study was to focus on the theoretical estimates of the organic resources generated and potentially available within Northern Ireland for AD and their biogas production potential. Organic resources potentially available as AD feedstocks are set out below and classified in Figure 2.

- Organic (biodegradable) fraction of municipal solid waste (OFMSW).
- Sewage sludge.
- Organic industrial and commercial wastes – that is, food/beverage/tobacco processing wastes, slaughterhouse/rendering wastes, dairy wastes.
- Manure from livestock.
- Food wastes from households (separately collected/source segregated), catering, restaurants, hotels.

3. Results

3.1 Municipal and commercial and industrial organic waste arisings

Data on waste arisings for municipal and commercial and industrial (C&I) wastes have improved significantly in recent years. In particular for municipal wastes, the introduction of the WasteDataFlow web-based system for municipal waste data reporting has enabled faster and more accurate data collection of municipal waste statistics (WDF, 2017). The

Figure 1. Hierarchy of feedstocks and energy potential for organic resources for AD

Figure 2. Classification of feedstocks potentially available for AD in Northern Ireland (source: reproduced from Groom and Orozco (2014))

accuracy of the data on C&I waste has also improved, with a number of national C&I waste arisings studies being carried out in England and Wales, Scotland and Northern Ireland over the last 10 years.

Across the period 2002–2013, reported municipal waste recycling and composting rates in Northern Ireland increased from approximately 9% to approximately 45%. The baseline year for the study was the 2012–2013 reporting year and the *Northern Ireland Local Authority Collected Municipal Waste Management Statistics Annual Report 2012/13* (Burgess, 2013) reported that the total local authority collected municipal waste (LACMW) arisings were 913 546 t (the statistics have subsequently been updated for the years 2014/2015 and 2015/2016, and recommendations on updating have been included in discussion and conclusions). Of this amount, 91 216 t of municipal compostable waste excluding all wood, was collected at the kerbside and 59 555 t collected at civic amenity sites (150 772 t total) with 142 798 t (or 15·6%), reported as being composted.

- The total household waste arisings (2012/2013) were 803 624 t, with 141 428 t (or 17·6%, excluding all wood) reported as being composted.
- The estimated available compostable material, as household kerbside collected waste, was 239 418 t. Of this quantity, 90 938 t (37·9%) was captured in the 2012–2013 period, meaning that 148 480 t or 62·1% of compostable material was not captured in household kerbside separate collections.
- An amount of 276 702 t of biodegradable local authority collected municipal waste (BLACMW) was sent to landfill.

The Food Waste Regulations (Northern Ireland) 2015 (HMG, 2015) set out the following.

- Require food waste producers to present food waste for separate collection.
- Introduce an obligation on district councils to provide receptacles for the separate collection of household food waste.

- Introduce a ban on mixing separately collected food waste.
- Introduce a ban on the landfilling of separately collected food waste.
- Introduce a ban on the non-domestic discharge of food waste into the public sewer network.

The *Partial Regulatory Impact Assessment* (RIA) (DoENI, 2013) completed for the above regulations estimated

- the food waste collected by councils for the period 2011/2012, to be 12 820 t (comprising 12 113 t co-mingled and 707 t from separately collected food waste)
- the (indicative modelled) estimate of food waste that could be diverted from landfill if councils were to offer a separate food waste or co-mingled collection service as 79 960 t per annum (tpa), comprising 21 119 tpa from co-mingled collections and 58 841 tpa (maximum 59 062 tpa, minimum 58 619 tpa) from separate collections.

The RIA also provided figures for non-domestic food waste arising in Northern Ireland. In the lack of specific data for Northern Ireland, these were based on the assumption that commercial food waste composition and arisings in the UK were broadly indicative of that in Northern Ireland pro rata. The most reliable figures available to the Department of the Environment when preparing the RIA were the Waste and Resource Action Programme's (Wrap) *Tackling Priority Materials in Northern Ireland* report (Wrap, 2012), which suggested (indicatively) that for 2009, of Northern Ireland's

1.3 million t C&I waste arisings, approximately 150 000 t was food waste, managed as follows

- 36 443 t (in residual waste) disposed to landfill
- 34 935 t other
- 15 441 t reused
- 61 579 t recycled/composted.

The *Northern Ireland Organic Energy Study* (OES) report, published by Invest NI (Nicholl C and Smyth G, personal communication, 2010), reviewed the magnitude and extent of organic and food waste arisings in Northern Ireland. The information and data were collected by using a combination of methods including engagement with a range of public and private sector organisations, interviews and a survey of all companies of significant magnitude operating in the range of commercial and industrial sectors within Northern Ireland.

The final report referenced is the Southern Waste Management Partnership (Swamp) *Waste Management Plan* (Swamp, 2013), which provides its estimates for the quantities of municipal and C&I organic/biowaste generated within the south-west region of Northern Ireland and also Northern Ireland as a whole. There is a wide variation in the final total organic/biowaste arisings estimates, possibly as a result of differing methods or classification systems, which requires further investigation (Table 1).

4. Manures

Agricultural manures were previously excluded from regulations that controlled the management of household, C&I

Table 1. Northern Ireland organic/biowaste arisings

Waste	Quantity: t/year			
Data source	OES ^a	Wrap ^b	Swamp ^c	Current management
Municipal				
Household	188 000	381 320	162 811	Composting, landfill
Sewage sludge (dry)	39 000	37 700	39 000	Incineration
Total municipal	227 000	419 020	201 811	Average municipal = 282 610
C&I				
Retail food	35 700			Composting, pet food, returned to original supplier
Catering	4140			Composting, landfill, to drain sewer
Food processing	26 000			Composting, landfill, animal feed
Slaughterhouse	178 230			Land spreading, rendering, animal food
Dairy	13 200			Land spreading, landfill, animal feed
Drinks and distillery	12 000			Animal feed
Animal and vegetable waste			145 573	Composting, landfill, animal feed
Green and food waste		189 150		Composting, landfill, animal feed
Total C&I	269 270	189 150	145 573	Average C&I = 201 331
Total organic waste	496 270	608 170	347 384	Average total = 483 941

^aNicholl and Smyth, personal communication

^bWrap (2012)

^cSwamp (2013)

waste. The implementation of The Waste Management Regulations (Northern Ireland) 2006 (HMG, 2006), as amended, has however resulted in waste management controls applying to agricultural manures in accordance with the European Waste Framework and Landfill Directives (EC, 1999, 2008).

Table 2 shows that approximately 10.8 million t of manure are produced in Northern Ireland per year. The manures considered are cattle, pig and poultry. For cattle it was assumed that they are kept indoors for 6 months. Cattle manure is the main contributor to the total manure available in Northern Ireland. It is important to note that the ‘animal units’ in Table 2 can vary within a year, and numbers present may not be counted for the full year in the agricultural census. This is especially true for poultry units, due to the short life span for broiler chickens (about 5–8 weeks).

5. Agricultural crops

According to analysis by Goulding and Power (2013), biogas produced from grass silage can make a significant contribution to electrical and thermal energy production in the Republic of Ireland, with no negative effect on food production. Most agricultural land in Northern Ireland is under grass, as grass is the main feedstock of the ruminant livestock sectors – beef, dairy and sheep. An area of 0.78 Mha (excluding hill and rough land) is utilised for growing grass and clover in Northern Ireland. Much of the land under grass is unsuitable for alternative arable use, due to the topography and climatic conditions (Sharma *et al.*, 2011). If 5% of the grassland area in Northern Ireland was dedicated to grass silage production for AD (39 000 ha), the electrical output from this would be 1326 GWh (Smyth *et al.*, 2009).

Reasons for using grass to produce renewable energy in Northern Ireland include the following.

- Ninety-two per cent of agricultural land in Northern Ireland is under grass.
- Grass/silage yields on the island of Ireland are among the highest in Western Europe (Smyth *et al.*, 2009).
- The production of renewable energy (as biogas) from grass requires no major changes in agricultural practice and

would provide an additional option to farmers for income generation.

- Agriculture accounted for 26% of Northern Ireland’s GHG emissions in 2010 (CCC, 2015). AD is a proven method for mitigating GHG emissions from agricultural production (Kaparaju and Rintala, 2011).
- In 2010, 96% of fuel used in Northern Ireland was imported and the vast majority of this was from fossil sources (Department for the Economy, 2017). AD has the potential to reduce this dependence on fossil fuel.
- Biomethane production from grass is one of the most sustainable indigenous, non-residue-based European transport fuels in terms of GHG emissions (Murphy and Power, 2009).

6. Biogas and energy potential

Table 3 shows the theoretical estimates of biogas potential of different materials used as feedstocks for AD.

7. Potential biogas, biomethane and energy production from waste and grass silage in Northern Ireland

Table 4 shows that the estimates of the potential of electricity and heat production from wastes streams and grass silage is in the range 458–2020 GWh_e and 655–2885 GWh_h, respectively. It is important to note that these figures are the theoretical maximum potential (as explained in Figure 1). The figures in Table 4 do not include parasitic demands in the AD process. It is assumed that the AD process of an installed electrical power of 500 kW_e digesting crops only utilises 4% of electricity and 17% of heat (Weiland, 2010). The additional electricity requirement for upgrading was assumed to be 0.2 kWh per N m³ of biogas, based on water scrubbing. A review of a range of sources for the energetic requirements of biogas upgrading technologies suggested the energy requirements could potentially be much higher and the discussion and conclusions included a recommendation for a sensitivity analysis to evaluate the impacts of key assumptions on the estimates for the energetic requirements of biogas upgrading (Patterson *et al.*, 2011).

8. Reduction in GHGs

While the primary aim of the research was the quantification of feedstocks, the project did attempt to provide an estimate of the potential reductions in GHG emissions associated with the generation of energy and heat from the AD of the feedstocks. Table 5 sets out the potential for GHG emissions reduction from the replacement of fossil fuels with biogas, relative to grid electricity.

Table 2. Manure produced in Northern Ireland from housed livestock

Animal sector	Approximated manure: t/year
Cattle	10 million
Pig	500 000
Poultry	300 000
Total	10.8 million

Table 3. Biogas potential of different materials used as feedstocks for AD

Waste category	Waste amount: t/year	TS: %	VS: % of TS	Methane (CH ₄) yield: m ³ N CH ₄ /t VS	Methane yield average: m ³ N CH ₄ /t VS	Methane content: %	Methane content average: %	Biogas: m ³ /year	Methane: m ³ /year
Household ^a	244 043	10	80	350–480	415	70–80	75	10 802 999	8 102 249
Sewage sludge (2–5% VS) ^b	38 566	2.5	65	140–210	175	60	60	182 789	109 673
Retail food ^c	35 700	36	66.5	200–440	320	60	60	4 558 176	2 734 905
Catering ^d	4140	29	95	467–529	498	60	60	946 673	568 003
Food processing ^e	26 000	15	80	276–738	507	60	60	2 636 400	1 581 840
Slaughterhouse ^f	178 230	10	77	400–610	505	60	60	11 550 789	6 930 473
Dairy ^g	13 200	31.5	89.5	455–708	581.5	60–80	70	3 091 428	2 163 999
Drinks and distillery ^d	12 000	5	91	335–385	360	60	60	327 600	196 560
Dairy cattle manure ^e	10 000 000	8.5	80	110–240	175	55–75	65	183 076 923	119 000 000
Pig manure ^e	500 000	5.5	80	175–400	287.5	70–80	75	8 433 333	6 325 000
Chicken manure ^e	300 000	20	80	210–480	345	60–80	70	23 657 142	16 560 000
Grass silage ^h	1 937 170	20	91	341–483	412	60	60	242 094 606	145 256 763
Total								491 358 862	309 529 470
Approximation								491 million	309 million
									310 million

TS, total solids; VS, volatile solids

^aZhang et al. (2014)

^bPitk et al. (2013)

^cAlkanok et al. (2014)

^dBrowne and Murphy (2013)

^eSteffen et al. (1998)

^fKarlsson and Ejlertsson (2012)

^gLuna-del Risco et al. (2011)

^hNizami et al. (2012)

Table 4. Potential biomethane and energy production from waste and grass silage in Northern Ireland

Feedstock	Biomethane ^a : million m ³ N CH ₄ /year	Gross energy ^b : TJ/year	Electrical energy ^c : GWh _e /year	Heat energy ^c : GWh _h /year
Organic waste				
Total municipal	5–15	164–529	16–51	23–74
Total C&I	4–22	159–786	15–76	22–109
Total organic waste	9–37	324–1315	31–128	45–183
Agricultural				
Cattle manure	41–261	1455–9253	142–900	202–1286
Pig manure	2–5	68–178	7–17	9–25
Poultry manure	4–35	157–1227	15–119	22–171
Total manure	47–300	1680–10 658	163–1037	233–1481
Grass silage	76–247	2706–8785	263–855	376–1221
Total potential	133–585	4709–20 758	485–2020	655–2885

^aYiridoe *et al.* (2009)

^bMonson *et al.* (2007)

^cMurphy and Power (2009)

Table 5. Potential for GHG emissions reduction from the replacement of fossil fuels with biogas

Feedstock	Quantity: t/year	Biogas production average: million m ³ /year	Carbon dioxide reduction with CHP production: optimal use ^a : t carbon dioxide/year
Total organic wastes	421 827	23	76 927
Total manure	10 800 000	174	579 223
Grass silage	1 901 250	162	539 475
Total	13 791 995	359	1 195 626

^aWhiting and Azapagic (2014)

9. Digestate production and use

While the focus of AD has traditionally been biogas production and utilisation, circular and bioeconomy processes are leading to increased emphasis on the digestate outputs from the AD process, which account for approximately 90% of the outputs by weight (Tampio *et al.*, 2016). One interesting approach is to place AD within the anaerobic biorefinery concept, to allow for an integrated approach, which maximises synergies between them (Sawatdeenarunat *et al.*, 2016). The use of the anaerobic biorefinery concept allows the evaluation of both energy (electricity and heat) and chemical/material/nutrients management pathways in an integrated way and can contribute to the development of a roadmap for a regional bioeconomy (Vazquez-Rowe *et al.*, 2015). While digestate utilisation was not part of the original aims of the quantification of feedstocks project, the authors have submitted a companion paper (Pérez-Camacho and Curry, 2018), which applies the anaerobic biorefinery concept to the feedstock estimates generated by this research study, to identify utilisation options for the digestate outputs from the AD process using the anaerobic biorefinery concept.

10. Discussion and conclusions

This research investigation has enhanced understanding of potential feedstocks for AD in Northern Ireland and contributed to the development of an evidence base for the planning and implementation of a regional bioeconomy. While the investigation was developed based on the Northern Ireland region, the issues identified and discussed in this paper can provide insights for other projects on the bioeconomy potential at regional or sub-national level and help set out the priorities for research to support this important policy area. The outputs of the project have provided a snapshot of the potentially available AD feedstocks and estimated the quantities of wastes available for AD, which has the potential to benefit the regional bioeconomy significantly.

An important limitation of the research is the data and assumptions used to progress from waste flows to estimates of biogas production and ultimately to total potential electricity production. In terms of waste quantities, the baseline year for the project was 2013/2014 (this was required to ensure compatibility of the quantification of feedstocks with other

elements of the research programme) and it recommended that these data be updated. Additionally, a sensitivity analysis of key assumptions (such as biogas yield, parasitic loads, biogas upgrading energy requirements etc.) would allow the identification of future research priorities in this rapidly developing field.

One other important limitation of the research, within the context of the rapidly evolving concept of the bioeconomy, was its focus on feedstocks for AD. In recent years, the concept of the bioeconomy has further developed to include, in addition to biochemical processes such as AD, thermochemical processes, such as pyrolysis and gasification (producing syngas and biochar), and catalytic or enzymatic processes, such as fermentation. This evolution of the bioeconomy concept has the potential not only to increase significantly the range and quantity of feedstocks but also to enable the production of higher added-value products, thus contributing to the economic sustainability of the bioeconomy. A seminal report on the bioeconomy by the UK House of Lords, categorised feedstocks based on relative ease of access to carbon, and emphasised the challenge of ensuring that the 'feedstock-process-product combination represents an economically and environmentally viable proposition' (HLEUC, 2014: p. 13). The report identified the following process/sub-process categories for the bioeconomy.

- Thermochemical: pyrolysis, gasification.
- Chemical: catalytic processes, esterification.
- Bioprocessing: enzymatic processes; fermentation; biocatalysis; aerobic conversion (composting); AD.

Clearly, investigating the full range of process/sub-process categories allows for the identification of a wider range of feedstocks and product outputs and can allow the identification of potential synergies between these feedstock–process–product flows. Sawatdeenarunat *et al.* (2016) have identified the anaerobic biorefinery concept as a promising new approach for producing biobased products, with the potential to maximise potential economic benefits, and one potentially valuable area of further research is to apply the anaerobic biorefinery concept developed to the full range of process/sub-process categories for the bioeconomy. This identifies a number of interesting and important priorities for ongoing research, including

- feedstock evaluation – future evaluations should attempt, as far as possible, to identify the full range of potential feedstocks for the bioeconomy
- anaerobic biorefinery – further development of the anaerobic biorefinery approach by way of its application to the full range of process/sub-process categories for the bioeconomy.

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 future research.

Acknowledgements

This project was carried out by the QUESTOR centre at Queen's University Belfast and was part financed through Invest NI by the European Regional Development Fund under the European Sustainable Competitiveness Programme for Northern Ireland. Both Dr Elaine Groom and Dr Angela Orozco have been staff at QUESTOR when this project was undertaken. This paper was then prepared as part of the 'Biogas to Biorefinery' project to raise awareness about biogas in NI. The 'Biogas to Biorefinery' project was funded by the Centre for Advanced Sustainable Energy (CASE) through the Invest NI Northern Ireland Competence Centre programme, which bridges the gap between industry research needs and academic research offerings.

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