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Anaerobic digestion for biogas production forms one of the fundamental building blocks of the Bioeconomy, and a research programme has been underway 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. We report on the outputs of the Quantification of Feedstocks for Anaerobic Digestion research, which has identified the organic feedstocks available for biogas production on a regional basis and categorised these: organic (biodegradable) fraction of municipal solid waste (OFMSW), sewage sludge, organic industrial and commercial wastes, and manure from livestock, food wastes and energy crops. The research further quantified the biogas and energy potential of these feedstocks and possible reductions in Greenhouse Gas (GHG) emissions. The limitations of the research are acknowledged and opportunities to address these and build on and extend the research are identified, including the extension of the research to include feedstocks for other Bioeconomy processes and the application and further development of the biorefinery concept.

Keywords: biorefinery, anaerobic digestion, feedstock, bioeconomy

Introduction.

The increasing interest in the Circular Economy and the growing evidence for its benefits in terms of material savings, emissions reductions and job creation (Mitchell & Morgan, 2015) (Mitchell & Doherty, 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 (Economy, 2017) and accounts for a much higher proportion of the Region's total Greenhouse Gas emissions (GHG's), at 29% as opposed to 9% in the rest of the UK (Committee on Climate Change, 2015). In addition, the sector has set ambitious growth targets to 2020 (growth of sales by 60% to £7bn and sales outside Northern Ireland by 75%), which will result in a commensurate growth in wastes from this sector (Board, 2013). Anaerobic Digestion (AD) has been proposed by a range of researchers and policy makers as central to reducing emissions of GHG's from agriculture and food production (Kaparaju & Rintala, 2011) (Bacenetti et al., 2016), waste management (Davidsson, et al, 2007) and as a source of renewable energy (Curry & Pillay, 2012) and/or biofuels (Singh, Smyth, & Murphy, 2010) (Börjesson & Mattiasson, 2008).

In response to these drivers and challenges a programme of research has been on-going 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 & 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; and
- Provision of research expertise and facilities for manufacturers to commercialise ideas from R&D activities.

We report on one of the main outputs of this research, namely the Quantification of Feedstocks for Anaerobic Digestion. The need for classification and quantification of feedstocks is widely recognised by researchers and policy makers as essential to planning and implementation in all areas of waste and resource management (Thomas, C, 2004), and particularly for the information needs of the Bioeconomy (House of Lords European Union Committee, 2014). This research 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 greenhouse gas 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 e.g. commercial operations and district heating schemes;
- Upgrading biogas (biomethane) to be used as a biofuel for vehicles e.g. road freight, agricultural and similar plant and machinery.
- Upgrading biogas (biomethane) to natural gas quality for injection into the gas grid.

Methodology.

The research focussed on the theoretical estimates of the organic resources generated and potentially available, based on the methodology set out by Slade (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.

Figure 1.

Figure 1. Hierarchy of feedstocks and energy potential for Organic Resources for Anaerobic Digestion

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, i.e. food/beverage/tobacco processing wastes, slaughterhouse/rendering wastes, dairy wastes;
- Manure from livestock; and
- Food wastes from households (separately collected/source segregated), catering, restaurants, hotels.

Figure 2.

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

Results.

Municipal and Commercial & Industrial Organic Waste Arisings.

Waste arising's data for municipal and commercial & industrial wastes has 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 (WasteDataFlow, 2017). The accuracy of the data on commercial &

industrial (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 to 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 2012-2013' reported that (Burgess, 2013) the total Local Authority Collected Municipal Waste (LACMW) arisings were 913,546 t (the statistics have subsequently been updated for the years 2014/15 and 2015/16, and recommendations on updating have been included in discussion and conclusions). Of this amount, 91,216t 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 141,428t (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.
- 276,702 t of Biodegradable Local Authority Collected Municipal Waste (BLACMW) was sent to landfill.

The Food Waste Regulations (implemented in 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; and

- Introduce a ban on the non-domestic discharge of food waste into the public sewer network

The (partial) Regulatory Impact Assessment (RIA) (Ireland, 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); and
- The (indicative modelled) estimate of food waste that could be diverted from landfill if councils were to offer a separate food waste or comingled collection service as 79,960 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 Northern Ireland- specific data, 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 (Waste and Resource Action Programme, 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 'Organic Energy Study Report', published by Invest NI (Nicholl & Smyth, 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 ‘SWAMP2013 Waste Management Plan’, 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. The 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. Northern Ireland Organic/Biowaste Arisings

Table 1.

a(Smyth & Nicholl, 2010), b(Waste and Resource Action Programme (WRAP), 2012), c(SWAMP, 2013)

Manures

Agricultural manures were previously excluded from regulations that controlled the management of household, commercial and industrial waste. The implementation of the Waste Management Regulations (Northern Ireland) 2006 (S.R. No. 280 of 2006), as amended, has however resulted in waste management controls applying to agricultural manures in accordance with the European Waste Framework and Landfill Directives.

Table 2 shows that approximately 10.8 million tonnes 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 to 8 weeks).

Table 2. Manure produced in Northern Ireland from housed livestock.

Table 2.

Agricultural crops.

According to analysis by Goulding & 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, Lyons, & McRoberts, 2011). If 5% of the grassland area in Northern Ireland was dedicated to grass silage production for anaerobic digestion (39,000 ha), the electrical output from this would be 1,326 GWh (Smyth, Murphy, & O'Brien, 2009).

Reasons for using grass to produce renewable energy in Northern Ireland include:

- 92% 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, Murphy, & O'Brien, 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 greenhouse gas emissions in 2010 (Committee on Climate Change, 2015). AD is a proven method for mitigating GHG emissions from agricultural production (Kaparaju & 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, 2013). AD has the potential to reduce this dependence on fossil fuel
- Bio-methane production from grass is one of the most sustainable indigenous, non-residue based European transport fuels in terms of GHG emissions (Murphy & Power, 2009).

Biogas and Energy Potential

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

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

Table 3

a(Zhang et al., 2014), b(Pitk et al., 2013), c(Alkanok et al., 2014), d(Browne & Murphy, 2013), e(Steffen et al., 1998), f(Karlsson & Ejlertsson, 2012), g(Luna-del Risco et al., 2011), h(Luna-del Risco et al., 2011), (Steffen et al., 1998), i(Steffen, et al, 1998), j(Steffen, et al, 1998), k(Steffen, et al, 1998), l(Nizami et al., 2012).

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 of 458 – 2,020 GWh_e and 655 – 2,885 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 Nm^3 of biogas, based on water scrubbing. The author's 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).

Table 4. Potential Biomethane and Energy Production from waste and grass silage in N Ireland.

Table 4

a(Yiridoe et al., 2009), b(Monson et al., 2007) (TJ/y), c and d(Murphy & Power, 2009)

Reduction in Greenhouse Gases (GHG's).

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

Table 5.

a(Whiting & Azapagic, 2014)

Digestate production and use.

While the focus of anaerobic digestion 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 anaerobic digestion 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 article to this, which applies the Anaerobic Biorefinery concept to the feedstock estimates generated by this research, to identify utilisation options for the digestate outputs from the AD process using the anaerobic biorefinery concept

Discussion and conclusions.

The research has enhanced our understanding of potential feedstocks for anaerobic digestion 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 significantly benefit the regional Bioeconomy.

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 2013/14 (this was required to ensure compatibility of the quantification of feedstocks with other elements of the research programme) and it recommended that this 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 Anaerobic Digestion. In recent years, the concept of the Bioeconomy has further developed to include, in addition to biochemical processes such as anaerobic digestion, 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 to not only significantly increase the range and quantity of feedstocks but also 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'* (House of Lords European Union Committee, 2014). 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); anaerobic digestion.

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; and
- Anaerobic Biorefinery: the further development of the anaerobic biorefinery approach via 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.

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Waste	Quantity (tonnes/year)			Current management
Data source	OES [a]	WRAP [b]	SWaMP [c]	
Municipal				
Household	188000	381320	162811	Composting, landfill
Sewage sludge (dry)	39000	37700	39000	Incineration
Total Municipal	227000	419020	201811	Average Municipal = 282610
Commercial and Industrial				
Retail food	35700			Composting, pet food, returned to original supplier
Catering	4140			Composting, landfill, to drain sewer
Food processing	26000			Composting, landfill, animal feed
Slaughter house	178230			Land spreading, rendering, animal food
Dairy	13200			Land spreading, landfill, animal feed
Drinks and distillery	12000			Animal feed
Animal and vegetable waste			145573	Composting, landfill, animal feed
Green and food waste		189150		Composting, landfill, animal feed
Total C&I	269270	189150	145573	Average C&I = 201331
Total Organic Waste	496270	608170	347384	Average total = 483941

Table 1. Northern Ireland Organic/Biowaste Arisings

Animal sector	Approximated manure (tonnes/year)
Cattle	10 mill.

Pig	500000
Poultry	300000
Total	10. 8 mill.

Table 2. Manure produced in Northern Ireland from housed livestock.

Waste category	Waste amount (tonne/year)	TS (%)	VS (% of TS)	CH_4 Yield (m^{3}N CH_4/tonne VS)	CH_4 Yield Average (m^{3}N CH_4/tonne VS)	CH_4 Content (%)	CH_4 Content Average (%)	Biogas (m^3/year)	CH_4 (m^3/year)
Household [a]	244043	10	80	350-480	415	70-80	75	10802999	8102249
Sewage sludge (2-5% VS)[b]	38566	2.5	65	140-210	175	60	60	182789	109673
Retail food [c]	35700	36	66.5	200-440	320	60	60	4558176	2734905
Catering [d]	4140	29	95	467-529	498	60	60	946673	568003
Food processing [e]	26000	15	80	276-738	507	60	60	2636400	1581840
Slaughter house [f]	178230	10	77	400-610	505	60	60	11550789	6930473
Dairy [g]	13200	31.5	89.5	455-708	581.5	60-80	70	3091428	2163999
Drinks and distillery [h]	12000	5	91	335-385	360	60	60	327600	196560
Dairy cattle manure [i]	10000000	8.5	80	110-240	175	55-75	65	183076923	119000000
Pig manure [j]	500000	5.5	80	175-400	287.5	70-80	75	8433333	6325000
Chicken manure [k]	300000	20	80	210-480	345	60-80	70	23657142	16560000
Grass silage [l]	1937170	20	91	341-483	412	60	60	242094606	145256763
							Total	491358862	309529470
							Approximation	491 mill m^3/y	309 mill m^3//y
									310

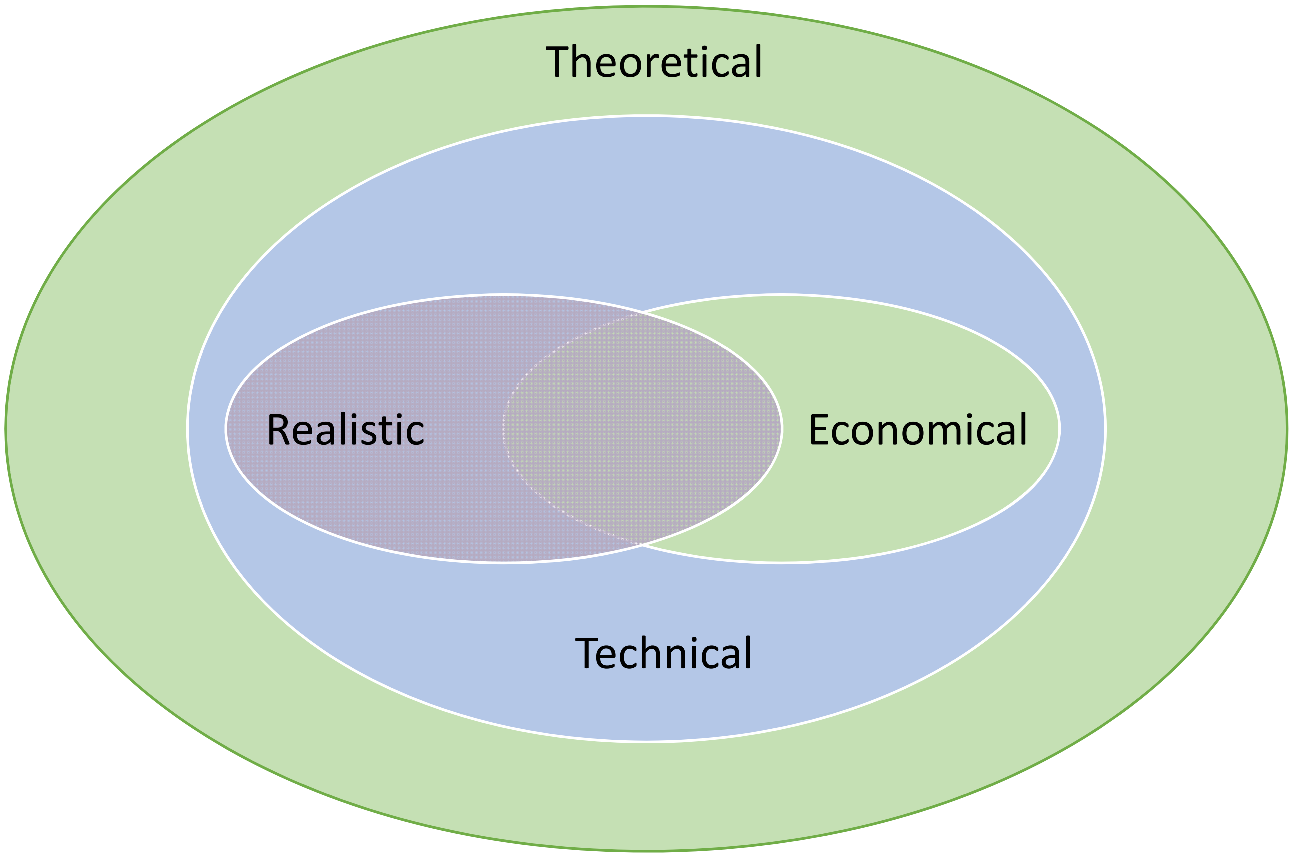
Table 3. Biogas potential of different materials used as feedstocks for Anaerobic Digestion.

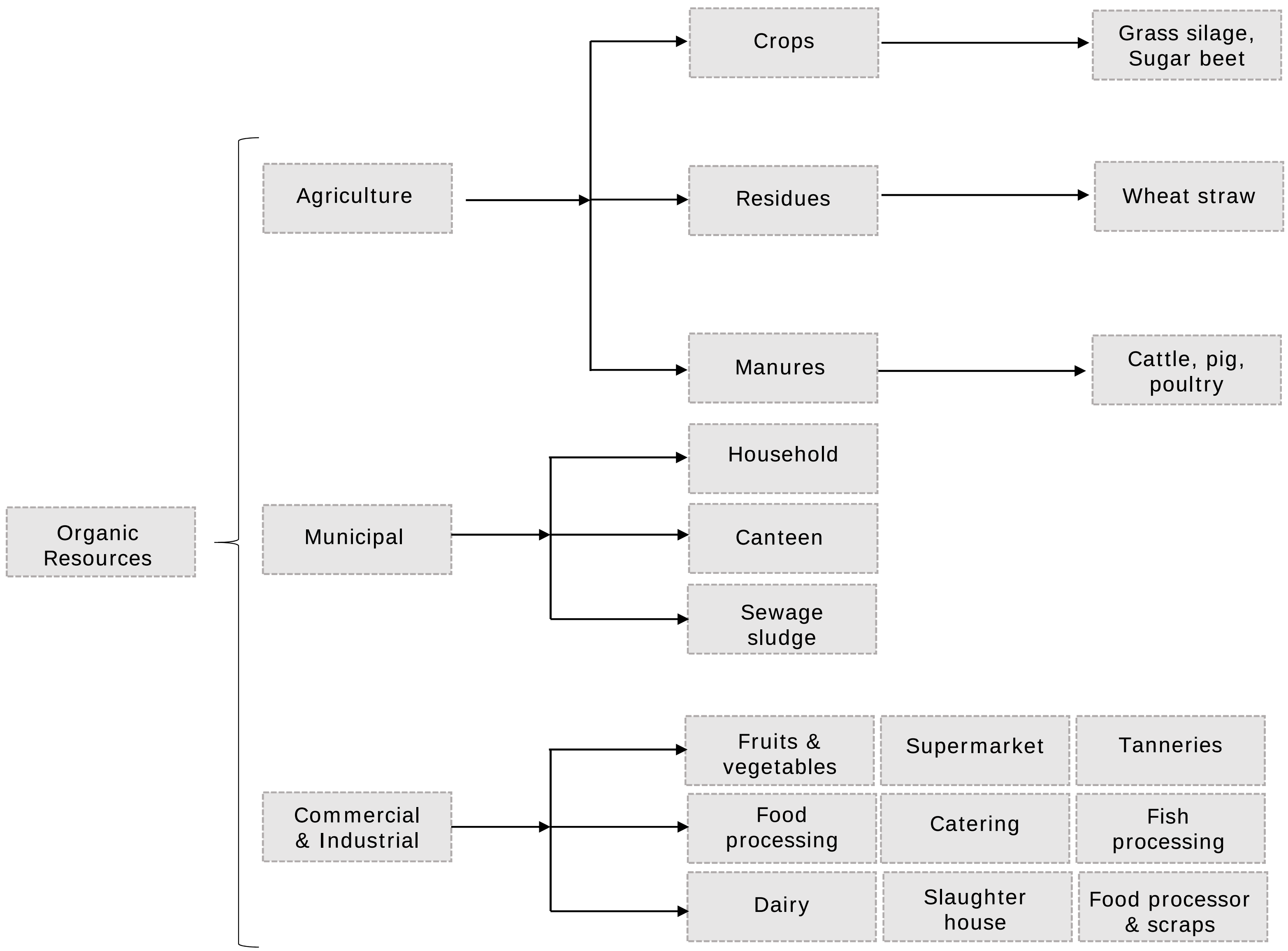
Feedstock	**Bio Methane** [a] (m^3N CH_4/y)*millions	**Gross Energy** [b] (TJ/y)	**Electrical Energy** [c] (GWh_e/y)	**Heat Energy** [c] (GWh_h/y)
Organic Waste				
Total Municipal	5 - 15	164 – 529	16 – 51	23 – 74
Total C&I	4 – 22	159 – 786	15 – 76	22 – 109
Total Organic Waste	9 - 37	324 – 1,315	31 – 128	45 – 183
Agricultural				
Cattle Manure	41 – 261	1,455 – 9,253	142 – 900	202 – 1,286
Pig Manure	2 – 5	68 – 178	7 – 17	9 – 25
Poultry Manure	4 – 35	157 – 1,227	15 – 119	22 – 171
Total Manure	47 – 300	1,680 – 10,658	163 – 1,037	233 – 1,481
Grass Silage	76 - 247	2,706 – 8,785	263 – 855	376 – 1,221
Total Potential	133 - 585	4,709 – 20,758	485 – 2,020	655 – 2,885

Table 4. Potential Biomethane and Energy Production from waste and grass silage in N Ireland.

Feedstock	Quantity (t/yr)	Biogas Production Average (m3/yr)*million	CO_2 reduction with CHP production: optimal use [a] (t CO_2/yr)
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

Table 5. Potential for GHG emissions reductions from the displacement of fossil fuels with biogas.


Theoretical
Realistic
Economical
Technical


Organic Resources
Agriculture
Crops
Grass silage, Sugar beet
Residues
Wheat straw
Manures
Cattle, pig, poultry
Municipal
Household
Canteen
Sewage sludge
Commercial & Industrial
Fruits & vegetables
Supermarket
Tanneries
Food processing
Catering
Fish processing
Dairy
Slaughter house
Food processor & scraps