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Biogas from cattle slaughterhouse waste: Energy recovery towards an energy self-sufficient industry in Ireland

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ABSTRACT

This study was carried out to assess the energy recovery potential from organic industrial by-products of a cattle slaughtering facility. There are several processes to convert organic material to energy; the technology of interest in this study was anaerobic digestion, the biological conversion of degradable organic material into methane. The scenario was initially confined to a full scale cattle slaughtering facility processing 3.28% of heads slaughtered in Ireland. The methane potential of dissolved air flotation sludge, paunch, soft offal as well as a mixed waste stream (combination of individual waste streams) was determined through a series of biochemical methane potential assays under mesophilic conditions. The methane potential of the characterised waste streams ranged from 49.5 to 650.9 $mLCH_4\ gVS^{-1}$. The potential energy recovery from the mixed waste stream resulted in the prospective subsidy of 100% of the energy demands of the slaughtering facility as well as the energy demands for the production of the biogas. When investigating the impact of energy recovery from the entire sector the potential energy recovery equated to 1.63% of the final energy demands of the Irish industrial sector. This could potentially increase the RES in Ireland from 7.8% to 8.13% contributing to both RES-E and RES-H.

1. Introduction

1.1. Beef industry in Ireland

Despite unprecedented growth of the Irish economy since the early 1990s, the agri-food sector remains one of Ireland's largest industries as measured by wealth generation (7.7% of GVA), exports (11.5% of total merchandise exports) and employment (9.2% of total employment) [1,2]. A major facet of this sector is Irelands beef industry producing 516,900 tonnes of meat from the slaughtering of over 1.59 million heads of cattle in 2013 [3]. Ireland is the biggest net exporter of beef in the EU and the 5th largest in the world [4]. Export volumes stand at approximately 90% of annual production and contribute 22.3% (2.57% of total merchandise exports) of exports in the agri-food sector in Ireland. High amounts, as much as 45–53% of the live weight of the animal, of organic by-products which are considered to be industrial organic wastes are generated from this industry [5]. As regards the main organic wastes streams, there is blood of the bleeding process, paunch from the removal of the rumen and intestinal content, the intestinal residues from the evisceration processes, fat from the meat trim step as well as the head and the limbs (mostly bone). Moreover, sludge from the wastewater treatment plant of the slaughterhouse is generated. These wastes are characterised by high organic content mainly composed of animal proteins and fats [6–8]. They are strictly managed by legislation, Animal By-Products Regulation (ABPR 1069/2009/EC), in order to prevent the outbreak and spread of diseases such as Bovine Spongiform Encephalopathy and the dangerous human disease Creutzfeld-Jacob [9].

1.2. Treatment of organic waste streams

There are a number of permissible disposal routes under the ABPR with the most common being; material sent for rendering (bones, inedible offal, blood, trimmings etc.) or land spreading (sludge's, paunch, lairage washings etc.). The high organic content of the waste streams generated from the slaughterhouse make them an attractive feedstock for anaerobic digestion (AD) which is considered a suitable treatment method provided approved pre-treatments are applied if required under the ABPR, excluding SRM; material with the highest risk or carrying disease (heads, spinal cord, condemned meat etc.) which is only suitable for

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Nomenclature

ABPR	animal by-products regulation
AD	anaerobic digestion
BMP	biochemical methane potential
C	carbohydrates
CHP	combined heat and power
CSO	central statistics office
DAF	dissolved air flotation
GFC	gross final energy consumption
GVA	gross value added
H	hydrogen
HRT	hydraulic retention time
LCFA	long chain fatty acids
N	nitrogen
NaOH	sodium hydroxide
NREAP	national renewable energy action plan
PA	paunch
RES	renewable energy share
RES-E	renewable energy share-electricity
RES-H	renewable energy share-heat/thermal
SHWM	slaughterhouse waste mixed at annual production ratios
SMY	specific methane yield
SO	soft offal
SRM	specified risk material
TS	total solids
UNFCCC	United Nations framework convention on climate change
VS	volatile solids

incineration or landfilling [7,10–12]. AD has long been considered to be one of the best alternatives for nutrient and energy recovery from organic solid wastes with high protein and fat content [13]. In AD the organic waste is converted to biogas, primarily methane, and a nutrient rich digestate through a series of biochemical processes. The methane produced can be utilised for energy production while the nutrient rich digestate can be employed as a soil conditioner [6]. This alternative treatment method is an effective option, combining material and energy recovery allowing the possibility of an energy self-sufficient industry while incorporating a holistic waste treatment system [6,7,14,15].

1.3. Focus of paper

The focus of this paper is to determine the methane potential of the available organic waste streams, in order to identify the potential energy that could be recovered through the exploitation of AD as an alternative waste treatment within the confines of a full-scale cattle slaughterhouse. The potential energy recovery is assessed in terms of subsidising the process energy of the slaughtering facility and evaluating the degree of energy self-sufficiency that could be achieved. Advancing from the boundaries of a single slaughtering facility, the cattle slaughtering sector in Ireland is also appraised. The contribution of the potential renewable energy generation from the entire sector is assessed in terms of progress towards meeting Irelands 2020 renewable energy targets, RES of 16%, mandated under the Renewable Energy Directive (2009/28/EC) [16].

2. Materials and methods

2.1. Determination of potential methane yield

2.1.1. Slaughterhouse wastes

The sampled slaughterhouse was located in Cork, Ireland and processed approximately 52,000 heads of cattle annually (3.28% of total annual slaughterings in 2013). The slaughtering waste streams considered for this study were paunch (PA), soft offal (SO) (intestinal residues, fat and meat trimmings and some blood) as well as dissolved air flotation sludge (DAF) from the wastewater treatment facility onsite. SRM was not included as per the ABPR regulations while the limbs were not included due to their low biodegradability (primarily made up of bone). As well as treating the three selected waste streams on an individual basis they were mixed together according to their annual production ratios (1:2.55:3.22-PA:DAF:SO), referred to as SHWM from this point on, in order to investigate the implications of treating the three waste streams collectively. Pasteurisation (70 °C for min 1 h) was applied to the SO prior to testing in all cases as per the ABPR for the treatment of category 3 material. The consistency of the wastes in their sampled state did not permit their direct use in accurate BMP assays or composition analysis and thus all samples were mixed and blended thoroughly in order to reduce particle size (<8 mm) and create representative specimens with a uniform particle size. It is important to note that even after the preparation process the offals are still characterised as heterogeneous this reality enforces the need for triplicate testing [6].

2.1.2. Analytical systems

The composition analysis was carried out in terms of basic, organic and elemental characterisation. The basic parameters used for substrate and inoculum description were the Total Solids (TS) and Volatile Solids (VS) content determined in accordance to Method 1684 of the U.S. EPA for Total, Fixed and Volatile Solids in Water, Solids and Biosolids [17]. The organics (VS) within the substrates were further broken down into primary constituents of fats, proteins and carbohydrates. Fats and proteins were determined by an approved laboratory for the microbiological testing of animal by-products in accordance with Commission Regulation 142/2011/EU implementing the ABPR [9,18]. The difference between VS, fats and protein content was designated as carbohydrates. The elemental composition (C, H, N) was determined following the standard operating procedure of a CE440 Elemental Analyser, with O being designated as the difference between VS and the C, H and N content.

2.1.3. Theoretical methane yield

The elemental composition of the substrate (C, H, O) determined from the elemental analysis was used to calculate the gas composition in terms of % CH_4 and CO_2 based upon the stoichiometry of the degradation reaction using the Buswell equation [19];

$$C_cH_hO_o + \left(c - \frac{h}{4} - \frac{o}{2}\right)H_2O \rightarrow \left(\frac{c}{2} + \frac{h}{8} - \frac{o}{4}\right)CH_4 + \left(\frac{c}{2} - \frac{h}{8} + \frac{o}{4}\right)CO_2 \quad (1)$$

Eq. (1) in most cases will be optimistic in terms of methane yield since neither non-degradable organics nor energy demand of the bacterial populations is considered [20]. However it can provide a suitable indication as to the biogas composition of the substrates.

2.1.4. Biochemical methane potential experiments

The methane potential of the solid organic waste streams was determined using Biochemical Methane Potential (BMP) assays under mesophilic conditions (39 °C). The BMP protocol followed in this study was based on principles described in DIN 38 414 (S8) and VDI 4630 with alterations to the gas measurement system for direct measurement of the methane fraction of the biogas produced and is fully described in Ware and Power (2016) [21–23]. The inoculum employed was sourced from a mesophilic reactor treating dairy processing waste and was pre-incubated under the same temperature range as the operational temperature of the BMPs to deplete any residual biodegradable organic material. The inoculum to substrate ratio for the BMP assays was 2 based on VS content and performed in a working volume of 900 mL using a 1000 mL reactor. The large reactor size employed was to ensure an adequate sample size to allow representative sampling of the organic waste streams, due to their heterogeneous nature. Triplicate BMP assays were carried out for each of the solid waste streams and were incubated for a period of 30 or 50 days in tandem with triplicate control assays (containing only inoculum). The guideline for the termination of the assays was when the daily gas production was equivalent to approximately 1% of the total volume produced over the period of the test. The initial incubation period selected for this study was 30 days as the majority of the biodegradation would be completed at this stage, if required an extended period of 50 days was employed [20].

The methane production was determined directly through positive liquid displacement and the use of an alkaline solution (0.5 M NaOH), removing the carbon dioxide fraction and consequently the need for offline gas composition analysis. The methane production was measured daily to allow the kinetics of the process to be followed and to provide direction as to the stability of the process. At the end of the incubation period, a pH measurement was taken of all BMP assays to ensure that the methane production had not ceased due to acidification or if alkaline solution had been drawn into the reactors. The net methane production from the substrate was calculated by subtracting the methane production of the control reactors from that of the active reactors. The methane potential of the substrates were evaluated based on their Specific Methane Yield (SMY) defined as the net volume of methane produced during the incubation period per amount of VS content of substrate initially added to the reactor, measured as $mLCH_4\ gVS^{-1}$. Statistical analysis of the results from the BMP assays was carried out using SPSS (IBM SPSS 22).

2.1.5. Kinetic modelling

In this study the modified form of the Richards sigmoidal function by Zwietering et al. (1990), Eq. (2), was applied to the experimental data to determine the maximum methane production potential (A), maximum rate of methane production (μ_m) and the duration of the lag phase (λ) [24]. The modified Richards model also incorporates a fourth parameter (v) that permits flexibility in the shape of the curve, fundamental when dealing with the possibility of methane production curves varying from the typical sigmoidal elongated S-shape or reverse L-shape.

$$y = A\left\{1 + v\cdot\exp(1+v)\cdot\exp\left[\frac{\mu_m}{A}\cdot(1+v)^{\left(1+\frac{1}{v}\right)}\cdot(\lambda - t)\right]\right\}^{-1/v} \quad (2)$$

λ is an indication of the minimum time taken for the methanogenic bacteria to acclimate to the environment and is defined as the x-axis intercept of the tangent of the inflection point of the curve [24,25]. A nonlinear least square regression analysis was performed using Microsoft Excel 2013 to determine A, μ_m, λ and v. The coefficient of determination or correlation coefficient (R^2) was obtained to determine the correlation of the modelled and experimental data.

2.2. Net energy analysis methodology

The potential energy recovery within the confines of the full scale cattle slaughtering facility was determined through a net energy analysis. A net energy analysis is the examination of how much energy is available for utilisation after correcting for how much of that potential energy is exhausted in generating a unit of the energy in question [26]. The principal aims were to; determine the energy input for the production of biogas from the slaughterhouse waste stream, and determine the level of energy recovery within the slaughtering facility through the combustion of the raw biogas in a CHP unit.

2.2.1. System boundaries

A flow diagram of the process chain of the biogas production system and energy recovery is shown in Fig. 1. The series of events are as follows; (1) production of organic waste/feedstock in slaughtering facility, (2) maceration and homogenisation of the feedstock, (3) transport of macerated feedstock (4) pasteurisation of feedstock as per ABPR, (5) feedstock digested in AD reactor, (6) raw biogas combusted in CHP unit to produce electricity and heat. It was assumed that the biogas production facility was located on the same site as the slaughtering facility; as such transport of the waste on a large scale would be surplus to requirements and was not considered in the analysis. Also it is worth noting that due to the pasteurisation of the waste stream prior to AD the digestate may be utilised as a fertiliser without any further treatment. As such further handling of the digestate is not considered within the boundaries of this study. The biogas production is based on a one stage "wet" mesophilic AD process treating the feedstock in a round monolithic concrete reactor. The digestion technology represents solid waste digestion as it is developed in Western Europe. In the one stage process the initial hydrolysis and acidification takes place in the same reactor vessel as the methane production. It was assumed that the heat demand of the reactor to maintain a digestion temperature of between 35 and 40 °C was met from the preheating of the feedstock to 70 °C during the pasteurisation step. The movement of the feedstock within the system was accommodated by an eccentric screw pump. The eccentric screw pump operates under constant pressure therefore continually propels the feedstock from the maceration unit, through the pasteurisation stage and then into the digester at a steady pace, accounting for the feedstock conveyance from point of maceration to entering the digester [27]. Due to the close proximity of the biogas facility energy losses from the transmission of electricity and thermal energy from the CHP unit to the slaughtering facility were deemed negligible. The energy inputs indicated for each of the processes outlined in Fig. 1 were assumed to be met by the Irish national electrical grid which operates with a generation efficiency of 48.29% (transformation losses of 45.73% and transmission losses of 5.98%) [28].

2.2.2. Inputs and outputs within system boundaries

2.2.2.1. Biogas production and utilisation. On exiting the slaughtering facility the organic waste streams typically exist in a state that is non-conforming to efficient biogas production i.e. large solid particles, high heterogeneity, separated waste streams etc. As such the initial step in the system analysed is the maceration and homogenisation of the waste streams. The maceration unit is based on a heavy duty grinder, suitable for bulk reduction and proven successful in the maceration and reduction of organic waste particle

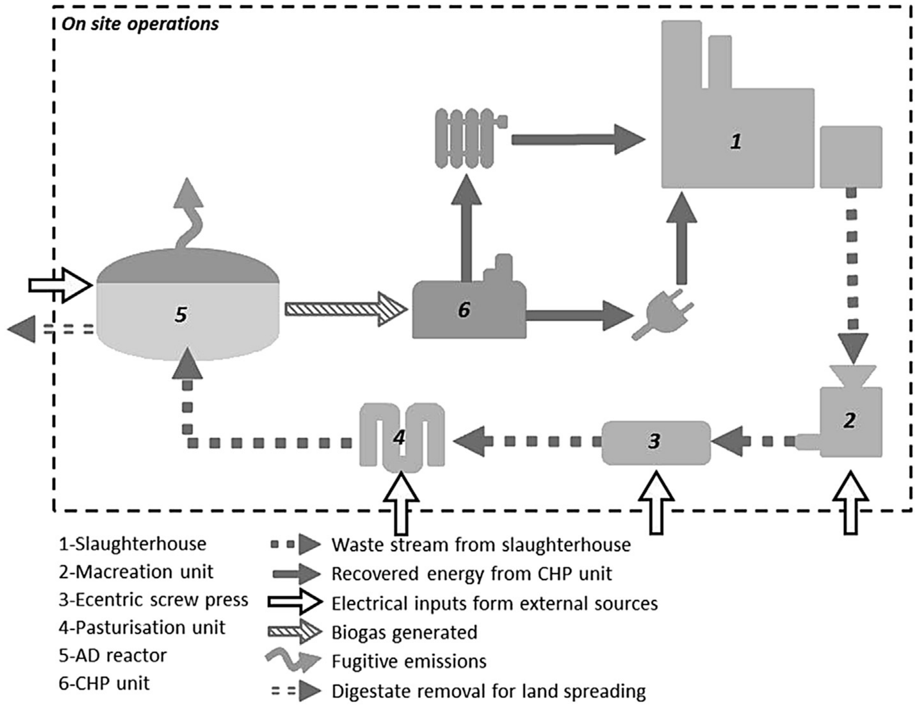

Fig. 1. Process chain of biogas production system and energy recovery.

size, to offer a more homogeneous mixture in active biogas facilities [29]. The unit operates at 1200 kg/h and an electricity consumption of 7.5 kWh which equates to 6.25 kWh/t of feedstock [29]. The eccentric screw pump incorporated was a generic model described as a rotary self-priming piston pump, suitable for substrates with high viscosity, and capable of being combined with a macerator [27]. The eccentric screw pump has an electricity consumption of 7.5–55 kW and a throughput of 0.5–4 m^3/min [27]. Taking that the macerator is operating at 1200 kg/h it was assumed that the screw conveyor could operate on its lowest setting of 0.5 m^3/min and be more than capable of handling the throughput. This results in an electrical consumption the same as that of the maceration unit at 6.25 kWh/t of feedstock. The pasteurisation process incorporated was in accordance to ABPR, 70 °C for a minimum of 1 h, due to the presence of Category 3 material (SO) [9]. The electrical consumption required was to raise the temperature of the water within the feedstock from 10 °C, assumed ambient storage temperature, to 70 °C and was calculated using Eq. (3).

$$kWh/kg\ of\ water = \frac{\Delta T \times C_w}{3.6 \times 10^{-3}} \quad (3)$$

where;

ΔT Temperature difference (60 °C).
C_w Specific heat capacity of water (4.184 kJ/kg/°C).
3.6×10^{-3} Change from MJ to kWh.

This resulted in an electrical demand of 69.7 kWh/t of water in the feedstock. The energy demand of the rector is taken as 10 kWh/t of feedstock [30]. Fugitive emissions (i.e. losses) of biogas produced prior to utilisation are common place in modern facilities, they may occur from biogas storage tanks, valves, pipe connections etc. [31]. The fugitive emissions in this study were estimated according to the UNFCCC-Clean Development Mechanism which provide default emission values for methane fugitive emissions from anaerobic digesters in their methodological tool "project and leakage emissions from anaerobic digesters" [32]. The default fugitive emission value applied was 0.028 of the methane produced associated with a lined concrete digester of monolithic construction [32].

Few studies exist correlating the relationship between BMP assays as predictors for large scale AD. *Bishop* et al. determined that the prediction of methane production from BMP assays for full scale application is accurate, with a correlation of $R^2 = 0.83$ and an over prediction of just 1.54% [33]. Thus the methane production data from the BMPs were used to determine biogas recovery values. The utilisation pathway consisted of the combustion of the raw biogas with a Lower Heating Value (LHV) of 37 MJ/m^3 CH_4 in a CHP unit with a total net efficiency of 90%, 41% generated as electricity and 49% as heat [34]. The recovered electrical and thermal energy are then fed back into the slaughtering facility.

2.2.2.2. Energy consumption of slaughtering facility. The energy consumption of slaughtering facilities vary depending on the technologies utilised, energy/waste saving schemes employed, scale as well as the level of processing i.e. whole carcass chilled/frozen, finer cuts deboned chilled/frozen [35–37]. Within Ireland a study was carried out over a period of 7 years, 2003–2008 by Enterprise Ireland on the sustainable practices in Irish beef industry [38]. As part of this studies the energy consumption of 16 slaughtering facilities were investigated in order to determine a mean energy demand of the slaughtering process. The mean energy demand per head reported for 2008 was 897 MJ/head slaughtered with a 43:57 split of electrical and thermal demands [38]. Taking an average carcass weight of 309.4 kg, based on CSO stats on livestock slaughterings in 2008 the total energy demand equates to 2899 MJ/t carcass weight, 1247 MJ/t electrical and 1653 MJ/t thermal [39].

3. Results

3.1. Assessment of slaughterhouse waste streams

3.1.1. Characterisation of organic waste streams

The characterisations of the studied waste streams are presented in Table 1. As was expected the characterisation identifies the waste streams as having high organic contents indicated by their high VS content, 81.9–98.6%. Fat content was highest (58.1%) in the SO with SHWM, DAF and PA showing fat contents of 28.4%, 1.9%, and 0.5% respectively.

Protein was highest (33.7%) in the DAF primarily due to the high quantities of blood mixing with the wastewater, followed by SHWM, SO and PA at 27.3%, 26.5% and 13.8%. The carbohydrate content varied quite significantly from 78.4 to 14.0%. The high carbohydrate content in the PA was expected as it is partly digested animal feed. The high fat contents of the SO and SHWM bode well in terms of methane production with fats having a 85% and 75% higher methane potential than carbohydrates and proteins respectively [22,40].

3.1.2. Methane yields of organic waste streams

Cumulative methane yields of the slaughterhouse wastes are presented in Fig. 2. While the SMY along with biogas composition based on the elemental composition of the waste streams are presented in Table 2. The highest methane yield was achieved from the SO at 651 mLCH$_4$ gVS^{-1} followed closely by SHWM (642 mLCH$_4$ gVS^{-1}). With PA accumulating less than half of this with a yield of 229 mLCH4 gVS^{-1} and finally the DAF had a much lower yield of 50 mLCH$_4$ gVS^{-1}.

The kinetics of the methane production for the waste streams differed greatly established by the varied methane production curves observed in Fig. 2 and the results of the kinetic modelling presented in Table 3. These results are by no mean trivial and provide valuable insight as to the biodegradability characteristics of the waste streams [20]. All of the kinetic models provided good fits with R^2 values in the range of 0.959–0.999 as well as good visual fits. Thus the modified Richards models were reasoned as a good fit for the biogas transformation of the tested waste streams. The reverse L-shape of the cumulative curves for PA and DAF and the λ value of 0 days for both indicates that the majority of the available organic solids were hydrolysed quite rapidly. The similarity in the A and the SMY value also indicates that maximum degradation occurred over the 30 days for both waste streams. This indicates that there were no complex compounds present which could extend the hydrolysis period or no immediate concerns to suggest inhbition of any kind.

The DAF presented with a very low SMY and 80% of the methane yield was observed after only 3 days. Given that the DAF was primarily made up of large amounts of degradable organic matter including; meat, fat and tissue scrapings as well as manure and paunch particles this low methane yield was unexpected. The results of the triplicate reactors agreed and no apparent signs of inhbition were observed and consequently the average methane yield was taken as a somewhat conservative energy value for the DAF. Paunch produced the second highest SMY of the individual substrates. The high carbohydrate content of the paunch would suggest that the methane production would be limited by the hydrolytic phase given the complex nature of carbohydrates (lignin, cellulose). However due to the fact that the paunch is removed from the stomach of the ruminant before it can be fully digested by the cattle the proportion of more bioavailable carbohydrates such as monosaccharides and disaccharides are much higher than what would be present in cattle manure. These more degradable carbohydrates in comparison to cellulose and lignin (polysaccharides), manifest in a reverse L-shape methane production curve typical of less complex feedstocks. The presence of the readily degradable carbohydrates is evident from the fact that 80% of the methane yield occurs within the first 11 days and the maximum daily methane yield occurring on day 1.

The methane production of the pasteurised SO demonstrated a

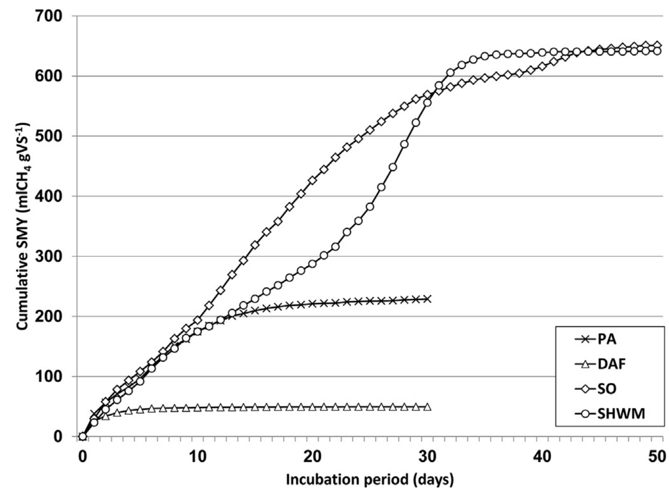

Fig. 2. Cumulative SMY of waste streams.

Table 1
Characteristics of organic waste streams.

	PA	DAF	SO	SHWM
TS[a]	22.2 (0.03)	5.7 (0.20)	53.9 (3.24)	33.8 (1.21)
VS[a]	92.7 (0.36)	81.9 (0.21)	98.6 (0.08)	96.7 (0.16)
Fat[b]	0.5	1.9	58.1	28.4
Protein[b]	13.8	33.7	26.5	27.3
Carb[b]	78.4	46.3	14.0	41.0
C[b]	46.8	43.2	65.8	54.5
H[b]	6.3	6.3	10.8	8.4
O[b]	37.4	26.6	18.9	29.8
N[b]	2.2	5.7	3.1	3.9

PA: Paunch, DAF: Dissolved air flotation sludge, SO: Soft offal, SHWM: mixture of PA, DAF and SO at annual production ratios.
[a] % (standard deviation).
[b] % of TS.

Table 2
Normalised methane yield and biogas composition based on elemental characterisation.

	PA	DAF	SO	SHWM
SMY[a]	228.8 (6.8)	49.5 (10.1)	650.9 (7.2)	641.6 (2.1)
CH_4	55%	60%	69%	63%
CO_2	45%	40%	31%	37%

PA: Paunch, DAF: Dissolved air flotation sludge, SO: Soft offal, SHWM: mixture of PA, DAF and SO at annual production ratios.
[a] SMY: specific methane yield in mlCH$_4$ gVS^{-1} (standard deviation).

Table 3
Kinetic parameters estimated by the modified Richards model.

	PA	DAF	SO	SHWM
A (mlCH$_4$ gVS^{-1})	226.7	48.6	663.2	639.5
μ_m (mlCH$_4$ gVS^{-1} d^{-1})	19.8	19.3	23.8	32.1
λ (days)	0.00	0.00	1.5	12.9
v	0	0	0.1	13.2
R^2	0.995	0.959	0.999	0.992
$\frac{SMY-A}{SMY} \times 100$	−0.91%	−1.90%	1.89%	−0.34%

A: maximum specific methane production potential, μ_m: max. specific methane production rate, λ: lag-phase, t: incubation time, v: shape coefficient, R^2: correlation coefficient.
PA: Paunch, DAF: Dissolved air flotation sludge, SO: Soft offal, SHWM: mixture of PA, DAF and SO at annual production ratios.

gradual but constant production of methane resulting in 80% of the methane yield within the first 26 days. The effect of the pasteurisation process on the methane yield as well as the biodegradation of the SO is discussed by Ware and Power (2016) [23]. The high fat content of the waste stream signalled that acute LCFA inhibition may occur given that the bacterial consortiums within the inoculum had not being previously exposed and adapted to substrates with such high fat contents [7,41]. However this did not occur evident from the λ value of only 1.52 days. Inhibition did not occur due to the limited available surface area of the fats for the hydrolytic bacteria to act on. The large particle size of fats in the SO resulted in a lower surface area for the hydrolytic bacteria to act on reducing the rate of accumulation of LCFA and thus avoiding inhibition i.e. liquefaction of fats was rate limiting resulting in an extended incubation period of 50 days [42]. The gradual but constant breakdown of the fats resulted in the protracted shallow curve as seen in Fig. 2.

The mixing of the three single waste streams to create the SHWM saw a statistically insignificant 1.45% decrease in the SMY from that of the SO ($p = 0.76$, $\alpha = 0.05$). Although there was no significant increase or decrease of the SMY achieved, a definite change in the methane production kinetics was observed producing an elongated S-shape curve. This form of methane production was not seen for any of the single waste streams so it raises the question of what altered the biodegradability characteristics once mixed. The fat (28.4%) and carbohydrate (41.0%) content of the SHWM were lower than those seen in the SO and the PA in which they may have caused issues in LCFA accumulation and hydrolytic lag phase respectively. These issues did not transpire as discussed above and as such should not have occurred in the SHWM with lower levels of the "problematic" compounds. Given that the substantial methane production was continual throughout the incubation period no obvious signs of inhibition are evident. This suggests that the organics in particularly the fats were less bioavailable to the bacteria. This is underpinned by the fact that the maximum daily methane yield was achieved on day 28 for the SHWM and on day 1 for the SO, implying the addition of the PA and the DAF must have impeded the physical availability of the large particles of fat somehow. It was noted during the mixing of waste streams that the fibrous nature of the PA caused it to bind around the particles of the SO. This could have impeded the hydrolysis of the fats as the layer of paunch would of have to been broken down first before the fats could be accessed by the bacterial populations. This is reinforced by the kinetics observed during the lag phase (12.52 days), the initial slope of the SHWM and PA cumulative methane curves (Fig. 2) are matched indicating the rapid hydrolysis of the PA, DAF and any SO organics freely available. As these were physically degraded, in particularly the paunch layer surrounding the SO particles, the SO fats would have become more accessible to the hydrolytic bacteria and began to break them down into more soluble compounds and subsequently converted to methane as indicated by the second phase of rapid methane production.

Overall the same amount of methane was produced from the SHWM over the same incubation period of 50 days when statistically compared to the best performing individual waste stream SO. Yes the period of maximum methane production of the SHWM shifted to the latter period of the incubation period, due to the fibrous PA, but in order to obtain 80% of the SMY they would need to be digested for similar periods of time (26 days for SO and 29 days SHWM). As such it can be said that the digestion of the three individual waste streams as a single feedstock is possible without sacrifice in methane yield if the SO was to be digested on its own. For this reasoning the net energy analysis was carried out assuming the treatment of all waste streams together.

3.2. Net energy analysis

The net energy analysis carried out is outlined in Table 4. The sampled slaughtering facility processes 52,000 heads of cattle annually resulting in the annual availability of; 3781, 1485 and 4789 t of DAF, PA and SO respectively. This equates to a SHWM feedstock availability of 10,055 t annually. It is worth noting that only 80% of the SMY of the SHWM was utilised in the analysis. If 100% were to be utilised a HRT of 50 days would be assumed, in reality such a long HRT would be unfeasible and inefficient in a full scale operation. A typical HRT for slaughterhouse wastes feedstock would be approximately 20 days with continuous feeding. The representation of methane production in a full scale reactor (continuously fed) in comparison to a BMP (batch fed) is slightly different. First off the sole purpose of the BMP is to determine the maximum organic degradation, thus a high incubation period of 30+ days. While in a full scale operation the aim is to get the maximum amount of methane in the shortest period of time. Furthermore the lag phase within the BMP determined by the kinetic modelling (12.5 days for the SHWM) would not be seen in full scale operation. The lag phase is defined as "minimum time for the methanogenic bacteria to acclimate to the environment" and as such would not exist in large scale operation as the bacterial populations would be well establishes and operating at full capacity in a healthy continuously fed digester [24,25]. Taking this into account 80% of the methane yields would be reached by 16.5 days. Therefore taking 80% of the methane yield assumes a HRT < 20 days in the reactor which is more representative of a full scale digester in operation.

The available feedstock produced a gross methane yield of 1,628,258 m^3CH_4, equating to 2,584,537 m^3 of biogas (@ 63% CH_4). Taking a lower heating value of 37 MJ/m^3 for the methane a primary energy production pre utilisation of 16,735 MWh was realised. Direct combustion of the raw biogas in the CHP unit (41%η_{elec} and 49%η_{therm}) recovered 6,861 MWh_{elec} and 8,200 MWh_{therm}. The annual energy demand of the slaughtering facility was calculated as 13,660 MWh pa, constituting of 5,874 MWh_{elec} and 7,786 MWh_{therm}. The potential energy subsidy for the slaughtering facility was evaluated at 100% for both electrical and thermal requirements with a surplus of 987 MWh_{elec} and 414 MWh_{therm} observed. As such the slaughtering facility could become completely energy self-sufficient if the available waste streams were treated through AD. The surplus thermal energy would most likely go to waste, save an additional large thermal market in the immediate vicinity, due to the non-existence of district heating in Ireland. With the surplus electricity potentially delivered to additional consumers through the national grid at a transmission loss of 5.98%. However given that the energy demand for the production of the biogas equated to 690 MWh_{elec} the surplus electrical energy produced (928 MWh_{elec}) could subsidise this demand resulting in the biogas facility itself being energy self-sufficient also.

4. Discussions

The BMP results indicate that the AD of the mixed individual waste streams is viable producing a high methane yield of 641.55 $mLCH_4\ gVS^{-1}$. The high methane yield of the potentially available feedstock would result in ample energy recovery in the sampled slaughtering facility creating an energy self-sufficient facility. The results discussed to this point have been confined in scope to the potential energy recovery from the available feedstock within the confines of the sampled cattle slaughtering facility. The total slaughterings in this facility account for only 3.28% of total annual slaughterings in 2013. Based on the SHWM production at the sampled slaughtering facility the SWHM production per head

Table 4
Net energy analysis of biogas produced from annual available feedstock from slaughtering facility combusted in a CHP unit.

Gross energy production
CH_4 yield of SHWM from BMP = 208.25 m^3CH_4/t of feedstock
80% methane yield achieved (HRT < 20 days) = 166.6 m^3CH_4/t of feedstock
Annual SHWM production = 10,055 tpa.
CH_4 production = 10,055 × 166.6 = 1,675,163 m^3CH_4 pa.
2.8% fugitive emissions prior to utilisation [32] = 1,675,163 × 0.972 = 1,628,258 m^3CH_4 pa.
LHV_CH_4 = 37 MJ/m^3
Annual gross energy production = 1,628,258 × 37 = 60,245,546 MJ = 16,734,878 kWh
Energy input
Electricity consumption of maceration [29] = 6.25 × 10,055 = 62,844 kWh
Electricity consumption of eccentric screw press [27] = 6.25 × 10,055 = 62,844 kWh
Electricity consumption of pasteurisation = 69.73 × 10,055 × 0.62 = 464,151 kWh
Electricity consumption of reactor [30] = 10 × 10,055 = 100,550 kWh
External electricity input at biogas facility = 690,389 kWh
Net energy production from CHP unit
Electricity @ 41% efficiency [34] = 0.41 × 16,734,878 = 6,861,300 kWh_{elec}
Thermal @ 49% efficiency [34] = 0.49 × 16,734,878 = 8,200,090 kWh_{therm}
Potential energy substitution
Energy demand of slaughtering facility [38] = 2899.16 MJ/t carcass weight
Heads slaughtered = 52,000
Assuming carcass weight of 326.2 kg[a]
Annual output of slaughtering facility = 52,000 × 0.3262 = 16,962 t carcass weight pa.
Annual energy demand of slaughtering facility = 16,962 × 2899 = 49,176,711 MJ pa. = 13,660,198 kWh pa.
Electricity consumed at slaughtering facility @ 43% [38] = 0.43 × 13,660,198 = 5,873,885 kWh_{elec}
Thermal energy consumed at slaughtering facility @ 57% [38] = 0.57 × 13,660,198 = 7,786,313 kWh_{therm}
Potential electricity subsidised = 100% (987,415 kWh_{elec} surplus)
Potential thermal energy subsidised = 100% (413,778 kWh_{therm} surplus)
Total energy demand of facility subsidised = 100%

Note: rounding errors may occur in calculations.
MJ-KWh divide by 3.6.
[a] Average carcass weight calculated according to CSO stats on livestock slaughterings in 2013 [3].

was estimated as 193.37 kg/head equating to a national available SHWM feedstock of 306,163 t from the slaughtering of 1,583,300 heads of cattle in 2013. Given the high potential for energy recovery from this waste stream as demonstrated above the national perspective must be taken into account.

4.1. *Potential energy recovery from industry*

Based on the same inputs and outputs for the boundary conditions outlined for the net energy analysis of the single slaughtering facility, the recovered energy from the cattle slaughtering industry can be determined. In an ideal world 100% of the potential feedstock production would be available for AD but in reality this would not be the case for a number of reasons. For example smaller scale facilities and artisan butchers (which all contribute to annual slaughtering figures) scale of operations does not justify investment in a biogas facility, as such would dispose of waste streams through traditional routes. As such it was assumed that a maximum of 90% of the waste produced could be recovered annually from the cattle slaughtering sector. Table 5 outlines the potential energy recovery from the AD of 90% of the available feedstock as well as its contribution towards the annual final energy demand of the industrial sector in Ireland in 2013. A potential electrical recovery of 188,027 MWh_{elec} and thermal recovery of 224,715 MWh_{therm} could be realised. The recovered energy has the potential to subsidise 2.07% and 1.38% of Irelands industrial sectors final electrical and thermal demands in 2013 (1.63% of total industrial final energy demand of 25,389 GWh, 36% electrical and 64% thermal) [28]. Assuming that all electrical and thermal energy produced can be consumed by the slaughtering facilities adjacent to the biogas production, i.e. not accounting for any thermal losses or transmission losses for surplus electricity. This is equivalent to powering 39,676 (2.4% of housing stock) and heating 16,151 (0.97% of the housing stock) houses in Ireland using an average dwelling consumption of 18,652 kWh, 75% thermal demand and 25% electrical demand [28].

Table 5
Net energy analysis of biogas produced from 90% of annual available feedstock from cattle slaughtering industry combusted in a CHP unit.

Annual feedstock availability @ 90% = 306,163 × 0.90 = 275,546 tpa
90% feedstock available @ 80% yield of 208.3 m^3CH_4/t = 166.6 × 275,546 = 45,906,038 m^3CH_4pa
2.8% fugitive emissions = 45,906,038 × 0.972 = 44,620,669 m^3CH_4
Annual gross energy production @ 37 MJ/m^3CH_4 = 44,620,669 × 37 = 1,650,964,753 MJ = 458,601,322 kWh
Energy recovery from CHP scenario
Electricity recovery @ 41% = 458,601,322 × 0.41 = 188,026,542 kWh
Heat recover @ 49% = 458,601,322 × 0.49 = 224,714,648 kWh
Irish industrial electrical demand = 99,140 GWh
Irish industrial thermal demand = 16,249 GWh
Potential electricity subsidised in industrial sector = 188,026,542/99,140 × 10^6 = 2.07%
Potential thermal energy subsidised in industrial sector = 224,714,648/16,249 × 10^6 = 1.38%
Total energy demand of industrial sector subsidised = 1.63%

Note: rounding errors may occur in calculations.
MJ-KWh divide by 3.6.
GWh-KWh multiply 10^6.

4.1.1. Contribution towards meeting renewable energy targets

The substantial recovery of energy from renewable sources raises the query as to the effect that the potential renewable energy generation could have on the progress towards the renewable energy targets set out under Irelands NREAP and enforced under the Renewable Energy Directive 2009/28/EC [16,43]. Current contributions of RES-H and RES-E towards Ireland's 2020 targets of 12% and 40% stand at 5.7% and 20.9% respectively. The electricity recovered on a national scale from the CHP utilisation pathway equates to 0.43% of the final electrical consumption in Ireland, adjusting the RES-E contribution to 21.33%. While the heat recovered compares to 0.44% of the thermal consumption in Ireland adjusting the RES-H to 6.14%. The overall standing for RES for the gross final energy consumption (GFC) in Ireland stands at 7.8%, with a 2020 target of 16% [16,28,44]. The inclusion of the recovered energy from the CHP scenario outlined in Table 5 considering both RES-E and RES-H contribution increases the RES share to 8.13% a 0.33% increase.

5. Conclusions

The organic waste streams from the sampled slaughtering facility proved to have high potential for energy recovery when treated as a single waste stream. The combined waste stream was characterised with high fat levels (28.4%) contributing to a high methane yield of 641.55 $mLCH_4\ gVS^{-1}$. The net energy analysis indicated that both the thermal and electrical demand of the slaughtering facility could be met from the energy generated through combustion of the biogas in a CHP unit with electrical and thermal efficiencies of 41% and 49% respectively. The surplus electrical energy generated could be used to replace 100% of the demand for the production of the biogas making the entire system analysed 100% energy self-sufficient. So the alternative management of the available organic waste stream could create an energy self-sufficient cattle slaughtering facility. Contemplating the industry as a whole in terms of progression towards the renewable energy targets, the RES of the GFC the addition of the renewable energy from the cattle slaughtering sector causes a 0.33% increase to 8.13%. When broken into RES-H and RES-E this equates to a 0.44% and 0.43% increase respectively, bringing their overall contribution to 21.33% and 6.14% from the alternative treatment of waste streams from an existing thriving industry in Ireland.

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