A Bio-Economic Model of producing silage as a feedstock for Anaerobic Digestion in Ireland

Authors; Maurice J Deasy, Fiona Thorne

Affiliations; TEAGASC

Email address of corresponding Author

Abstract

The economic case for the production of silage for Anaerobic Digestion (AD) can only be established by analysis of the potential costs and returns at farm level. This paper uses farm level data from Ireland in a bio-economic modelling framework to provide total costs per hectare and per tonne for production of silage for an off farm AD facility.

Whilst perennial rye grass has traditionally been the sward of choice for livestock farmers in Ireland, the economics of a multi-cut nitrogen fixing crop such as red clover has been relatively unknown.

The results from the simulated bio-economic model show that the total costs of production silage for AD has increased significantly in the past twenty four months. The modelled cost of Red-Clover based silage fertilised with digestate has increased from €29.35 to €43.68 per ton between 2018-2020 to 2022, an increase of 49%.

The results also highlight the importance of accounting for the opportunity cost of nutrient content of digestate which increased from €370 to €907 between 2018-2020 and 2022. Furthermore, a 17% cost saving can be made while reducing overall GHG emissions by utilising digestate in a separate farm enterprise.

Keyworks: Anaerobic Digestion, Biomethane, Bio-Economic Model,

1. Introduction

Various EU and Irish policy documents highlight the role for bioenergy at farm level in contributing to GHG emission target reductions from agriculture and energy. Within the Climate Action Plan (CAP) there are targets set for emissions reductions by 2030 of 50% in the transport sector, 35% in industry, and 25% in agriculture from a 2018 baseline. Consequently, there is a need to increase our understanding of the role which technologies, such as Anaerobic Digestion (AD), can contribute to the economic sustainability of farming in Ireland. The use of grass silage for AD is considered a second generation biofuel in EU's Renewable Energy Directive II and is a renewable alternative to fossil fuels. AD has the potential to contribute to the circular bio economy and reduce Green House Gas (GHG) emissions, particularly when wastes such as animal slurries are co-digested.

Agriculture in Ireland is dominated by grassland accounting for over 90% of the utilizable agricultural area (UAA). The majority of this forage is utilized by grazing animals in a pasture based systems but there is a requirement to preserve silage for the winter housing period. Conversion of grassland to growing annual crops for AD would constitute a land use change and potentially increase carbon emissions due to release of soil carbon in the case of adopting of inversion tillage. Conversely, silage would not constitute a land use change, coupled with pre-existing knowledge and experience in the farming community, thereby reducing the perceived risk of adoption. Consequently, farmers may have an important diversification opportunity which merits careful financial analysis.

A bio economic model is used to examine the existing costs of producing silage in Ireland based on simulated data for a red clover (RC) and a Perennial Ryegrass (PRG) sward. Given the environmental sustainability limits identified within the Renewable Energy Directive (RED) II and the ensuing need to limit synthetic nitrogen usage for growing feedstocks for AD, the role of nitrogen fixing swards, in the production of feedstock was examined. This study seeks to address some of the information deficit about the economics of biomass crops in Ireland. This data is compared to farm level data in period of 2018-2020 for tradition PRG sward while the modelled production is used to evaluate the input price shocks that have occurred in early 2022.

The paper proceeds as follows: the background to the research question is outlined in section 2, section 3 outlines the results of the analysis and section 4 summarises the findings from the research and outlines conclusions from the research.

2. Background

AD has been operational in Europe on a small scale in niche areas particularly since the oil crisis in the late 1970's. On a small scale the biogas generated, which typically comprises 55% Methane and 45% CO2, is combusted for heat. Since the 1990's there was a development of large scale AD utilizing the biogas for electricity generation driven by legislation and incentives. The electricity is generated from combusting the gas in a Combine Heat and Power (CHP) unit which would operate continuously with the exception of maintenance, however there is a more recent trend to increasing biogas storage on site and providing electricity on demand at a premium[1]. More recently biomethane has come to prominence whereby the biogas is upgraded to >99% Methane and CO2 can be captured for use also. Biomethane can be injected into the gas grind with certificates generated and traded for this renewable or green gas.

2.1 AD in Ireland to date

To date in Ireland the development of the AD sector has been slow by comparison to other European countries. A combination of complex planning and licensing, grid connection costs, unattractive electricity tariffs, financing issues and uncertainty in waste policy have led to relatively few plants in Ireland to date [2], [3].

AD plants generally require financial support to compete with fossil fuels. In 2006, Ireland developed a Renewable Energy Feed in Tariff (REFIT) program providing funding for AD combined heat and power (CHP) for up to 15 years. The tariff offered to producers (2.78-4.17 euro cents per MJ) has generally been lower than that across other European countries, for instance Germany has a rate of 1.63-6.59 (euro cents per MJ) or UK (3.17 – 4.56 euro cents per MJ)[3]. Consequentially AD plant operators within Ireland have been making the system economically viable by charging gate fees from food waste[3].

According to the European Biogas Association (EBA), in 2019 Ireland had 6 biogas plants per 1 Mio capita and a total of 29 Biogas Plants including sewage and landfill plants. Both metrics would have Ireland in the lower quartile compared with European neighbours. By contrast IEA rank Ireland as the 3rd in the world for wind energy penetration in the electrical grid [4] which is also supported by REFIT however wind energy suffers from intermittency creating issues for further expansion.

The EU requires Member States to achieve 3.5% advanced biofuels in transport by 2030, and renewable gas from AD could provide this as an advanced biofuel while it would be possible to provide 10% of transportation from co-digestion of cattle slurry and grass silage[5]

2.2 Policy background

The EU has set the target of building a net-zero carbon economy by 2050 as outlined in the European Green Deal in January 2020 along with ambitious goals in the Farm to Fork strategy [6]. This is in line with the Paris Agreement objective to keep global temperature increases to below 2°C and target 1.5°C.

The Farm to Fork strategy targets a 50% reduction in use of pesticides and nutrient losses from soils and a reduction in synthetic fertiliser usage by at least 20% by 2030[6]. AD is specifically mentioned in the Farm to Fork strategy as part of the circular bio economy for farmers and their cooperatives to digest waste and residues to produce renewable energy while reducing methane emissions. [7].

The Irish Climate Action Plan increased the target for Anaerobic Digestion with a 5.7TWh Biomethane target announced recognising the role Anaerobic Digestion can play in reducing emissions and creating a circular bioeconomy.

AD is covered by EU legislation called the Renewable Energy Directive (RED) II which sets targets for renewable energy sources consumption by 2030 at 32%. RED II sets limits for the quantity of GHG emissions offset by the generation of renewable fuels from 65% for transportation fuels to 80% for electricity heating and cooling by 2026.

There is also an added incentive for advanced biofuels and biogas for transport being considered to be twice their energy content. The target share of advanced biofuels and biogas of final consumption of energy in the transport sector will be at least 0,2 % in 2022, at least 1 % in 2025 and at least 3,5 % in 2030. The feedstocks for the production of these advanced biofuels and biogas include food and feed crop residues, straw, husk, grassy energy crops with a low starch content as well as cover crops before and after main crops and ley crops with full list given in Part A of Annex IX of RED II Directive[8].

2.3 Economic literature

The temperate climate conditions in Ireland allow for high productivity of pasture based swards which is not typical across Europe where a larger UAA would be dedicated to arable crops. Several economic analysis have been carried out into crop based biofuels showing biomethane as more economically viable than ethanol[9] however grass was also proposed as a suitable feedstock for biomethane [10].

McEniry et al (2011) investigated the cost grass silage for on-farm biomethane production in Ireland compared to crop based ethanol production[11]. The Grange Feed Costing Model (GFCM), a static agro-economic simulation model, was used to compare the cost of grass silage, wheat grain and sugarbeet finding grass silage was the cheapest feedstock per GJ of biofuel produced. A brief survey was carried out to compare the model to traded prices of silage finding that some farms either sell below the apparent cost of production or have lower costs of production than those assumed by the GFCM.

Himanshu (2018) also used the GFCM to evaluate the effect of varying quality, cost and proportions of grass silage and cattle slurry as feedstocks on the cost of methane production in Ireland[12]. The cost of methane production from mono-digestion of cattle slurry compared to grass silage in the same volumetric plant was 87% higher when omitting any benefit from the digestion of digestate.

Multiple economic analysis have been carried out across Europe of feedstocks for AD [13]–[17] using Net Present Value (NPV) and Internal Rate of Return (IRR). The main economic output is evaluated as energy in the form of electricity or biomethane, with some studies also including digestate as a fertiliser replacement[13]–[15]. For the purpose of this study the fertiliser replacement value will be modelled using the nutrient value of nitrogen, phosphorus and potassium, which is a novel addition to the literature..

3. Materials and methods

3.1 Bio-Economic Model

This paper used a spreadsheet based bio-economic model to facilitate the calculation of PRG and PRG-RC as sward costs on a per hectare and dry matter yield basis for use in a regional AD plant. The model was used to quantify the cost of producing and utilising a RC sward, for which historic data from our Teagasc, National Farm Survey Data was not available. It is based on a single year deterministic input framework, but is re-simulated under different annual conditions. Agronomic defaults in terms of field operations are based on literature sources[18] and output from the Grange Feed Cost Model (GFCM)[19]. The economic input variables are mainly take from farm contractors of Ireland costings and CSO data for fertiliser based on annual input costs at prevailing 2018-2020 & 2022 prices.

The limitation of bioenergy is the finite availability of land, hence the opportunity cost of land has been used in studies on the investment returns in agriculture[20]–[22]. In the GFCM land rent is included in the costs of production however in NFS data there is no charge on owned land while some land may be rented. To allow comparison land charge is excluded in this analysis of cost of production. The paper abstracts from issues of scale of production by conducting the evaluations in per hectare terms.

3.2 Cost and Return of Silage Crops

3.2.1 Data from the Teagasc, NFS for PRG

The existing costs of producing PRG silage in Ireland are based on data produced by Teagasc, National Farm Survey (NFS) from 2018-2020. To avoid problems of allocation of fixed costs associated with owned machinery, farms were selected that used contractor for the majority of field operations. To achieve this farms without any contractor charges were excluded along with the 5% of the remaining farms with the lowest contracting charges per ton of silage produced. The remaining farms had a machinery hire as greater than 60% of total direct cost of silage. Hence, all machinery and labour costs are therefore assumed to be variable costs.

Farms without any expenditure on fertiliser for silage were also excluded to remove organic farms whom have a lower sample size in the NFS.

Farms that did not produce silage were excluded along with the lowest 5% of farms in terms of tons of silage produced. This resulted in a yield of silage greater than 50 tons per farm which is a sufficient quantity of silage that could fill a truck for transportation.

The weightings are applied to the resultant farms to calculate national figures which are shown in Table 1. The number of farms is smaller and the UAA size is larger than the national average due to the selection criteria used in the analysis.

Table 1 Data on silage production on Irish Farms from NFS

Average of 2018-2020	Ireland
Number Farms	63,200
Average UAA Size (ha)	43.2
Average yield of a silage (t/Ha)	20.6
Average yield of silage per ha adjusted to entire year (t/Ha)	45.6
Fertiliser cost per ton of silage (€/t)	€4.35
Slurry Opportunity Cost & Spreading (€/t)	€2.91
Direct cost per ton of Silage (€/t)	€26.22
Total Cost per ton of Silage (€/t)	€29.92

Source: Author’s analysis of Teagasc NFS data

Average yield of silage per ha adjusted to entire year is an estimation of the land area to yield same quantity of silage over an entire year. This is an adjustment made to account for the yield from silage area which is not harvested but grazed by animals instead. This would for instance occur if only a single cut of silage is harvested and therefore the adjusted area is a reduction in area compared to the area on which the actual silage is harvested. The total yield potential is calculated from PastureBase Ireland which provides estimations of grass yields based on grass growth measurement data across Ireland.

The average yield of silage harvest is the yield of silage over the total area harvested for silage in that year. Typically the first cut of silage has the highest yield per ha which on average is 21-24t per ha, normally with the fields being closed to grazing from late March to early April and harvested in late May. If harvest is delayed the yield of silage may increase, however after the seed head appears the digestibility of the grass reduces.

A second or third cut of silage is possible with typically lower yields of silage per ha however with high digestibility. Analysis of the NFS show that on beef farms 61% operate a single cut system for making silage with 41% operating with a 2 cut system. On dairy farms two cut system is predominant at 62% with three and single cuts also being used.

McElhinney et al (2015) investigated silage quality in Ireland across 2-years finding typical dry matter content of silage to be 24.7% varying from 19% to over 31%[23]. When evaluating silage yields in this analysis the average figure of 24.7% is used. It must be noted that for instance a 3 cut system, while it is more expensive per ton of silage, it may have increased Dry Matter yield and therefore quality. Data on the Dry Matter content of silage is not collected as part of the NFS.

The fertiliser cost is the cost of the synthetic NPK fertiliser which is allocated to the silage crop, along with animal slurries which are also used in some instances to supplement other nutrients. The opportunity cost of NPK nutrients in animal slurry and the cost of spreading is calculated based on the silage crop requirement, the availability of animal slurry and contracting rates. In a typical animal system the silage crop is feed to animals and slurry will be available for subsequent crops; however when silage is exported for AD these nutrients are exported off farm. Thus, the opportunity cost of replacing these nutrients are costed.

Fertiliser usage is predominantly nitrogen, with 67% of the kg of nutrient spread in the form of nitrogen which has the most significant bearing on the GHG emissions of the AD process. The renewable energy directive (REDII) sets GHG emissions savings criteria to allow the energy created from AD to be classified as renewable. The most significant in terms of GHG emissions is the nitrogen as this is associated with Nitrous Oxide (N2O) emissions which is equivalent to 265 times the GHG potential of CO2.

Grass silage can be produced without applying synthetic nitrogen and instead using legumes to fix atmospheric nitrogen such as clover or Multi species sward (MSS). This will likely be a requirement of supplying silage to AD to ensure the overall sustainability of the AD facility. It is assumed that the adoption rates of these sustainable technologies of glass clover and MSS are low across the typical farming systems in Ireland and thus these crops will be modelled using research data on yields and typical contracting rates for operations.

3.2.2 Data from the Teagasc, Grange Feed Cost Model for PRG & RC

The Grange Feed Costing Model (GFCM) has been adapted to model production of a Perennial Ryegrass (PRG) and a Perennial Ryegrass-Red Clover (PRG-RC) silage under a multi cut system. The long term field data from Clavin et al [18] was used for a 4 cut silage system however the 4th cut isn't harvested for silage and instead either grazed or zero-grazed due to the high cost per ton silage and possible challenges with ensiling. An average yield is assumed of 13t Dry Matter (DM) per ha fresh silage with 1.3t DM aftermath for both PRG and PRG-RC, which is conservative based on Clavin et al (2016) [18].

The crops are fertilised based on nutrients in the silage offtakes to ensure fertility is maintained with the exception of nitrogen on red clover. Red clover is a legume which has nodules on its roots which contain bacteria (Rhizobia) that is capable of biological nitrogen fixation and therefore does not require nitrogen fertilisation. Clavin[18] showed a slight decrease in yield when applying 50kg/ha of chemical nitrogen; however in practice red clover crops are fertilised with slurry to return phosphorus and potassium, which also contains nitrogen.

There is an opportunity cost associated with this nitrogen which could be used elsewhere in the agricultural system as a whole. Theoretically the most efficient would be for digestate to fertilise other crops which are not capable of biological nitrogen fixation offsetting GHG emissions of nitrogen fertiliser for that crop while P & K fertiliser is used to fertilise the PRG-RC crop.

To investigate the use of digestate an opportunity cost is applied to nutrient in silage/digestate minus the added cost of spreading digestate over the cost of spreading chemical fertiliser. Three modelled scenarios for PRG RC crop fertilisation were investigated and compared to a modelled PRG scenario;

- 0% digestate whereby chemical fertiliser is used to supply crop P & K requirements and the digestate is used elsewhere;
- 42% digestate whereby the first cut of silage is fertilised with digestate and subsequent crops are fertilised with chemical P & K fertiliser;
- 100% digestate a fully circular system whereby all crop requirements are provided by digestate.
- Perennial Ryegrass requires synthetic nitrogen fertiliser in addition to all digestate.

The nitrogen in slurry and digestate is in the readily available form of ammonia, which is assumed to be 58% and 85% respectively while there is also a quantity in slow release forms. The quantity of ammonia available to the plant also depends on the losses during spreading which are dependent on temperature at application and application equipment such as Low Emissions Spreading Systems (LESS) which is assumed to be used as part of best practice.

Table 2 Nutrient supply to crop under different digestate usage scenarios

Crop	**PRG-RC**			**PRG**
Digestate	**0%**	**42%**	**100%**	**100%**
ton / hectare	0	25.7	60.4	60.4
N *(kg/ha)*	0	67	122	261
P *(kg/ha)*	39	39	39	39
K *(kg/ha)*	261	270	282	282

4. Results

4.1 Baseline results from Teagasc NFS, for PRG sward

Analysis of the data was carried out to evaluate the distribution of direct cost of silage per ton for a PRG sward. The top, middle and bottom performing farms achieved direct costs of €19, €26 and €33 respectively, based on data for 2018-2020 shown in Figure 1. This shows the range of cost of silage production that is achievable by farms across the country. The top performing farms achieved the highest yields per ha while also used the least amount of synthetic fertiliser. Contractor charges are typically based on area thus maximising yield minimises this cost while fertiliser is the largest cost after contracting.

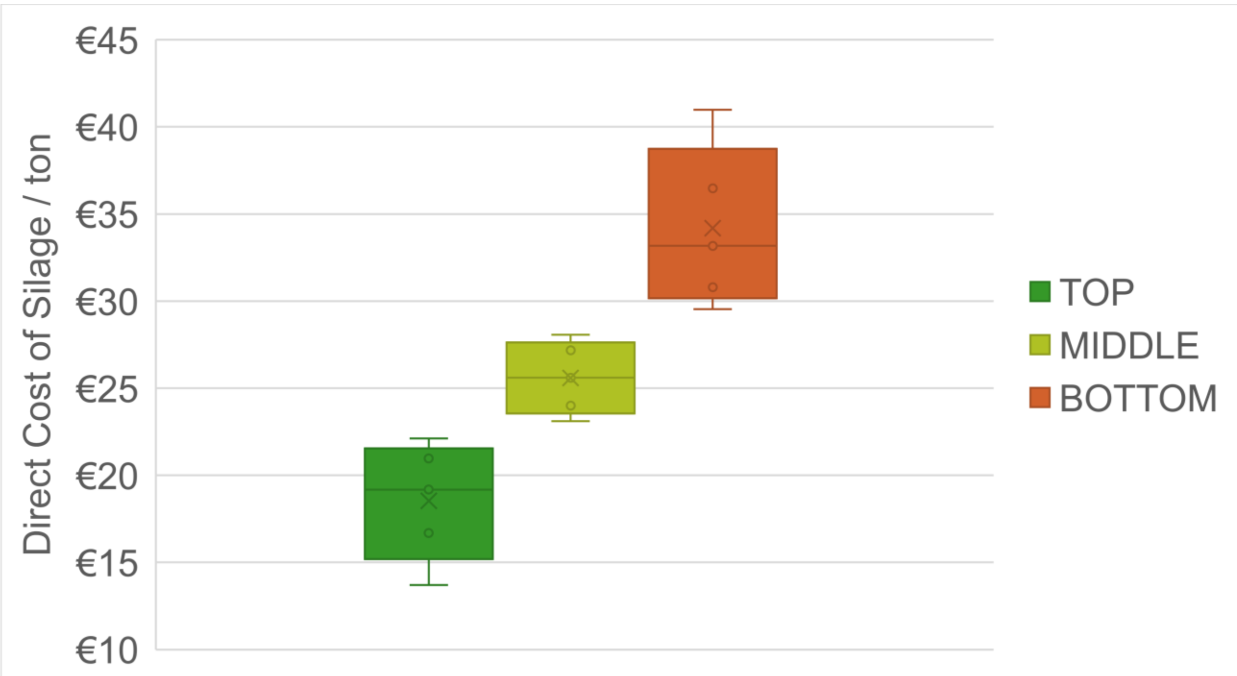

Figure 1 Distribution of direct cost of PRG silage per ton in NFS Data for 2018-2020

It must be noted that the analysis of direct cost silage per ton is using the average dry matter content of 24.7% and thus does not account for variation in dry matter of the silage produced. It is possible for farmers in the bottom performance of direct cost to be harvesting a relatively lower total yield per hectare of 30% DM silage with high digestibility, and operating three cuts per year.

While management has a very important role in productivity, nutrient status of soil also has a major impact which is dependent on soils physical characteristics as well as the long term nutrient balance of the land area in question. For the purposes of this analysis using the middle performance and average DM content of silage will give the widest applicability.

4.2 GFCM Results

The initial study period is the years 2018-2020 whereby input costs were stable and growing seasons were without any major weather events. The bio-economic model cost of 3 cut PRG silage including the nutrient opportunity cost (NOC) as seen in Figure 2 shows good agreement with the higher cost silage cohort from the NFS data for PRG in Table 1 at €33 per ton of silage. This is to be expected as the GFCM uses a bottom up approach costing using standard costs and yield when in some situations varying less of technical efficiency are achievable.

The costs of production of PRG-RC silage are shown in Figure 2 to be lower than those of PRG for all scenarios. The major cost difference is due to the reduction in nitrogen fertilisation with rates modelled in different scenarios as seen in Table 2. The reduction in usage of nitrogen in the digestate to fertilise the PRG-RC reduces the cost of production when this opportunity cost is included (Incl. NOC) however when this is excluded (excl. NOC) the cost of production increases due to increase in chemical fertiliser usage. In the scenario where 0% digestate is used, the chemical fertiliser used to fertilise the PRG-RC is related to reduction in usage of fertiliser elsewhere in farming system due to it being replaced with digestate which has an associated GHG emissions saving[24]. This would suggest it to be the most economic and environmentally efficient scenario when opportunity costs can be realised.

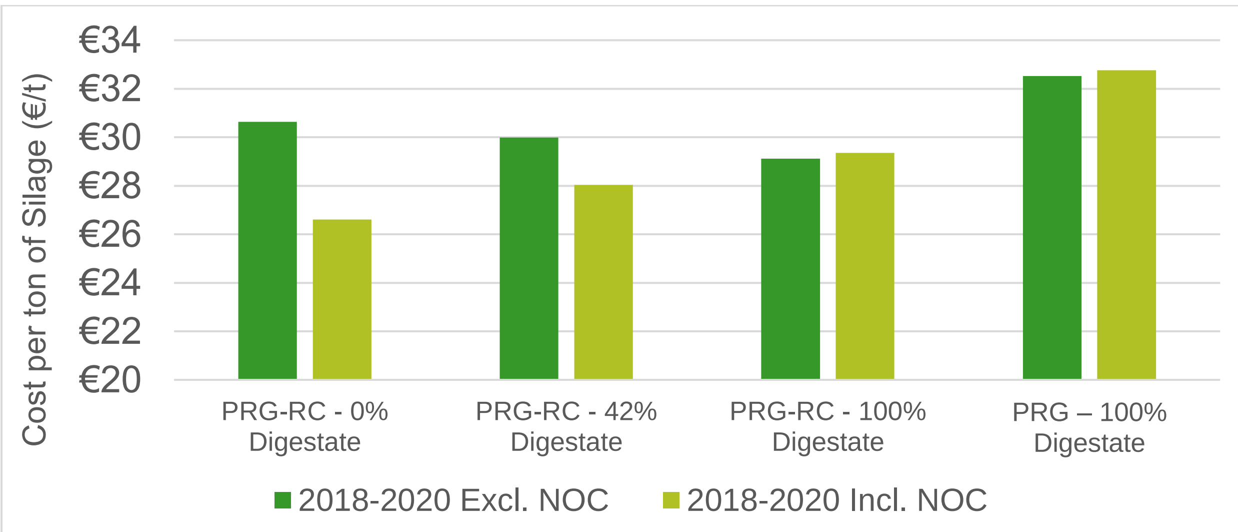

Figure 2 Variation between including and excluding the opportunity costs of nutrients (NOC) on the cost per ton of Silage

While detailed farm level data is available for the time period of 2018-2020 from TEAGASC NFS, there is none yet available for 2022. The advantage of the bio-economic model is that the data on the input price shock of 2022 can evaluated to determine the changes in cost of production. Data from CSO and FCI was updated for 2022 in the bioeconomic model show that growing silage, from a red clover sward, for AD in Ireland has increased significantly over the past twenty four months. The modelled cost of Red-Clover based silage fertilised solely by digestate has increased from €29.35 per ton in 2018-2020 to €43.68 per ton in 2022, an increase of 49%. In the PRG-RC fertilised using 0% digestate scenario, when the opportunity cost of the nutrient is accounted the increase in the cost of production of silage is reduced to 37%.

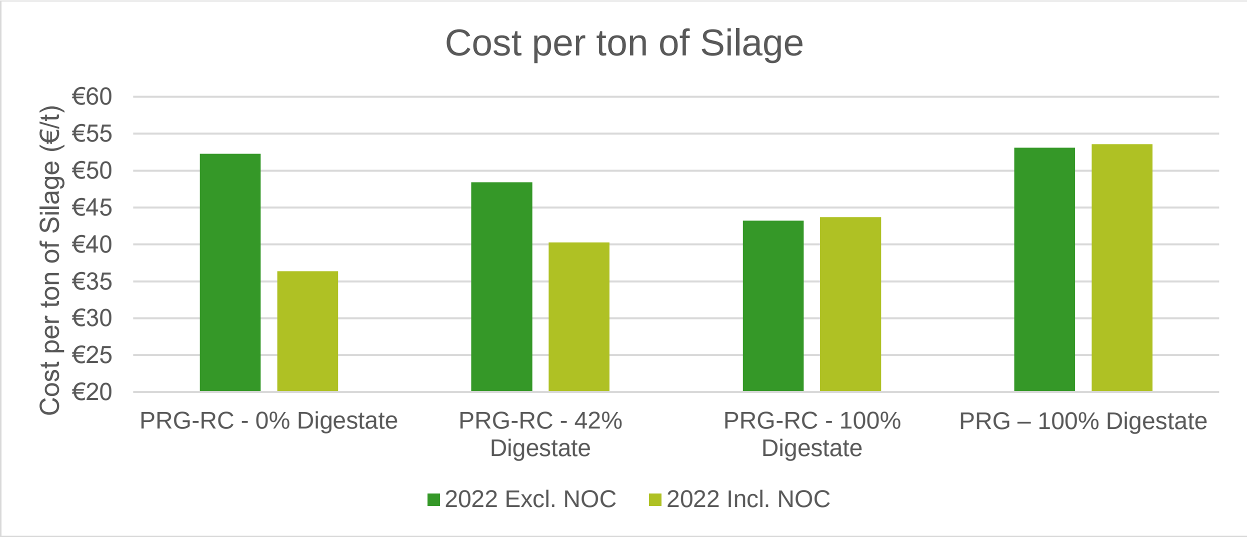

Figure 3 Variation between including and excluding the Nutrient Opportunity Costs (NOC) of nutrients on the cost per ton of Silage

The results also highlighted the importance of accounting for the opportunity cost of nutrient content of digestate, particularly in a high fertiliser price environment like 2022. The opportunity cost of the nutrient off take per ha of 13t DM of silage increased from €372 to €907 between 2018-2020 and 2022. Many previous studies do not account for this nutrient opportunity cost which may not be as important in a beef system when the silage and slurry remains on farm.

When accounting for the opportunity cost of nutrients in the digestate, a significant proportion of this value is accounted for by nitrogen content, which is not required by the red-clover based sward, due to the nitrogen fixing ability of the crop. The utilization of the digestate in another enterprise and replacing nutrients with synthetic fertiliser would lead to a 17% cost saving in a PRG-RC system and 32% saving compared to PRG system as well and reduced GHG emissions of entire farming system, see Table 3.

Table 3 Modelled cost of production of Silage for Anaerobic Digestion in 2022 including Opportunity Costs of Nutrients

2022	**PRG-RC**			**PRG**
Digestate	**0%**	**42%**	**100%**	**100%**
Production Costs per ha (€/ha)	€1,526	€1,689	€1,832	€2,246
Dry Matter Silage Cost (€/t DM)	€146	€161	€175	€214
Silage Cost (€/t)	€36.38	€40.27	€43.68	€53.57

5. Discussion and Conclusions

The economic case for growing silage for AD was evaluated using a total cost bio-economic modelling approach showing good agreement between modelled production costs and farm level data. The model was used to evaluate the costs of PRG-RC silage showing lower costs for production of a red-clover sward compared to a traditional perennial ryegrass sward.

When the opportunity cost of the nitrogen, phosphorus and potassium are accounted for, further reduction in production costs of silage for AD can be made when the digestate is utilised elsewhere in the farming system such as in crop production.

Whilst this paper focuses on economic sustainability criterion, the adoption of AD could have additional environmental sustainability benefits to the agriculture industry, by reducing farm level GHG emissions and reducing dependency on artificial fertilisers. The use of digestate as a fertiliser could stimulate the circular bio-economy while reducing the GHG emissions from fertiliser manufacture and the needs for imports.

Finally, the socio-cultural elements also need to be evaluated in the context of a developing AD industry in Ireland. The potential to increase the productivity to supply AD while increasing the viability levels of original enterprises could potentially prove attractive.

Acknowledgements

The authors would like to acknowledge the contributions of Brian Moran and the TEAGASC NFS team and participants. This research has been made possible through the support of SEAI RD&D programme and is co-funded by Gas Networks Ireland.

References

[1] P. Hochloff and M. Braun, "ScienceDirect Optimizing biogas plants with excess power unit and storage capacity in electricity and control reserve markets," *Biomass and Bioenergy*, vol. 65, pp. 125–135, 2014, doi: 10.1016/j.biombioe.2013.12.012.

[2] P. Leonard, "Advice Notes on Anaerobic Digestion Economics for the NPA Region," 2017. [Online]. Available: http://grebeproject.eu/.

[3] A. Auer *et al.*, "Agricultural anaerobic digestion power plants in Ireland and Germany: policy and practice," *J. Sci. Food Agric.*, vol. 97, no. 3, pp. 719–723, 2017, doi: 10.1002/jsfa.8005.

[4] IEA Bioenergy, "Implementation of bioenergy in Ireland – 2021 update," 2021. [Online]. Available: https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_Ireland_final.pdf.

[5] D. M. Wall, P. O'Kiely, and J. D. Murphy, "The potential for biomethane from grass and slurry to satisfy renewable energy targets," *Bioresour. Technol.*, vol. 149, no. 2013, pp. 425–431, 2013, doi: 10.1016/j.biortech.2013.09.094.

[6] L. Montanarella and P. Panagos, “The relevance of sustainable soil management within the European Green Deal,” *Land use policy*, vol. 100, no. June 2020, 2021, doi: 10.1016/j.landusepol.2020.104950.

[7] Europäische Kommisson, “Farm to Fork Strategy,” *DG SANTE/Unit ‘Food Inf. Compos. food waste’’,’* no. DG SANTE/Unit ‘Food Inf. Compos. food waste’’,’ p. 23, 2020, [Online]. Available: https://ec.europa.eu/food/farm2fork_en.

[8] European Parliament, “Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources,” *Off. J. Eur. Union*, vol. 2018, no. L 328, pp. 82–209, 2018, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN.

[9] J. D. Murphy and N. Power, “Technical and economic analysis of biogas production in Ireland utilising three different crop rotations,” vol. 86, pp. 25–36, 2009, doi: 10.1016/j.apenergy.2008.03.015.

[10] J. D. Murphy and N. M. Power, “An argument for using biomethane generated from grass as a biofuel in Ireland,” *Biomass and Bioenergy*, vol. 33, no. 3, pp. 504–512, 2009, doi: 10.1016/j.biombioe.2008.08.018.

[11] J. McEniry, P. O’Kiely, P. Crosson, E. Groom, and J. D. Murphy, “The effect of feedstock cost on biofuel cost as exemplified by biomethane production from grass silage,” *Biofuels, Bioprod. Biorefining*, vol. 5, no. 6, pp. 670–682, 2011, doi: 10.1002/bbb.322.

[12] H. Himanshu, J. D. Murphy, J. J. Lenehan, and P. O’Kiely, “Impacts of characteristics of grass silage and cattle slurry feedstocks on the cost of methane production,” *Biofuels, Bioprod. Biorefining*, vol. 13, no. 1, pp. 129–139, 2019, doi: 10.1002/bbb.1947.

[13] C. Vaneeckhaute *et al.*, “Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions : A multi-dimensional sustainability assessment,” *Resour. Conserv. Recycl.*, vol. 136, no. March, pp. 110–117, 2018, doi: 10.1016/j.resconrec.2018.03.027.

[14] S. A. Gebrezgabher, M. P. M. Meuwissen, B. A. M. Prins, and A. G. J. M. O. Lansink, “Economic analysis of anaerobic digestion—A case of Green power biogas plant in The Netherlands,” *NJAS Wageningen J. Life Sci.*, vol. 57, no. 2, pp. 109–115, Jun. 2010, doi: 10.1016/j.njas.2009.07.006.

[15] D. Ruiz, G. San Miguel, B. Corona, A. Gaitero, and A. Domínguez, “Environmental and economic analysis of power generation in a thermophilic biogas plant,” *Sci. Total Environ.*, vol. 633, pp. 1418–1428, Aug. 2018, doi: 10.1016/j.scitotenv.2018.03.169.

[16] M. Carlini, E. M. Mosconi, S. Castellucci, M. Villarini, and A. Colantoni, “An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste,” *Energies*, vol. 10, no. 8, pp. 1–15, 2017, doi: 10.3390/en10081165.

[17] D. Lovarelli, G. Falcone, L. Orsi, and J. Bacenetti, “Agricultural small anaerobic digestion plants: Combining economic and environmental assessment,” *Biomass and Bioenergy*, vol. 128, no. April, 2019, doi: 10.1016/j.biombioe.2019.105302.

[18] D. Clavin, P. Crosson, J. Grant, and P. O’Kiely, “Red clover for silage: management impacts on herbage yield, nutritive value, ensilability and persistence, and relativity to perennial ryegrass,” *Grass Forage Sci.*, vol. 72, no. 3, pp. 414–431, 2017, doi: 10.1111/gfs.12249.

[19] E. Finneran, P. Crosson, P. O'Kiely, L. Shalloo, D. Forristal, and M. Wallace, "Simulation modelling of the cost of producing and utilising feeds for ruminants on Irish farms," *J. farm Manag.*, vol. 14, no. 2, pp. 95–116, 2010.

[20] I. Lewandowski, J. C. Clifton-Brown, J. M. O. Scurlock, and W. Huisman, "Miscanthus: European experience with a novel energy crop," *Biomass and Bioenergy*, vol. 19, no. 4, pp. 209–227, 2000, doi: 10.1016/S0961-9534(00)00032-5.

[21] D. Clancy, J. P. Breen, A. M. Butler, F. Thorne, and M. Wallace, "a Discounted Cash Flow Analysis of Financial Returns From Biomass Crops in Ireland," *J. Farm Manag.*, vol. 13, no. 9, pp. 1–17, 2009.

[22] D. Clancy, J. P. Breen, F. Thorne, and M. Wallace, "A stochastic analysis of the decision to produce biomass crops in Ireland," *Biomass and Bioenergy*, vol. 46, pp. 353–365, 2012, doi: 10.1016/j.biombioe.2012.08.005.

[23] C. Mcelhinney, M. Danaher, C. T. Elliott, and P. O'Kiely, "Mycotoxins in farm silages - a 2-year Irish national survey," *Grass and Forage Science*, vol. 71, no. 2. pp. 339–352, 2016, doi: 10.1111/gfs.12191.

[24] Ricardo Elementenergy, "Sustainable BioEnergy for Heat: Spatial Assessment of Resources and Evaluation of Costs and Greenhouse Gas impacts," 2022.