BioEnergy Research (2022) 15:1232–1239
https://doi.org/10.1007/s12155-021-10287-z

Techno-economic Feasibility of Extrusion as a Pretreatment Step for Biogas Production from Grass

M. F. Souza[1] · N. Devriendt[1,2] · B. Willems[3] · R. Guisson[4] · J. K. Biswas[1] · Erik Meers[1]

Received: 26 September 2020 / Accepted: 30 April 2021 / Published online: 28 May 2021

Abstract
Grass clippings have a good biomethane potential and, if acquired from roadside verges, nature management or natural grasslands do not compete for arable land, avoiding the food versus fuel debate. However, before the grass is processed in a wet anaerobic digester, a pretreatment step is advisable to minimize the problems associated with its fibrous nature. In this study, the effects of a semi-industrial extrusion pretreatment on fresh and ensiled grass were investigated through an energetic and economic assessment. Extrusion improved the mixing properties of the grass feedstock and reduced the formation of a floating layer even at a solid concentration of 10% (w/v). This pretreatment also enhanced the biomethane potential of ensiled grass and fresh grass by, respectively, 18 and 11% on a fresh matter basis, while shredding reduced this value by 14% when compared to fresh grass. This was attributed to changes in the volatile solids (VS) content of the treated samples, as all conditions resulted in similar biomethane yields when calculated per ton of VS, ranging from 325.5 to 337.6 Nm^3 CH_4/ton VS. However, ensiling resulted in a longer lag phase during biogas production attributed to the leaching of readily available sugars from the ruptured plant cells; nevertheless, this is not expected to be significant in a buffered industrial system. The revenue resulting from the extrusion treatment, between €6 and €17 per tonne of FM, compensated the cost of this additional step, indicating that extrusion would be a techno-economically sound process for the anaerobic digestion of grass.

Keywords Grass clippings · Anaerobic digestion · Extrusion pretreatment · Energy balance · Circular economy · Bioeconomy

Introduction

As the European Union (EU) is evolving into more sustainable energy systems and moving away from fossil and nuclear fuels for its energy consumption [1], two transition plans were drafted: the Renewable Energy Directive, which requires that 20% of all energy produced in the EU is renewable by 2020, and the Green Deal, which foresees no net emissions of greenhouse gases by 2050 [2].

M. F. Souza and N. Devriendt contributed equally to this work.

✉ Erik Meers
erik.meers@ugent.be

1 Department of Green Chemistry and Technology, Laboratory of Analytical Chemistry and Applied Ecochemistry, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium

2 ProNatura, Galgenstraat 60, B-9900 Eeklo, Belgium

3 Innolab, Marechalstraat 70, 8020 Oostkamp, Belgium

4 Vito, Boeretang 200, 2400 Mol, Belgium

In a temperate oceanic climate, such as Northwestern Europe, biomethane from grass has a large potential as a contributor to renewable energy and biofuels, as (i) it has a better energy balance than first-generation liquid biofuels indigenous to Europe, such as rapeseed biodiesel [3]; (ii) greenhouse gas savings of more than 60% are technically and economically feasible in the grassland-to-biofuel process when compared to fossil fuels [4]; (iii) grass feedstock can originate from 'underutilized' grassland and roadside verges, which allows for an abundant potential grass supply [5–7].

The optimal conversion of grass to biomethane is influenced by several factors, such as grass species, harvest date, feedstock conservation, pretreatment, and operational parameters of the anaerobic digestion [7–10]. Grass biomethane potential can range from 263 up to 2252 Nm^3 CH_4 per hectare, where the highest value was found for perennial ryegrass harvested during summertime [8, 11]. Delaying the harvest date may reduce the specific methane yield and affect biogas quality, as the higher fibrous content of the grass influences its digestibility [8, 12]. Therefore, it is important to find a balance between the digestibility of grass and the yield of grasslands. To ensure a predictable quality and a constant supply of this feedstock, ensiling and drying of grass are well-established options, albeit with some small yield losses [9, 13].

One of the hurdles in using grass as a feedstock for biogas production is its low digestibility, as lignocellulosic feedstocks have a low accessible surface area, high crystallinity, and presence of recalcitrant molecules like lignin [14]. Therefore, the pretreatment of grass can enhance the biogas potential and production rate [15]. Several types of pretreatment have been proposed, including biological [16, 17], (thermo)mechanical [18], and (thermo)chemical [19], increasing the biomethane yield up to 60% [15]. Mechanical processes seem to be the most promising ones in terms of yield increase due to their effect on reducing the particle size, which also results in a better homogenization within the reactor [15]. This is especially important when using grass as an anaerobic digestion feedstock, as long grass fibres tend to float, leading to increased stirring expenses, and can also get tangled with moving parts, causing failures in operation [12]. However, mechanical treatments tend to have high energy expenditure, and therefore, their adoption depends on the gain in biogas yield outweighing the increased energy input [12], a parameter that is often overlooked mainly because most of the studies are conducted at lab scale and would not provide reliable data for economic calculations.

Extrusion is a thermomechanical pretreatment in which the feedstock is fed to a closed vessel and moved along it by a rotating screw. Because of the compression and expansion zones in the feeding screw, abrasion of the feedstock occurs and this results in particle size reduction and plant cell wall lysis [20]. Furthermore, the friction of the feedstock with the feeding screw and the vessel gives rise to an increase in temperature, causing depolymerization of macromolecules and enhancing their biodegradability [21]. In comparison with other pretreatment procedures, extrusion has some clear advantages as it has a low consumption of energy and is a continuous process, being easily scalable and already applied in several industries [20, 21].

The pretreatment of grass by extrusion prior to anaerobic digestion has been scarcely studied, but with promising results. Even though an insignificant increase in biogas yield was observed after 90 days of anaerobic digestion of extruded grass when compared to its untreated counterpart, a 62% increase in yield was observed after 28 days of digestion, indicating that the treatment made the recalcitrant molecules more bioavailable and that it would possibly reduce the hydraulic retention time, improving the economic attractiveness of the process [20]. Similar results were found by Khor et al. [22], with an increase in methane yield of 30–50% for extruded grass after 30 days of digestion, depending on the treatment intensity.

The objective of the present study was to further evaluate extrusion as a pretreatment for the anaerobic digestion of grass, considering that only a couple of studies are currently available. A semi-industrial extruder coupled to a feeding belt was used for data acquisition at a relevant scale, and its processing capacity and energy consumption were monitored. The effect of extrusion on grass stirrability, biomethane potential (BMP), and biogas production kinetics was analysed, as well as the energetic and economic feasibility of the proposed treatment process.

Material and Methods

Types of Grass

The ensiled grass and fresh grass feedstocks used in this study originated from terrain management of natural grasslands in the Province of West Flanders (Belgium) and were collected by ANB, the agency responsible for the management of forest and nature in Flanders. Both grass feedstocks came from three origins: one-third was flailed grasslands, one-third came from various sources with a high content of woody biomass, and one-third originated from waterfronts with a quality similar to cultivated grasslands. These three grass feedstocks were mixed to create a homogeneous initial feedstock of fresh grass. The ensiled grass was harvested 2 years before the extruder pretreatment experiments. It was shredded to a length of 4–6 cm with an agricultural machine, compressed in potholes appropriate for ensiling, and enclosed by airtight plastic at Ichtegem, Belgium. The fresh grass was harvested with a cutter bar and left for a few days to dry on the field. On the location of the extruder pretreatment experiment, a fraction of the fresh grass feedstock was shredded (similar as described above) while the rest was left untouched. This led to two fresh grass feedstocks: fresh grass and fresh shredded grass. In total, three types of grass feedstock were fed to the extruder: shredded ensiled grass (SEG), fresh grass (FG), and shredded fresh grass (SFG).

Extruder Treatment Set-up

A full-scale experiment with a semi-industrial double-screw extruder was performed at the site of the anaerobic digester of Goemare at Ichetegem, Belgium, following a similar methodology as described by Hjorth et al. [20]. At the plant, three grass types (described in the "Types of Grass" section) were fed in a semi-continuous way to the extruder with the aid of a cratch and a 5.5-m-long conveyer belt. The extruder consisted of two counteracting-rotating screws driven by a 55-kW motor (Model MSZ

B55e; Lehmann Maschinenbau GmbH, Pöhl, Germany). The outlet of the extruder determines the intensity of the pressure build-up inside the extruder and thus the intensity of the pretreatment. The outlet was fixed at 19 mm diameter after conducting some preliminary tests on the grass feedstock. After extrusion, the biomass was carried off on a 4.1-m-long conveyer belt and piled up. Several tons of each biomass type were processed and this resulted in three different homogenous types of grass feedstock: extruded shredded ensiled grass (ESEG), extruded fresh grass (EFG), and extruded shredded fresh grass (ESFG).

Feedstock Analysis

To measure the total solids content (TS), samples were heated for 24 h at 105 °C in a laboratory oven (Bind 910, Binder, Germany). The total volatile solids (VS) were then assessed by incinerating the dried samples at 550 °C in a muffle furnace (Thermoconcept KL15, Thermoconcept, Germany). Kjeldahl nitrogen (TKN) was measured according to the ISO 5663 standard [23]. The C/N ratio was based on the determination of the Kjeldahl nitrogen and the VS, assuming that 50% of the VS consisted of carbon [24]. The stirring behaviour, pH, and electrical conductivity (EC) were tested on-site directly after the treatments of each grass sample. The stirring behaviour was determined qualitatively by adding a certain amount (3.5 or 10% on fresh weight base) of grass into a 1-L beaker with a magnetic stirrer and observing the behaviour of the mixture. The pH was measured in the same beaker after equilibration of the grass with water by using a pH glass electrode (Model 520A, Orion, Boston, MA, USA). EC was measured in the same manner by using a microprocessor conductivity meter (LF 537, WTW, Germany).

Biomethane Potential Assay

A representative sample of 2 kg was taken from each grass type and kept refrigerated. These samples were subjected to a biomethane potential (BMP) assay within 4 h after sampling following the recommendations of VDI [25]. The batch tests were executed in 5-L reactors with a 3-L working volume and in duplicate. They consisted of a mixture of inoculum and grass in a ratio of 4 g of VS per litre of inoculum; digestate from the anaerobic digestion of agricultural substrates was used as inoculum (4.85% DM and 54.54% VS). The reactors were run for 10 weeks at 38 °C under mesophilic conditions. The biogas production was determined daily, and after 10 weeks, the biogas was analysed for the methane and hydrogen sulfide content with a GA 2000 gas analyser (Geotechnical instruments, UK).

Energy Balance

The energy balance of the studied extrusion process was calculated based on the methodology described by Hjorth et al. [20]. The energy demand of the extrusion pretreatment and the supply conveyer belt was measured every 5 min, resulting in a total of approximately 100 readings, with a VIP Energy Analyzer (Elcontrol-Energy, Italy) and calculated according to Eq. 1:

$$E_{consumptionpretreatment} = \mathrm{I} \times \mathrm{U} \times \cos\Phi \times \sqrt{3}/C \quad (1)$$

where $U = 400$ V, $\cos \Phi = 0{,}82$, I is the average electric current, and C is the average capacity of the extruder. The latter two varied according to the processed feedstock, with an average measured capacity of 2 ton FM/h.

The amount of electricity that could be generated via methane production from the grass feedstock was calculated with Eq. 2:

$$E_{produced} = LHV \times \eta \times V_{CH4}/M_{biomass} \quad (2)$$

where LHV is the lower heating value of methane (10 kWh/m^3), η is the efficiency of the combined heat and power generator, V_{CH4} (L) is the volume of methane at standard gas conditions (273 K and 101.3 kPa), and $M_{biomass}$ is the weight of biomass (kg).

The energy balance was calculated as the difference between the electricity generated by the extra biomethane produced after the extrusion pretreatment and the electricity consumption of the extrusion pretreatment (Eqs. 3 and 4):

$$E_{extraproduced,pretreatment} = E_{produced,pretreatedfeedstock} - E_{produced,untreatedfeedstock} \quad (3)$$

$$E_{net,pretreatment} = E_{extraproduced,pretreatment} - E_{consumptionpretreatment} \quad (4)$$

Results and Discussion

Feedstock Composition

Six samples of grass were evaluated for biogas production. Fresh grass was used as a control and was subjected to three treatments: shredding, extrusion, and shredding followed by extrusion. Shredding was added as a treatment to allow for a comparison of the effects of extrusion in fresh and ensiled grass, as the ensiled grass used had been shredded before ensiling; moreover, shredding is also used as a baseline scenario, as the fibre length of grass is commonly reduced before feeding into the reactor to reduce mixing problems.

Table 1 Composition of the various grass feedstocks used in this experiment (*FG*, fresh grass; *SFG*, shredded fresh grass; *EFG*, extruded fresh grass; *ESFG*, extruded shredded fresh grass; *SEG*, shredded ensiled grass; *ESEG*, extruded shredded ensiled grass)

Grass sample	TS (%)	VS (%TS)	TKN (g/kg TS)	C/N	EC (µS)	pH
FG	25.7 ± 2.0	88.1 ± 8.2	6.5 ± 0.5	17.4 ± 2.1	2100 ± 84	8.8 ± 0.3
SFG	22.7 ± 1.8	85.6 ± 8.0	3.8 ± 0.3	25.7 ± 3.1	3190 ± 127	9.3 ± 0.4
EFG	28.6 ± 2.2	86.0 ± 8.0	6.9 ± 0.5	17.8 ± 2.2	3380 ± 135	7.8 ± 0.3
ESFG	27.1 ± 2.1	85.9 ± 8.0	4.5 ± 0.4	26.0 ± 3.2	3960 ± 158	8.5 ± 0.3
SEG	53.7 ± 4.2	54.2 ± 5.0	7.6 ± 0.6	19.1 ± 2.3	3100 ± 124	4.8 ± 0.2
ESEG	51.3 ± 4.0	53.7 ± 5.0	7.7 ± 0.6	17.9 ± 2.2	2670 ± 107	6.6 ± 0.3

In Table 1, the main characteristics of the six types of grass clippings further used for anaerobic digestion are presented.

It can be seen that the total solids (TS) content of the ensiled grass is much higher than that of the fresh grass samples; this can be attributed to the ensiling process, which requires a relatively high TS to be successful. The percentage of volatile compounds (VS) is also much lower for the ensiled grass samples because of the loss of organic matter due to gas formation during storage [26]. The effect of the extrusion pretreatment on the TS and VS contents was very low, even though it results in a temperature increase that might provoke the vaporization of water, and in the rupture of fibres and cell walls that may lead to leaching of water and plant constituents. A similar result, with a loss of only 3%, was found by Hjorth et al. [20].

The carbon over nitrogen ratio of the biomass should be within the range of 10 to 40 to serve as an input stream for an anaerobic digester and, in the most ideal case, it should be between 20 and 30 [27]. All of the grass samples analyzed were in this range while SFG and ESFG were even within the ideal range due to the significant loss of TKN during the shredding process. It may be possible that some grass juice was lost during the shredding due to cell wall rupture, as this fraction is rich in N-containing compounds such as proteins [28]. This is further confirmed by the increase in EC after shredding, which indicates that the cells were disrupted and their content was released when mixed with water for the EC measurement. Interestingly, an EC increase was also observed for the extruded grass, but without a change in the C/N ratio when compared to the fresh grass, indicating that the cell wall rupture that took place during shredding and extrusion were different. The results indicate that extrusion may have possibly caused enough damage to the cell wall for nutrients to leach out during the EC measurement, but not enough to cause grass juice loss during the pretreatment.

One of the difficulties when producing biogas from grass clippings lies in the agitation system, as long fibres might get tangled in it and a floating layer is often seen due to the low density of grass fibres [29]. Therefore, the stirring properties of the different grass samples were tested to assess if extrusion would help in reducing the floating layer and improve the stirring of the grass fibres.

Fresh grass got stuck to the magnetic stirrer, indicating that it might also get tangled in the impellers of the anaerobic digestion reactor in real conditions. The reduction in the size of the grass fibres achieved with shredding resulted in better stirring properties; however, a floating layer was still observed. Extrusion was able to further improve this, reducing the floating layer to only a very small percentage of the fibres. These initial tests were done with 3.5% solid concentration, while the usual solid concentration in a biogas digester needs to be around 7 to 9% to ensure stable operation [27]. Therefore, the solid concentration was increased to 10% for the extruded samples. Even though the fibres got stuck to the magnet stirrer at this high solid concentration, extrusion resulted in a workable suspension of grass with a greatly reduced floating layer, improving the stirring properties compared to fresh grass, which got stuck to the stirrer even at the lower solid content of 3.5%.

Methane Production

Biomethane yields were measured during batch tests to determine the effect of the different pretreatments in the anaerobic digestion process (Fig. 1).

In general, the composition of all the biogas samples ranged between 54 and 55% methane content, and H_2S was not detected in any of the samples. However, as can be seen

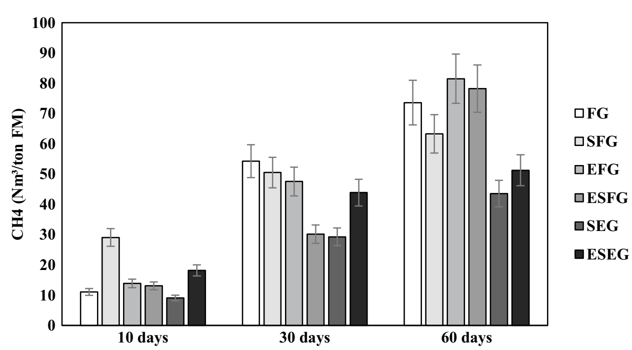

Fig. 1 Methane production during a 60-day biomethane potential assay of grass samples after different treatments (FG, fresh grass; SFG, shredded fresh grass; EFG, extruded fresh grass; ESFG, extruded shredded fresh grass; SEG, shredded ensiled grass; ESEG, extruded shredded ensiled grass). Standard deviations were calculated based on the average standard deviation of the BMP method, of 10%, as determined by Innolab (Belgium)

from Fig. 1, the different treatments affected biogas production and, consequentially, methane yields. Shredding of the biomass resulted in faster biogas production in the first 10 days. This can be attributed to the smaller particle size and thus a higher contact surface area and digestibility after shredding [30]. After 10 days, however, shredded fresh grass resulted in a lower conversion rate and a lower specific final methane yield of 63.3 in comparison to 73.7 Nm^3 CH_4/ton FM for fresh grass. This could be attributed to the difference in TS and VS in the shredded fresh grass; when calculating the yield per ton VS, the results were similar for SFG and FG (325.8 and 325.5 Nm^3 CH_4/ton VS), so shredding only improved the initial biogas production rate.

Extrusion pretreatment reduces the particle size to smaller proportions than shredding. Furthermore, it adds a disrupting effect on the cell wall and acts as thermal treatment, resulting in the release of cell content and a lower degree of polymerization of cellulose and hemicellulose [31]. Therefore, it would be expected that extrusion would enhance the biodegradability and result in a higher conversion rate of grass to biomethane. However, for the fresh grass samples that were extruded, ESFG and EFG, it was observed a longer lag phase when compared to the fresh grass, with ESFG having a significantly lower biomethane yield than fresh grass after 30 days of digestion. This lag phase can be attributed to a large amount of readily fermentable sugars present after extrusion; the rapid conversion of those sugars into volatile fatty acids (VFA) may have caused acidification and resulted in self-inhibition [32]. Interestingly, a lag phase was not observed in the extruded ensiled grass, further corroborating the hypothesis of readily fermentable sugars being responsible for this phenomenon; during ensiling, these sugars would have been mostly converted to lactic acid, resulting in different metabolic pathways during anaerobic digestion.

Even though the extruded samples of fresh grass showed a long lag phase, once this was overcome, the biogas production rate for these samples was similar to the other fresh grass treatments. Moreover, in a full-scale installation, this lag phase would probably not occur because of the mixing with other (buffering) substrates, the buffer capacity of the anaerobic digestion reactor itself, and the use of continuous reactors, which operate in a steady-state. The extrusion also resulted in a slight increase in digestibility and, consequently, in BMP, from 73.7 to 81.7 Nm^3 CH_4/ton FM for fresh grass. This change in biomethane yield can be directly related to the changes in VS content resulting from the extrusion pretreatment, as discussed before for the shredded fresh grass; this is true for all the fresh grass samples, as they all had similar biomethane yields per ton VS, ranging from 325.5 to 337.6 Nm^3 CH_4/ton VS.

The biomethane yields found in the present study are within the range of values previously reported, between 225 [11] and 455 Nm^3 CH4/ton VS [29]. The ensiled grass had a much lower BMP, between 150 and 186 Nm^3 CH4/ton VS. The BMP of the ensiled samples is also rather low if compared to the results from the literature, in which ensiled road grass and grasslands had a BMP of around 230 Nm^3 CH4/ton VS [17]. This can be explained by a longer period of microbial activity and the reduced water content in these samples, which lead to the formation of more recalcitrant organic solids, as the used grass was ensiled for a period of 2 years instead of the 9 to 12 months commonly practised. Extrusion can partially undo the increase in recalcitrance and cause slowly degradable compounds to become more easily degraded [20]. For this reason, a steeper biomethane production curve and a higher BMP were found for ESEG when compared to SEG.

Overall, when compared to the other results in literature in terms of Nm^3/ton VS, the extrusion process carried out in the present study had the least positive results when using fresh grass as the starting material. Hjorth et al. [20] observed a 9% increase in biomethane production after extrusion, while Khor et al. [22] reported an increase of up to 50% as a result of extrusion. However, when using ensiled grass, the present results are within the range found in the other studies, with an 18% increase in BMP after extrusion. This indicates that the starting material has a great influence on the extent of the changes undergone during the extrusion process. Moisture content seems to play a significant role in this, as both previous studies reported better results when using grass with a dry matter content of around 50%, while the fresh grass used in the present study had a dry matter content of only 25%. However, when using the ensiled grass, which had a dry matter content of 50%, the present extrusion results were much more significant. The significant influence of moisture in the extrusion of grass has also been observed in a previous study aiming to enhance the enzymatic hydrolysis of this biomass, in which the highest yields were found for the lowest moisture content due to increased friction and cell wall damaging [31].

Further studies focusing on biogas production from extruded grass should investigate the influence of moisture content in the extrusion efficiency to optimize grass handling and increase the impact of the extrusion treatment. This parameter becomes ever more important as it also has an impact on the economics of the process, given that lower moisture will result in higher energy expenditure during the operation of the extruder [20].

Energetic Cost–Benefit and Economic Evaluation

Pretreatments used to enhance anaerobic digestion processes should be evaluated in light of the energy consumed by this extra step and the surplus energy resulting from the extra

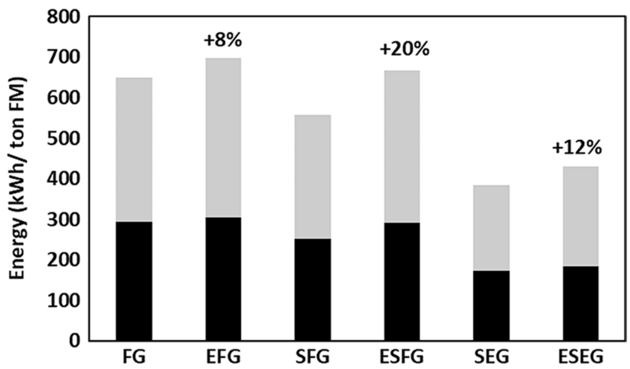

Fig. 2 The energetic cost–benefit of the extrusion pretreatment (E) on the three grass feedstocks SEG (shredded ensiled grass), SFG (shredded fresh grass), and FG (fresh grass) taking into account the net energy produced as electricity (black bar) and the net energy produced as heat (gray bar) after 60 days of the BMP assay. The electricity production presented in the graph represents the total electricity produced minus the electricity consumed by the extrusion treatment. The percentage above the bars give the increase of the net energy produced after the treatment relative to the energy produced with the untreated feedstock

biogas produced in comparison to the untreated feedstock. The energetic cost–benefit of the extrusion pretreatment is displayed in Fig. 2.

Even though the effect of extrusion largely differs depending on the grass feedstock, it was positive for all the samples tested, resulting in an energetic gain ranging from 20 to 8%. Therefore, the increase in biogas production with the addition of the extrusion step compensated for the extra energy expenditure of this pretreatment.

Nevertheless, the profitability of adding the extrusion step depends on local legislation and prices. In this study, the calculation was done for the Flemish region in Belgium. Table 2 gives an overview of the cost associated with the extrusion pretreatment. The electricity consumption of the extruder was assumed to come from the electricity production of the CHP. The price for energy produced from the biomethane was considered to be 45 €/MWh for the electricity and 97 €/MWh as a subsidy for the production of renewable energy. The cost of the extrusion pretreatment, therefore, was 6.8 €/ton FM; however, it should be noted that other peripherals (e.g. conveyer belt) and construction works were not taken into account in this calculation. The possible revenues are given in Table 3 for different hydraulic retention times (HRT) and grass feedstock.

Table 2 Extrusion expenditure

Extruder	200,000	€
Capex (at 5% interest rate)	25,452	€
Capacity	8000	t FM/year
Capital expenditure	3.2	€/t FM
Maintenance	0.6	€/t FM
Electricity consumption	21	KWh/t FM
Electricity cost	3.0	€/t FM
Total	6.8	€/t FM

Next to the electricity price of 132 (45 + 97) €/MWh, the subsidy concerning heat valorisation is 35 €/MWh [33]. It can be seen in Table 3 that the net revenue obtained with the extrusion pretreatment ranges from €6 to €17/t FM and is higher for longer HRTs.

Moreover, fresh grass will not be inserted into an anaerobic digestion continuous stirred tank reactor (CSTR) before a size reduction step because of its high viscosity and the possible formation of a floating layer, as previously discussed. For this reason, a comparison was made between SFG and EFG, and no revenue calculation is shown for FG. The results indicate that the shredding of the grass could be avoided, together with its associated cost, and replaced by the extrusion pretreatment.

The use of grass in anaerobic digestion is not yet widespread in commercial digesters. Therefore, a correct analysis of the economics of the extrusion pretreatment should not only compare grass before and after extrusion but also compare extruded grass with maize, as the latter would be the feedstock replaced by grass. From previous research, the BMP of maize was determined to be 79 Nm^3 CH_4/ton FM [17], which is similar to the BMP found for the extruded fresh grass (EFG) samples in the present study

Table 3 Revenues for the untreated and extruded scenarios for two different HRT

	Total energy production (kWh/ t FM)		Revenue (€/t FM)		Net revenue by extrusion (€/t FM)[b]
	Electricity	Thermal	Electricity	Thermal	
28 days[a]					
SEG	111	133	15.8	4.7	
ESEG	170	204	24.1	7.1	10.7
SFG	193	232	27.4	8.1	
ESFG	234	281	33.2	9.8	7.5
EFG	228	274	32.4	9.6	6.5[c]
40 days[a]					
SEG	147	176	20.8	6.2	
ESEG	201	241	28.6	8.5	10.1
SFG	216	259	30.7	9.1	
ESFG	309	370	43.8	13.0	17.0
EFG	271	325	38.5	11.4	10.1[c]

[a]Duration of the BMP assay after deducting the different lag phases for each feedstock

[b]Difference between revenues obtained with the same feedstock with and without extrusion

[c]Difference between revenues obtained with EFG and SFG

(82 Nm^3 CH_4/ton FM). The feedstock price of maize in Flanders is, on average, 25 €/t FM [33], while grass from natural grasslands or roadsides is considered waste and thus currently disposed of by composting with a gate fee between 20 and 40 €/t FM. If the price for accepting grass into anaerobic digesters would be lower, as the feedstock would generate revenue, the economic benefits of the (partial) replacement of maize by grass could outweigh the cost of the extruder pretreatment.

Conclusion

The extrusion pretreatment influenced the characteristics of the feedstock and improved the digestibility of the grass while simultaneously ensuring better mixing properties. From indicative trials, extrusion ensured a lower viscosity and no formation of a floating layer, which leads to a more stable digestion process with lower energy input for mixing and replacing an otherwise necessary comminution step such as shredding. The energetic cost–benefit evaluation indicated that the conversion of the extra biomethane produced with the extrusion treatment yields more electricity than that consumed by this extra step. Next to the electricity generated, there is an extra production of thermal energy that could also be valorised. The economic evaluation indicates that extrusion is profitable in comparison to the non-extruded grass feedstock. Furthermore, the extrusion of grass makes the replacement of energy maize possible without compromising the biomethane production while reducing the cost of the feedstock. However, care should be taken to optimize the hydraulic retention time (HRT) and to avoid acidification in the anaerobic digestion, possibly by co-digestion of the grass with other substrates.

Acknowledgements The authors would like to acknowledge Brecht Annicaert for his help in processing the data used in this study.

Author Contribution ND, JKB, and EM contributed to the study conception and design. Material preparation, data collection, and analysis were performed by ND, RG, and BW. The manuscript was written by ND and MFS and all authors read and approved the final manuscript.

Funding This work was developed under the Grassification project, which has received funding from the Interreg 2 Seas programme 2014–2020 co-funded by the European Regional Development Fund under subsidy contract No 2S03-042.

Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request

Code Availability Not applicable

Declarations

Conflict of Interest The authors declare no competing interests.

References

1. European Comission (2018) Renewable energy statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics. Accessed 25 Jun 2020
2. European Comission (2019) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: the European Green Deal. https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf. Accessed 12 Mar 2021
3. Smyth BM, Murphy JD, O'Brien CM (2009) What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renew Sustain Energy Rev 13:2349–2360. https://doi.org/10.1016/j.rser.2009.04.003
4. Korres NE, Singh A, Nizami A-S, Murphy JD (2010) Is grass biomethane a sustainable transport biofuel? Biofuels Bioprod Bioref 4:310–325. https://doi.org/10.1002/bbb.228
5. Brown AE, Ford JS, Bale CSE et al (2020) An assessment of road-verge grass as a feedstock for farm-fed anaerobic digestion plants. Biomass Bioenerg 138:105570. https://doi.org/10.1016/j.biombioe.2020.105570
6. Bedoić R, Čuček L, Ćosić B et al (2019) Green biomass to biogas – a study on anaerobic digestion of residue grass. J Clean Prod 213:700–709. https://doi.org/10.1016/j.jclepro.2018.12.224
7. Popp D, von Gillhaussen P, Weidlich EWA et al (2017) Methane yield of biomass from extensive grassland is affected by compositional changes induced by order of arrival. GCB Bioenergy 9:1555–1562. https://doi.org/10.1111/gcbb.12441
8. Chiumenti A, Boscaro D, Da Borso F et al (2018) Biogas from fresh spring and summer grass: effect of the harvesting period. Energies 11.https://doi.org/10.3390/en11061466
9. Chiumenti A, Pezzuolo A, Boscaro D, Da Borso F (2019) Exploitation of mowed grass from green areas by means of anaerobic digestion: effects of grass conservation methods (drying and ensiling) on biogas and biomethane yield. Energies 12.https://doi.org/10.3390/en12173244
10. Thamsiriroj T, Nizami AS, Murphy JD (2012) Why does monodigestion of grass silage fail in long term operation? Appl Energy 95:64–76. https://doi.org/10.1016/j.apenergy.2012.02.008
11. McEniry J, O'Kiely P (2013) Anaerobic methane production from five common grassland species at sequential stages of maturity. Bioresour Technol 127:143–150. https://doi.org/10.1016/j.biortech.2012.09.084
12. Prochnow A, Heiermann M, Plöchl M et al (2009) Bioenergy from permanent grassland – a review: 1. Biogas Bioresour Technol 100:4931–4944. https://doi.org/10.1016/j.biortech.2009.05.070
13. McEniry J, Allen E, Murphy JD, O'Kiely P (2014) Grass for biogas production: the impact of silage fermentation characteristics on methane yield in two contrasting biomethane potential test systems. Renew Energy 63:524–530. https://doi.org/10.1016/j.renene.2013.09.052
14. Stamatelatou K, Antonopoulou G, Ntaikou I, Lyberatos G (2012) The effect of physical, chemical, and biological pretreatments of biomass on its anaerobic digestibility and biogas production. Biogas Production. Wiley, Hoboken, pp 55–90
15. Rodriguez C, Alaswad A, Benyounis KY, Olabi AG (2017) Pretreatment techniques used in biogas production from grass. Renew

Sustain Energy Rev 68:1193–1204. https://doi.org/10.1016/j.rser.2016.02.022
16. Romano RT, Zhang R, Teter S, McGarvey JA (2009) The effect of enzyme addition on anaerobic digestion of Jose Tall Wheat Grass. Bioresour Technol 100:4564–4571. https://doi.org/10.1016/j.biortech.2008.12.065
17. De Moor S, Velghe F, Wierinck I et al (2013) Feasibility of grass co-digestion in an agricultural digester, influence on process parameters and residue composition. Bioresour Technol 150:187–194. https://doi.org/10.1016/j.biortech.2013.10.011
18. Bauer A, Lizasoain J, Theuretzbacher F et al (2014) Steam explosion pretreatment for enhancing biogas production of late harvested hay. Bioresour Technol 166:403–410. https://doi.org/10.1016/j.biortech.2014.05.025
19. Xie S, Frost JP, Lawlor PG et al (2011) Effects of thermo-chemical pre-treatment of grass silage on methane production by anaerobic digestion. Bioresour Technol 102:8748–8755. https://doi.org/10.1016/j.biortech.2011.07.078
20. Hjorth M, Gränitz K, Adamsen APS, Møller HB (2011) Extrusion as a pretreatment to increase biogas production. Bioresour Technol 102:4989–4994. https://doi.org/10.1016/j.biortech.2010.11.128
21. Duque A, Manzanares P, Ballesteros M (2017) Extrusion as a pretreatment for lignocellulosic biomass: fundamentals and applications. Renew Energy 114:1427–1441. https://doi.org/10.1016/j.renene.2017.06.050
22. Khor WC, Rabaey K, Vervaeren H (2015) Low temperature calcium hydroxide treatment enhances anaerobic methane production from (extruded) biomass. Bioresour Technol 176:181–188. https://doi.org/10.1016/j.biortech.2014.11.037
23. Technical Committee ISO/TC 147 (1984) ISO 5663 - Water quality — determination of Kjeldahl nitrogen
24. Sleutel S, De Neve S, Singier B, Hofman G (2007) Quantification of organic carbon in soils: a comparison of methodologies and assessment of the carbon content of organic matter. Commun Soil Sci Plant Anal 38:2647–2657. https://doi.org/10.1080/00103620701662877
25. VDI 4630 (2006) Fermentation of organic materials – Characterisation of the substrate, sampling, collection of material data, fermentation tests. Beuth Verlag GmbH., VDI Gesellschaft Energietechnik, Berlin
26. Borreani G, Tabacco E, Schmidt RJ et al (2018) Silage review: factors affecting dry matter and quality losses in silages. J Dairy Sci 101:3952–3979. https://doi.org/10.3168/jds.2017-13837
27. Yadvika S, Sreekrishnan TR et al (2004) Enhancement of biogas production from solid substrates using different techniques—a review. Bioresour Technol 95:1–10. https://doi.org/10.1016/j.biortech.2004.02.010
28. Damborg VK, Jensen SK, Weisbjerg MR et al (2020) Screw-pressed fractions from green forages as animal feed: chemical composition and mass balances. Anim Feed Sci Technol 261:114401. https://doi.org/10.1016/j.anifeedsci.2020.114401
29. Thamsiriroj T, Murphy JD (2010) Difficulties associated with monodigestion of grass as exemplified by commissioning a pilot-scale digester. Energy Fuels 24:4459–4469. https://doi.org/10.1021/ef1003039
30. Ferreira LC, Nilsen PJ, Fdz-Polanco F, Pérez-Elvira SI (2014) Biomethane potential of wheat straw: influence of particle size, water impregnation and thermal hydrolysis. Chem Eng J 242:254–259. https://doi.org/10.1016/j.cej.2013.08.041
31. Karunanithy C, Muthukumarappan K (2010) Effect of extruder parameters and moisture content of switchgrass, prairie cord grass on sugar recovery from enzymatic hydrolysis. Appl Biochem Biotechnol 162:1785–1803. https://doi.org/10.1007/s12010-010-8959-3
32. Siegert I, Banks C (2005) The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors. Process Biochem 40:3412–3418. https://doi.org/10.1016/j.procbio.2005.01.025
33. Vlaams Energieagentschap (2019) RAPPORT 2019 / 1 Deel 1 : Ontwerprapport OT / Bf voor projecten met een startdatum vanaf 1 januari 2020. Available at: https://www.energiesparen.be/sites/default/files/atoms/files/Rapport_OT_BF_deel1_2019_0.pdf. Accessed 12/02/2021