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Improving the energy balance of grass-based anaerobic digestion through combined harvesting and pretreatment

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ABSTRACT

An important challenge that has to be addressed to achieve sustainable anaerobic digestion of lignocellulosic substrates is the development of energy and cost efficient pretreatment methods. Technologies orientated to simultaneously harvest and mechanically pretreat the biomass at the field could meet these criteria as they can potentially reduce the energy losses. The objective of this study was to elucidate the effect of two full-scale harvesting machines to enhance the biogas production and subsequently, improve energy balance. The performances of Disc-mower and Excoriator were assessed on meadow and cultivated grass silages. The results showed that relatively high methane production can be achieved from meadow and cultivated grass harvested in different seasons. The findings indicated that the bioenergy production can be improved based on the selection of the appropriate harvesting technology. More specifically, Excoriator, which cuts and subsequently applies shearing forces on harvested biomass, enhanced the methane production up to 10% and the overall energy budget was improved proportionally to the driving speed increase.

1. Introduction

Biogas is an attractive renewable energy technology which can use versatile variety of organic substrates to produce methane through a biological process called Anaerobic Digestion (AD). Especially in Europe, the exploitation of agricultural land plays an important role to provide adequate biomass for expanding full-scale applications.

Specifically, permanent grassland, meadows and marginal areas are in abundance and in cases that they are not dedicated for food production or crop cultivation; their residues can be successfully utilized as feedstock for biogas production. Another advantage is that the grasslands in Europe are not commonly used for fodder production or pasturing [1], therefore the biomass is available to be used for other purposes. In case this substantial amount of biomass is utilized properly, considerably high amounts of bioenergy can be produced and the overall sustainability will be improved. Furthermore, through this alternative utilization of grass, side benefits will be also presented. For example, the biodiversity will be increased in the grasslands, as the trace elements and nutrients will be redistributed leading to increased biomass yields in the forthcoming future [2].

Nevertheless, specific obstacles, originating from grass maturation which increases lignification of the grasses, are necessitating efficient pretreatment in order to boost cellulose and hemicellulose solubilization and subsequently, increase the biodegradability [3]. Among the alternative pretreatments, mechanical methods have been widely investigated for lignocellulosic substrates due to their easiness in implementation [4]. These techniques apply mechanical stresses to the biomass, in order to break directly the lignocellulose and improve the accessibility to the degradable carbohydrates [5]. Mechanical pretreatment was proven to have positive impact in meadow grass biodegradability enhancing significantly the methane production [1,6,7]. However, the overall efficacy of these methods is still not clear, as the main drawback that hampers the full-scale applications is the increased energy consumption [8]. Hidaka et al. [9] found a positive energy balance in a process which involved as input the utilization of electrical energy to pretreat

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grass with shredders and as output the subsequent methane production from the AD of grass. However, these results are often obtained from lab-scale experiments and might not reflect the real practice applications. To further enlighten the efficiency of mechanical pretreatments and as a precursor for industrial scale implementation, the energy demands of commercially available machines should be taken into account in order to define the overall budget of the supply chain.

An efficient way to decrease the total energy demand, and thus increase the overall sustainability, is the improvement of individual process steps before feeding the biomass to the digester. Process steps as harvesting, collection, transportation and pretreatment are equally critical constraints which add substantial costs to the biogas economy [10]. Nevertheless, the overall AD process feasibility could be remarkably improved by combining the different procedures into single operational steps. Thus, as concluded in our preliminary study, the simultaneously harvesting and mechanically pretreatment of the biomass could be a potentially efficient way to enhance significantly the energy yield per hectare due to the selection of appropriate harvesting machine [11].

Moreover, efficient combination of these two process steps could lead to further advantages. For instance, rapid drying of biomass is occurred due to the mechanical crushing of effective harvesting machines [11]. Hence, a product containing less moisture content and therefore of higher value, will be delivered to the feeding tanks of the biogas plant. Thus, the logistics and transport systems are improved and subsequently, the resultant costs are decreased [12].

The aim of this study was to elucidate the effect of two commercially available harvesting machines in the AD process of two different types of grass silages. Energy consumption of the harvesting machines under various operating conditions and subsequently, methane yield of the different treatments were measured in order to determine the most promising energy budget.

2. Materials and methods

2.1. Inoculum

The methanogenic inoculum used for the batch experiments was collected from a thermophilic full-scale biogas plant in Snertinge, Denmark. The feeding mixture of the biogas plant was consisted of animal slurry and residual products from ethanol industry. Before usage, the inoculum was placed in a thermophilic incubator for a total period of 10 days in order to reduce its residual methane productivity. Table 1 presents the main characteristics of the inoculum.

Table 1
Main characteristics of used inoculum.

Parameters	Values
Total Solids (TS) (g/kg)	2.75 ± 0.01
Volatile Solids (VS) (g/kg)	1.71 ± 0.01
TKN (g/kg)	3.63 ± 0.13
NH_4-N (g/kg)	3.51 ± 0.12
pH	8.31
Total Volatile Fatty Acids (TVFA) (mg/L)	91.6 ± 13.1
Acetate (mg/L)	70.7 ± 11.0
Propionate (mg/L)	10.5 ± 0.9
Isobutyrate (mg/L)	2.0 ± 0.1
Butyrate (mg/L)	4.2 ± 0.8
Isovalerate (mg/L)	2.1 ± 0.2

2.2. Meadow and cultivated grass

Meadow grass was harvested from natural grassland (~1.5 ha), which has never been plowed (first cut), in Kongeåvej 122, 6660 Lintrup, Denmark (Geo-coordinates: 55.437982°, 8.978604°). The height of meadow grass was in a range of 40–50 cm, before mowing and the cutting height was approximately 10 cm. The field was harvested in mid-July 2015 and subsequently, grass samples were vacuum packed so as to be ensiled.

The cultivated grass was harvested from a neighboring area (~1.3 ha) in Jutland, Denmark; Tobøl Fælledvej 10, 6683 Føvling (Geo-coordinates: 55.417155°, 8.920760°). According to Dansk Landbrugs Grovvareselskab (DLG), Denmark, the sample was a grass mixture number 43 (13% white clover, 40% tetraploid hybrid ryegrass, 22% diploid early perennial ryegrass and 25% diploid medium-early perennial ryegrass) and its height was 20–35 cm prior mowing and 6–8 cm after mowing. The crop was firstly established in 2013 and the samples were originated from the fourth annual cut. The cultivated grass was harvested in mid-October 2015 and spread out for about 48 h before ensilage. After two months at ambient temperature, in anaerobic conditions and in absence of light, the ensiling process was finished.

Regarding ensiling, no biological additives were added to enhance the biological process of both grass species, as in Denmark spraying the biomass with silage additives is not typically followed in practice [13]. The main physicochemical characteristics and trace elements of grass species are presented in Tables 2 and 3, respectively.

2.3. Description of harvesting procedure

Based on previous findings, two full-scale harvesting machines were examined [11]. An ordinary front mounted machinery (denoted as "Disc-mower") and an alternative harvester (denoted as "Excoriator") were used with an effective working width of 3.2 m. The first machinery was a trailed conditioner equipped with butterfly rear mounted and it did not provoke significant damages to the surface of the biomass. Thus, it was operated so as to produce the least possible treatment of the grass. In contrast, the Excoriator consisted of intermeshing stainless steel rolls so as to break down the lignocellulosic matrix. Two harvesting experiments were conducted. At the initial experiment, the plot was separated in 18 equally sized swaths of land and then, the meadow was harvested in every second treatment using either the Disc-mower or the Excoriator. No attention was paid on the operation of the machines around the field.

As for the cultivated grass, the test was conducted as a

Table 2
Main physicochemical characteristics of used grass silages.

Characteristics	Meadow grass	Cultivated grass
TS (g/kg)	420 ± 33	216 ± 14
VS (g/kg)	392 ± 19	197 ± 13
pH	4.29	5.28
COD (g/kgTS)	1115 ± 170	1152 ± 140
Cellulose (%TS)	36.1 ± 0.76	31.2 ± 3.5
Hemicellulose (%TS)	29.8.3 ± 0.95	17.2 ± 2.1
Klason Lignin (%TS)	19.9 ± 1.1	9.3 ± 3.5
Lactic acid (%TS)	5.51 ± 0.41	3.95 ± 0.05
Acetic acid (%TS)	1.84 ± 0.13	2.79 ± 0.30
Butyric acid (%TS)	0.24 ± 0.05	0.78 ± 0.02
Ethanol (%TS)	0.52 ± 0.03	0.12 ± 0.01
TKN (g/kg)	16.2 ± 0.1	29.1 ± 0.4
Proteins (g/kg)	82.5 ± 0.1	148.9 ± 12.1
C/N	25	14