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Mechanical pretreatment for increased biogas production from lignocellulosic biomass; predicting the methane yield from structural plant components

Panagiotis Tsapekos, Panagiotis G. Kougias *, Irini Angelidaki

Department of Environmental Engineering, Technical University of Denmark, Kgs. Lyngby DK-2800, Denmark

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ABSTRACT

Lignocellulosic substrates are associated with limited biodegradability due to the structural complexity. For that reason, a pretreatment step is mandatory for efficient biomass transformation which will lead to increased bioenergy output. The aim of the present study was to assess the efficiency of two pretreatment machines to enhance the methane yield of meadow grass. Specifically, the application of shearing forces with a rotated plastic sweeping brush against a steel roller significantly increased biomass biodegradability by 20% under relatively gentle operation conditions (600 rpm). The more intense operation (1200 rpm) was not associated with higher methane yield enhancement. Regarding an alternative machine, in which the brush was replaced with a coarse steel roller resulted in a more distinct effect (+27%) despite the lower rotating speed (~400 rpm). Moreover, the association of the substrate's individual chemical components and the practical methane yield was assessed, establishing single and multiple linear regression models. However, the estimation accuracy was rather low with either single (regressor: lignin, R^2: 0.50) or multiple linear regression analyses (regressors: arabinan-lignin-protein, R^2: 0.61). Results showed that poorly lignified plant tissue containing relatively high fractions of protein and arabinan is more susceptible to anaerobic digestion.

1. Introduction

Agricultural land (i.e. arable land, permanent crops, permanent meadows and pastures) covers more than 37% of the total land surface with lignocellulosic biomass as the main organic component (Faostat, 2016). Lignocellulosic biomass is considered as a potential feedstock for industrial biofuels production (e.g. biogas, bioethanol). This application has several advantages, e.g. besides of being CO_2 neutral, it is contributing to lower emissions compared to the common practice of burning the lignocellulosic residues on the field (Hayashi et al., 2014; Marañón et al., 2011). Among the different technologies for biofuel production using lignocellulosic materials, anaerobic digestion appears as the most promising application as it is more energetically favourable compared to liquid biofuels (Frigon and Guiot, 2010).

The biomass' characteristics, such as plant size, shape and moisture content are crucial for efficient biomethanation and also, optimal process performance. Thus, lignocellulosic materials need to be pretreated prior to their introduction in the anaerobic reactor in order to avoid operational problems (e.g. clogging, floating layers) (Mönch-Tegeder et al., 2014). Moreover, the pretreatment is essential in order to minimise the resistance of the solid feedstocks to enzymatic attack. Indeed, it is mandatory to disrupt the complex lignocellulosic structure in order to improve the conversion of structural carbohydrates to monomeric sugars (Katukuri et al., 2017; Ranjan and Moholkar, 2013). On this topic, it was recently shown that mechanical comminution machines can efficiently improve the biomass characteristics for biogas applications (i.e. size reduction, surface disruption, partial drying) (Tsapekos et al., 2017a). In general, mechanical pretreatments are considered more appropriate for industrial applications compared to the alternative methods (i.e. thermal, chemical, biological) (Carrere et al., 2015). The mode of action of mechanical methods relies on the application of shear and/or compression forces to boost biomass deconstruction (Kratky and Jirout, 2011). With respect to operational features, the selection of suitable construction materials is of major importance. Indeed, it was reported that using materials of high coarseness to equip a comminution device, the biogas enhancement could be significantly improved compared to other smoother materials (Tsapekos et al., 2015).

* Corresponding author at: Department of Environmental Engineering, Technical University of Denmark, Bld 113, 2800 Lyngby, Denmark.

E-mail address: panak@env.dtu.dk (P.G. Kougias).

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Moreover, for the overall sustainability of the pretreatment method, durability and robustness of equipment is of high importance. For instance, the performance of equipment can be deteriorated in real-life applications and in cases that large materials other than biomass are processed in error (e.g. metal pieces or stones). Thus, machine's lifetime can be markedly decreased or the equipment can collapse adding extra costs. In this context, the controlled and optimized operation of full-scale harvesting machines can remarkably reduce the energy input and in parallel, increase the output of lignocellulose-based AD (Tsapekos et al., 2017a,b). Likewise, it was revealed that the energy balance of AD using various crops is significantly affected by the performance of the used comminution machine (Herrmann et al., 2012). Hence, both a careful design of equipment in terms of materials and technology and also, the proper usage should always be ensured in order to efficiently apply vigorous mechanical forces and consequently, increase substrate's biodegradability.

Of equal importance with pretreatment's efficiency for high bioenergy output are the feedstock's characteristics. For instance, biomass biodegradability is negatively correlated to the level of cell walls lignification (Wang et al., 2009). In contrast, ensiled substrates are possibly associated with high methane production due to the fermentation of complex carbohydrates into metabolic intermediates (e.g. lactic acid) that took place during the ensiling process (Vervaeren et al., 2010). Despite well-established knowledge about the relations of biomass characteristics and biodegradability, a standardised and constant correlation between chemical characteristics and biochemical methane potential (BMP) is not yet existing (Dandikas et al., 2015). In addition, the BMP measurement provides important information about substrate's biodegradability but it is a time-demanding process (Charnier et al., 2016). Conversely, the analytical methods for biomass characterization are only requiring relatively short time. Hence, linking prompt methods with the BMP values could establish a fast decision-making tool in order to design and apply strategies that can lead to process optimization in full-scale applications (Fitamo et al., 2017). In a recent study, more than 200 samples were used to correlate the hydrolysis rate constant with the chemical composition of different biomasses, as a precursor for predicting the biogas production (Dandikas et al., 2018). The non-fibre structural sugars and crude protein contents were associated with the most efficient, but still moderate, prediction accuracy ($R^2 \sim 66\%$). Thus, the suggested approach can be followed for an initial assessment of feedstock degradation potential; however, a strong correlation that leads to accurate forecasting cannot be expected. Similarly, Edwiges et al. (2018) examined the correlation between the compositional components of fruit-vegetable residues and methane potential. Results interpretation revealed that lignin content is a strong predictor of solid waste, which is in accordance with a similar previous study (Triolo et al., 2011). However, lignin is significantly higher at agricultural residues compared to the fruit-vegetable waste, and additionally, its chemical structure differs markedly among the various lignocellulosic species. Moreover, lignocellulose characteristics, such as crystallinity, degree of polymerization, content and composition of monolignol precursors, can indirectly affect the anaerobic biodegradability. Hence, linking the chemical synthesis with the practical methane yield is still challenging.

The present study aims to elucidate the efficiency of two mechanical pretreatment methods for enhancing the biogas production from meadow grass. The performance was evaluated with respect to different operational parameters (i.e. different rotating speeds and biomass loads). Meadow grass was used a model biomass for the pretreatment tests due to its high availability in marginal lands and environmentally sensitive areas. Specifically, the meadow grass that is not used for grazing during summer due to its low fodder value can with great benefit be exploited for bioenergy purposes. Moreover, the correlation among substrate's chemical characteristics and methane yield was examined to develop a rapid and reliable model to predict lignocellulose's biodegradability. The development of an efficient prediction tool could allow the biogas plant operators to successfully assess the energy output that can be obtained by a given substrate. This application signifies, its high importance for real-life practices. On this subject, a heterogeneous dataset using various agricultural substrates were used to develop a prediction model.

2. Materials and methods

2.1. Inoculum

Inoculum was obtained from the effluent tank of a thermophilic biogas plant (Snertinge, Denmark). The inoculum was immediately transported to the laboratory and subsequently, was sieved to remove particles larger than 10 mm. Afterwards, the inoculum was incubated for 10 days at thermophilic temperature to remove background methane production. The main chemical characteristics of the inoculum were: pH: 8.07, Total Solids (TS): 24.1 ± 0.1 g/L, Volatile Solids (VS): 15.0 ± 0.1 g/L, Total Kjeldahl Nitrogen (TKN): 4.6 ± 0.2 g-TKN/L, Ammonium Nitrogen: 3.8 ± 0.1 g NH_4^+-N/L, and total Volatile Fatty Acids (TVFA): 0.7 ± 0.1 g/L.

2.2. Substrates

To define the correlation between methane production and lignocellulosic substrates' chemical composition, diverse species were examined; grass obtained from various meadows (i.e. M1–M7), grass clippings (GC), wheat straw (WS) and digested biofibers (DB). Samples of non-cultivated meadow grass were manually collected from natural grasslands. The meadow fields were mainly consisted of white clover, tetraploid hybrid ryegrass, diploid early perennial ryegrass and diploid medium-early perennial ryegrass. For proper silage fermentation, the grasses were kept intact at room temperature for two days to be partially dried, and then, were placed in anaerobically sealed plastic bags without injecting biological additives for sixty days. Grass clippings and wheat straw were collected from fields in Zealand, Denmark. Overall, ten different lignocellulosic substrates were examined in triplicate samples. The chemical composition of the used substrates is presented in Table 1. Samples were ground to 2 mm to determine their chemical characteristics.

2.3. Mechanical pretreatment

Meadow grass was used in order to assess the efficiency of mechanical pretreatments on biogas enhancement (Table 2). Two different mechanical pretreatment units were constructed in order to evaluate their effect on the anaerobic biodegradability of meadow grass. The first machine was consisted of a road sweeping brush and a steel mesh conditioner (crimper) (Fig. 1a). Pretreatment's efficiency was based on the principle that the plastic brush roller, which was placed diametrically opposed to the steel roller can intensively press the biomass towards the reversely rotating equipment. The brush roller was rotated at different driving speeds in order to define the most optimal operation (Table 2). Conversely, the steel roller was always rotating in the same speed as its main usage was to ensure a proper grass flow towards the brush roller. During all trials, the same amount of grass (1.4 kg/m^2) was treated to simulate the application of a full-scale harvester at a typical meadow field. Regarding the second test, the comminuting apparatus was partially amended in order to enhance the damage of biomass surface. Hence, a corrugated roller with coarse steel surface was rotating towards a stable coarse shell (Fig. 1b). Additionally,