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Steam explosion pretreatment of wheat straw to improve methane yields: Investigation of the degradation kinetics of structural compounds during anaerobic digestion

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HIGHLIGHTS

- Steam explosion treatment of straw from 140 °C to 178 °C for 30, 60, 120 min.
- Treatment caused a hydrolysis of hemicellulose and the formation of pseudo lignin.
- Investigation of the degradation process of biomass during anaerobic digestion.
- Increasing severity of pretreatment resulted in faster degradation of the biomass.
- Content of pseudo-lignin decreased during the anaerobic degradation experiment.

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ABSTRACT

Wheat straw can serve as a low-cost substrate for energy production without competing with food or feed production. This study investigated the effect of steam explosion pretreatment on the biological methane potential and the degradation kinetics of wheat straw during anaerobic digestion. It was observed that the biological methane potential of the non steam exploded, ground wheat straw (276 l_N kg VS^{-1}) did not significantly differ from the best steam explosion treated sample (286 l_N kg VS^{-1}) which was achieved at a pretreatment temperature of 140 °C and a retention time of 60 min. Nevertheless degradation speed was improved by the pretreatment. Furthermore it was observed that compounds resulting from chemical reactions during the pretreatment and classified as pseudo-lignin were also degraded during the anaerobic batch experiments. Based on the rumen simulation technique, a model was developed to characterise the degradation process.

1. Introduction

Producing energy from fossil fuels results in carbon dioxide emissions, which are largely responsible for the greenhouse gas effect. This, combined with finite and dwindling stocks of fossil fuels, has led to an increased interest in alternative energy sources. Policies have been enacted to increase the production of renewable energy. The European directive 2009/28/EC, states that by 2020 a share of 20% of the EU's overall energy consumption must come from renewable sources (Parliament, 2009). Alternative energy from solar radiation, wind and water faces technical challenges, such as uncertain availability and insufficient storage options. Energy production from biomass can overcome these problems as energy can be produced when it is actually needed. Biodiesel, bioethanol and biogas production have experienced a strong increase over the past several years. State-of-the-art technologies depend on sugar, starch and oil for conversion into energy carriers and therefore rely heavily on the availability of traditional energy crops such as maize, wheat or rapeseed (Borugadda and Goud, 2012). The use of energy crops can lead to a competitive situation between food (and respectively feed) and energy production (German National Academy of Sciences Leopoldina, 2012). Therefore, alternative biomass source are needed in order to ensure that

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renewable energy is being produced in an ecologically and socially sustainable fashion. The utilisation of lignocellulosic material is very promising, as it is the most abundant source of biomass worldwide and, depending on regional circumstances, is not in direct competition with food and feed production (Lin and Tanaka, 2006). The main components of lignocellulosic materials are cellulose, hemicellulose and lignin, which together form the lignocellulose complex. Depending on the type of plant and on the vegetation period in which it the biomass is harvested, the bond between lignin and the other components can be very resistant to digestion (Buruiana et al., 2013). In order to utilise this material for the production of energy carriers like ethanol or biogas, the material must be pretreated in order to make the cellulose and the hemicellulose available for the biological conversion to energy carriers. Due to its chemical structure, native lignin cannot be used for biological conversion into an energy carrier (Frei, 2013).

Depending on the type of biomass and on the desired biological conversion pathway, different strategies for lignocellulose pretreatment can be pursued. If lignocellulose is used as a feedstock for biogas production, reducing the particle size is a popular technique as it is easily implemented in biogas plants and is comparatively inexpensive. The disadvantage of this approach is that the process has a limited effect on feedstock properties but consumes large quantities of electrical energy in the process, leading to high operation costs (Kratky and Jirout, 2011; Taherzadeh and Karimi, 2008). The utilisation of thermophysical pretreatment technologies, such as steam explosion or liquid hot water pretreatment, is another promising strategy. Although these are more complicated to implement in a biogas plant, their significant effect on the lignocellulose feedstock promises high conversion rates in the biological degradation process (Hendriks and Zeeman, 2008). Steam explosion has proven to be a viable option for the pretreatment of several types of biomass (Bauer et al., 2014; Menardo et al., 2012). Pretreating biomass with steam explosion increase the specific biogas and methane yields significantly while also increasing the degradation speed of the biomass due to changes in the chemical composition. Chemical reactions take place during the pretreatment process due to high process temperatures (between 140 °C and 220 °C). Polysaccharide compounds such as hemicellulose are hydrolysed, leading to higher degradation speeds during the anaerobic process. These advantages allow the implementation of high performance fermenters with lower hydraulic retention times, reducing the energy required for fermenter homogenisation. Depending on the intensity of the pretreatment, inhibitors such as furfural and hydroxymethylfurfural and compounds classified as pseudolignin may also form (Bauer et al., 2014; Vivekanand et al., 2013).

The experimental setup for investigating biomass degradation in an anaerobic process is complex and cost intensive. Reliable models can provide an attractive alternative to the experimental approach, allowing the degradation process to be characterised and fundamental data to be calculated. The results of such models can be used to optimise the digestion process in existing biogas plants. Current models use the experimental determination of the methane yield at different points during fermentation to deduce the degradation of the biomass. In the field of feedstuff analysis there are models, which directly investigate the degradation of biomass based on its composition and a maximum degradation rate.

This study investigated the effect of steam explosion pretreatment on the biogas and methane yields of wheat straw. As the main fraction of wheat straw is lignocellulose, special focus was paid to the degradation kinetics of the structural compounds cellulose, hemicellulose and lignin, which were examined using a modified animal feed analysis method. Detailed knowledge of the digestibility and degradation speed of single compounds can serve as the basis for further improvements to the steam explosion pretreatment technology. The degradation behaviour of compounds resulting from reactions of sugars released by the hydrolysis of hemicellulose during steam explosion pretreatment is a yet unexplored field. Another objective of this study was to adapt a feedstuff analysis model for biomass degradation in an anaerobic process.

2. Methods

2.1. Steam explosion pretreatment

The biomass used for the experiments was wheat straw cultivated in eastern Austria in 2013. The steam explosion pretreatment was carried out at a testing facility at a biogas plant in Parndorf, Austria. The wheat straw was cut to a size smaller than 5 cm and then mixed with water to obtain a dry matter content of 30%. After transferring the material into the reaction vessel, it was preheated in order to obtain a steam-saturated atmosphere. The temperature was then increased until the final pretreatment temperature was reached. Pretreatment temperatures of 140 °C, 160 °C and 178 °C and pretreatment times of 0.5, 1 and 2 h were chosen for the experiment. After the retention time had elapsed, the pressure was reduced abruptly to atmospheric pressure, causing a sudden vaporisation of the water inside the vessel. The pretreated material was then transferred into a flash tank and, once cooled to room temperature, collected. The material was subsequently vacuum packed and stored at 4 °C for later analysis.

The severity factor combines both pretreatment temperature and time into one parameter (Overend and Chornet, 1987), allowing the results of the analysis to be displayed and analysed in a consistent manner. The severity factor is particularly useful when comparing the effects of pretreatment (see Eq. (1))

$$\mathrm{SF} = \log[t * \exp(T - 100/14,75)] \quad (1)$$

SF – severity factor,
t – pretreatment time,
T – pretreatment temperature.

2.2. Chemical analysis

In order to characterise the biomass, all samples were analysed for dry matter (DM) and volatile solids (VS) content as well as for cellulose (CEL), hemicellulose (H-CEL) and lignin (ADL) content.

The dry matter and the volatile solids content was determined according to the standard methods DIN 12880 (2001) and DIN 12879 (2001). The biomass was dried at 105 °C until a constant weight was reached. The dried material was then dry oxidised in a muffle furnace at 550 °C. After oxidation, the residue remaining was tagged as raw ash. The difference between dry matter and ash content represents the volatile solid content of the biomass.

Cellulose, hemicellulose and lignin content were determined according to the method of van Soest and Wine (1967) and the modification made by Naumann and Bassler (1976). After treatment with a neutral detergent solution, the insoluble residue is known as the neutral detergent fibre (NDF) content. After treatment with an acid detergent solution, the insoluble residue is known as the acid detergent fibre (ADF). The dried residue from the ADF determination was treated with 72% sulphuric acid to determine the lignin content (ADL). The hemicellulose content was calculated as the difference between NDF and ADF. Cellulose content was calculated as the difference between ADF and ADL.

After ADL determination, the dried residue was incinerated at 500 °C in order to determine the content of acid insoluble ashes.