Effect of Steam Explosion Pretreatment on the Specific Methane Yield of *Miscanthus* x *giganteus*

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Summary

A highly promising energy crop for biogas production can be *Miscanthus* x *giganteus*. It has multiple advantages, which include low soil requirements and the existence of genotypes adapted to dry conditions in comparison to other energy crops.

Miscanthus cannot be used in the biogas plant without a pretreatment due to the recalcitrant nature of lignocelluloses. One of the most efficient pretreatment methods for lignocellulosic biomass is steam explosion. This includes heating the biomass at high temperature values, followed by mechanical disruption of the biomass fibres by a rapid pressure drop. The objective of this study is to analyse the effect of the steam explosion pretreatment on the specific biogas and methane production of miscanthus. In addition methane hectare yields are calculated and compared to those of maize.

Steam explosion pretreatment was carried out in a laboratory scale facility in Ås, Norway. The miscanthus was mixed with water and heated up to the desired temperature. After a defined pretreatment time the pressure in the reaction vessel was reduced rapidly, which caused the liquid water to vaporize immediately. The material was cooled down in a flushing tank and was then stored at 5°C until further analytical procedures. Pretreatment temperatures were 190°C and 210°C; holding times were 5, 10 and 15 minutes. Determination of the specific methane yield was done in triplicate using batch tests according to VDI 4630. The material was inoculated with the liquid fermentation residue of a biogas plant. The produced gas was collected in eudiometers and then analysed for the CH_4 and CO_2 content.

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Introduction

In the last decades the demand for energy experienced an exponential growth, awaking concerns about safe and sustainable way for meeting those requirements. Besides solar, wind, water and geothermal energy, the utilization of biomass can be an important alternative to fossil energy sources. Biomass can be produced using existing agricultural equipment, it can be stored easily and it can be used for production of electricity and fuels. Apart from combustion, the production of liquid fuels like bioethanol and biodiesel, as well as the production of biogas are possible conversion pathways. Biogas can either be used to produce electricity and heat energy in a CHP (combined heat and power) or upgraded to biomethane, which can be used as fuel or fed into the public natural gas grid (Friedrichs et al., 2003).

Recent developments caused a discussion concerning the utilization of agricultural land for energy production instead of food and feed. Especially, growth of maize experienced strong criticism since in some regions it is not grown in crop cycles, but as monocultures. Maize serves as a feedstock for ethanol and biogas production, whereas for ethanol production only corn is used; for biogas production whole plant is ensiled and then fed to the fermenters throughout the year.

For providing a sustainable biomass feedstock for biogas production that is not competing with food and feed production there are different options (e.g. the utilization of residues and catch crops). Another alternative is cultivation of energy crops on inferior agricultural areas. Miscanthus can be grown on poor quality soils and still deliver high biomass yields due to its more efficient CO_2 utilization as a C4 plant. Moreover, it has low maintenance requirements, as it is a perennial crop. After planting nursery plants it needs about three years until maximum yields can be achieved. Despite the fact that yields are higher in autumn, harvest takes place usually between December and April as nutrients are retracted in the roots and dry matter content of above ground biomass allows easy storage. Miscanthus can be harvested 15 years until yields are dropping and cultivation has to be changed.

As miscanthus biomass is characterized by high lignocellulose content, it is necessary to apply a pretreatment prior to feeding it into the fermenter. Steam explosion pretreatment has already been proven as capable of significantly increasing methane yields compared to untreated samples (Bauer et al., 2009; Menardo et al., 2012). During the pretreatment hemicellulose and partly cellulose get hydrolysed and organic acids (e.g. acetic acid) are formed (Taherzadeh & Karimi, 2008). The objective of this study is to determine the effect of steam explosion on the methane yields of miscanthus. With the data obtained from the laboratory analysis, possible methane hectare yields (MHY) are calculated and compared to those of maize.

Methane hectare yield of maize

MHY of maize reported in literature are very different (Herrmann & Rath, 2012). The comparison is only possible if experimental setup for determination of the SMY is the same. The MHY of maize shown in table 3 has been calculated using a SMY determined in a eudiometer batch system at temperatures between 35 and 38 °C.

Table 1. Different MHY of maize reported in literature

Source	Methane hectare yield [m³ ha⁻¹ y⁻¹]	Variation
Amon et al. (2002)	3,064 – 6,571	maize variety, harvest time
Amon et al. (2003)	3,743 – 8,529	maize variety, harvest time
Amon et al. (2007)	7,226 – 9,039	maize variety, harvest time
Schittenhelm (2008)	7,453 – 9,370	maize variety, year, harvest time
Tatah (2008)	3,959 – 10,117	maize variety, year, harvest time, site

Material and methods

Raw material and steam explosion pretreatment

Miscanthus biomass used in the experiments was grown at a research site of the University of Natural Resources and Life Sciences, Vienna in Groß-Enzersdorf, about 10 km east of Vienna. It was harvested in February 2010, vacuumed and then stored until further use. The harvested biomass was pretreated with the steam explosion unit CAMBI in a test facility at the University of Life Sciences (UMB) in Ås, Norway. It consists of a 20 L reaction vessel, a steam boiler and a flash out tank. Pretreatment temperatures were 190°C and 210°C, and pretreatment times were 10, 15 and 20 minutes.

In order to unify the temperature and time parameters, the severity factor was calculated. This factor is widely used to compare the effect of steam explosion on the chemical composition and methane yields of biomass samples (Overend & Chornet, 1987).

$$SF = \log\left(t \cdot \exp\left[\frac{T-100}{14.75} \right] \right)$$

SF - severity factor
t - pretreatment time(min)
T - pretreatment temperature (°C)

Chemical analysis

Dry matter content (DM) was analysed by drying the material in a chamber at 105 °C until constant weight was reached. The dried material was burned in a muffle furnace at 550 °C and used to determine the raw ash content. The volatile solids (VS) were calculated by subtracting the raw ash content from the total solids (DIN 12880, 2001).

Determination of the specific methane yield according to VDI 4630

Anaerobic digestion batch trials were carried out in triplicate in accordance with VDI 4630 (VDI, 2006), employing eudiometer batch digesters of 0.25 L capacity. The analysed variants and the inoculum were weighed out in a ratio 1:3 (based on volatile solids content). The inoculum utilized was taken from a biogas plant in Utzenaich (Upper Austria). The digesters, incubated at 37.5°C, were continuously stirred and the biogas yields were monitored on a daily basis. Biogas and methane production were measured in norm litres (273 K and 1013 mbar) per kg of volatile solids (l_N kg⁻¹ VS). The portable gas analyser Dräger X-AM 7000 was used to determine the biogas composition (CH_4 and CO_2).

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Agric. conspec. sci. Vol. 79 (2014) No. 1

Results

Specific biogas and methane yields

In Table 1 the specific biogas and methane yields of the analysed samples are displayed. The pretreatment of miscanthus with steam explosion results in a strong improvement of the possible yields. While the untreated sample results in a methane yield of 84 l_N kg VS^{-1}, the steam explosion pretreated samples deliver methane yields between 248 and 345 l_N kg VS^{-1}

Calculation of methane hectare yields of miscanthus

For calculation of possible MHY it is first necessary to determine dry matter yields per hectare of miscanthus. Clifton – Brown (Clifton-Brown et al., 2004) developed a model for estimation of miscanthus yields considering different factors such as vegetation period, daily temperature, radiation use efficiency and water supply situation of the considered regions. Using GIS and FAO based data they established a model for possible dry matter yields of miscanthus for the whole of Europe.

As it can be seen in Figure 1, in most of the south-eastern region of Europe, dry matter yields between 20 and 40 tons of dry matter per hectare and year are possible. For validation of their calculated results, 20 field trials were carried out. The correlation between the calculated and observed yields shows a R^2 of 0.6. The yields calculated are peak yields; hence it is necessary to assume a mass loss as the harvest time is delayed from autumn to spring (Clifton-Brown et al., 2004). Using data from field trials in five different countries provided by Lewandowski (Lewandowski et al., 2003), this mass loss is 0.36% per day. Therefore, the yields would be 30% lower than the possible peak yields. Using this data and the results from the batch experiments, the MHY can
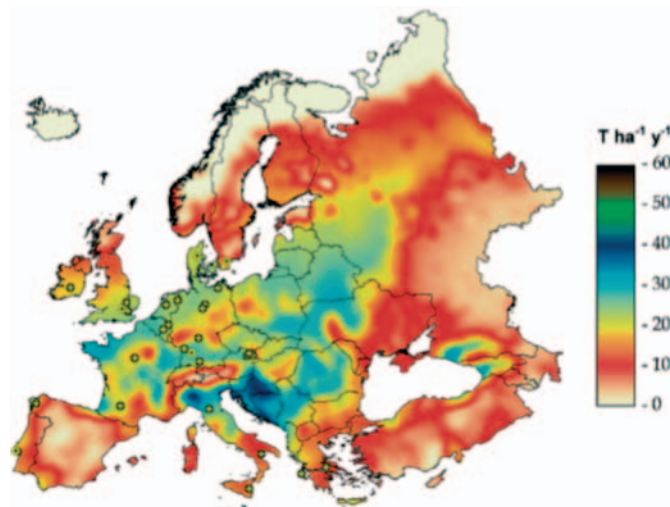
Figure 1. Dry matter yields of miscanthus per hectare in a rainfed system according to the model MISCANMOD (Clifton-Brown et al., 2004)

be calculated (Table 2). For covering different regions, three different yield levels (low, middle and high) were chosen.

Conclusion

The pretreatment of miscanthus with steam explosion can increase its SMY strongly. Compared to the untreated sample with $83 l_N$ kg VS^{-1}, the pretreatment at 210 °C for 10 minutes resulted in

Table 2. Dry matter and volatile solids content as well as specific biogas and methane production of untreated and steam explosion pretreated miscanthus

	DM [%FM]	VS [% DM]	Severity factor [Log(R0)]	Biogas [l_N kg VS^{-1}]	SD [l_N kg VS^{-1}]	Methane [l_N kg VS^{-1}]	SD [l_N kg VS^{-1}]
Untreated	88.4	97.9	-	130	15.7	84	10.4
190°C, 10 min	32.4	97.8	3.7	363	19.6	248	18.3
190°C, 15 min	36.0	97.7	3.8	448	29	279	18.1
190°C, 20 min	32.9	97.8	4	466	11.4	308	11.1
210°C, 10 min	28.0	97.4	4.2	541	11.8	345	9.2
210°C, 15 min	24.9	97.3	4.4	517	11.3	333	8.2
210°C, 20 min	24.0	97.6	4.5	511	4.4	331	4.6

SD: standard deviation

Table 3. SMY and MHY at three different yields levels of untreated and with steam explosionpretreated miscanthus

	Severity factor [Log(R0)]	Specific methane yield [l_N kg DM^{-1}]	Methane hectare yield [m^3 ha^{-1} y^{-1}]		
			Low	Middle	High
Untreated	-	82	1,151	1,727	2,303
190°C, 10 min	3.7	243	3,396	5,093	6,791
190°C, 15 min	3.8	273	3,816	5,724	7,632
190°C, 20 min	4	301	4,217	6,326	8,434
210°C, 10 min	4.2	336	4,704	7,057	9,409
210°C, 15 min	4.4	324	4,536	6,804	9,072
210°C, 20 min	4.5	323	4,523	6,784	9,046

MHY low = 14 t DM y^{-1}; MHY middle = 21 t DM y^{-1}; MHY high = 28 t DM y^{-1}

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Agric. conspec. sci. Vol. 79 (2014) No. 1

a yield of 345 l_N kg VS^{-1}. Consequently, also the MHY increases with a pretreatment of the biomass. Depending on the specific methane yields and on the dry matter yields of miscanthus, the MHY varies between 3,396 and 9,409 m³ ha^{-1} y^{-1}. This is in the same range as the MHY of maize. If there is a source of waste heat for the pretreatment of miscanthus (e.g. from a CHP), this would mean that it is possible to produce a similar amount of methane per hectare as with maize. Regarding that the cultivation of miscanthus requires less energy than that of maize, it could even result in a higher overall energy output.

List of abbreviations

CHP	Combined heat and power
DM	Dry matter
FM	Fresh matter
LN	Standard litre (dry gas at 273 K and 1013 mbar)
MHY	Methane hectare yield
SF	Severity factor
SMY	Specific methane yield
VS	Volatile solids

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