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Two-stage anaerobic digestion of sugar beet silage: The effect of the pH-value on process parameters and process efficiency

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ABSTRACT

The study investigated the influence of the target pH-values 4.5, 5, 5.5 and 6 in the acidification reactor on process parameters, such as substrate-specific methane yield and the intermediates, in the two-stage anaerobic digestion of sugar beet silage. The total specific methane yield ($Nl\ kg^{-1}\ COD\ d^{-1}$) increased with an increase in the pH (pH 4.5: 140.58 ± 70.08, pH 5: 181.21 ± 55.71, pH 5.5: 218.32 ± 51.01, pH 6: 256.47 ± 28.78). The pH-value also had an effect on the dominant intermediate in hydrolysate. At the pH-value of 4.5, almost no acidification and microbial activity was observed. At pH 5 and 5.5, butyric acid production dominated, guided by H_2 production. At pH 6 acetic acid was the main product. The absence of H_2 and the highest SMY makes it favorable under practical aspects.

1. Introduction

Due to the finite nature of fossil fuels and their negative environmental effects, the EU's Renewable energy directive sets to achieve the 20% final energy consumption from renewable sources by 2020 (European Environmental Agency, 2016). Anaerobic digestion makes an important contribution to the realization of this objective. However, the production of biogas from renewable raw materials in Europe is mostly based on corn silage, which can lead to one-sided crop rotation. For ecological reasons, economically equivalent substrates are wanted for biogas production.

The sugar beet is an economic alternative to maize in terms of the methane hectare yield (Starke and Hofmann, 2014). Other advantages are plant-growing aspects, such as the loosening of narrow maize fruit sequences, the high pre-crop value, the reduction of yield fluctuations and the good utilization of nutrients (Sekiguchi et al., 2001). The later harvesting time also helps to break work peaks.

Sugar beet silage (SBS) is very readily hydrolysable because of its low pH-value, high sugar content and low proportion of structurants. Therefore sugar beet can be quickly and almost completely converted into biogas (Sauthoff et al., 2016). Furthermore, sugar beets are an easier substrate to degrade compared to grass because of their lower fiber content: 17%, whereas for grass – 29% (Lehtomäki and Björnsson, 2006). Sugar beet can provide higher specific methane yield, comparable with maize (Lindner et al., 2016). On the basis of economic comparison, it was found that the profits from sugar beet cultivation for energy purposes could far exceed the gains from its traditional use as a substrate for sugar production (Przybył et al., 2011).

The research of the single stage biogas production from SBS, due to the high content of sucrose in sugar beet and high amount of pectin in its cell wall, problems arise with the process stability and process control due to the rapid and intensive acid formation as well as to intensive foam formation (Moeller et al., 2015). The known problem of foaming at a high loading rate is less frequent in two-stage systems with the anaerobic digestion of sugar beet pressed pulp (Stoyanova et al., 2014). The literature shows a clear advantage of the separation of hydrolysis and acidogenesis from methanogenesis for different substrates (Bouallagui, 2004; Dinopoulou et al., 1988; Guerrero et al., 1999; Kim et al., 2003). However, Parawira et al. (2008) reported that in the research of sugar beet pulp anaerobic digestion conducted by Weiland, there was no significant difference in the process efficiency between one- and two-stage systems and because of its simplicity, a one-stage system is preferred. Further conclusions from the comparison of both systems are presented by Hutnan et al. (2000). Investigations conducted on substrates other than SBS proved that, although the efficiency and the methane yield were slightly higher in the two-stage process through the better process control in a two-stage system (Demirel and Yenigun, 2004; Guerrero et al., 1999), the use of special high-performance methane reactors ensures rapid degradation with higher loading rate (Lettinga et al., 1999). For this reason, smaller reactor volumes are needed to convert the same amount of substrate. During a two-stage anaerobic digestion, gas with a methane content of up to 80% can be

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generated. This facilitates the purification of the gas to be fed into the natural gas network (Marin Perez and Weber, 2013).

Lindner et al. (2016) research proves that two-stage systems seem to be recommendable for the digestion of substrates with high sugar content. The degree of degradation of a lignocellulose rich substrate (hay/straw 22.5%) in a two-stage system is much lower than that of substrates with high sugar content, e.g. sugar beet (94.5%). The SBS has been evaluated as a relatively nutrient-poor substrate. External feeding of buffer substances and nutrients ensured a safe and stable process. The performance of the biogas digester can be improved by the application of the substrate with a high phosphate content (Demirel et al., 2008). The addition of potassium hydrogen carbonate was recommended to provide sufficient buffering capacity to maintain the stable pH-value (Demirel and Scherer, 2008). This is not suitable, however, for practical application. According to Lindner et al. (2016), the stable anaerobic digestion process of SBS can be achieved without using a buffer, but further research is still needed.

For efficient biogas production, it is also important to ensure adequate environmental and process conditions. The rate of methane production is about twice as fast if the temperature of the process is thermophilic for anaerobic digestion of whole sugar beet (Chavez et al., 2012) as well as for sugar beet pressed pulp (Stoyanova et al., 2014). According to Hutnan et al. (2000), the optimal pH-value in the first stage of the two-stage anaerobic digestion of dry sugar beet pulp is between 4 and 4.5, with pH being adjusted by $NaHCO_3$. However, there are many studies in which the pH-value is measured, but not adjusted by a buffer (Demirel et al., 2008; Parawira et al., 2008; Stoyanova et al., 2014).

In the literature, there is no specific data on the optimal pH in the acidification reactor during two-stage anaerobic digestion of SBS. Also, sugar beets are used in various forms and stored differently, which makes it difficult to directly compare the results. SBS is recommended due to its all-year availability.

The background of this study is the development of a two-stage AD process for biomethane production in praxis scale based on the substrate SBS because of its advantages mentioned above. Therefore, detailed knowledge of the influence of the most important parameters on the process is necessary. The experimental set up and the interpreted results takes into account practical aspects.

This paper demonstrates the results of the study on how the pH-value in the acidification reactor influences the performance and the efficiency of the two-stage anaerobic digestion of SBS, without using a buffer and with the pH-value in the acidification reactor being regulated by the exchange of liquid between the acidification reactor and anaerobic filters.

2. Methods

2.1. Laboratory two-stage plant

The research presented in this paper was carried out in the biogas laboratory of the State Institute of Agricultural Engineering and Bioenergy at the University of Hohenheim, Stuttgart. For this investigation, 2 two-stage laboratory installations, each consisting of one continuous horizontal acidification stirred tank reactor (AR) (working volume of 100 l) and two anaerobic filters (AFs) with a total working volume of 80 l, connected in series, were used. The exact description of these two-stage plants can be found in Lindner et al. (2015).

The produced gas was accumulated in gas bags (Tesseraux Spezialverpackungen GmbH Bürstadt, Germany) and analyzed, with the frequency depending on the gas production. The quality of the formed gas was measured by a gas analyzer (SICK MAIHACK S710, SICK Vertriebs-GmbH, Düsseldorf, Germany) and the quantity – by a drum gas meter (TG 20/5, Dr.-Ing. RITTER Apparatebau GmbH & Co. KG, Bochum, Germany) equipped with an electronic impulse device with a solution of 0.04 l/impulse. The gas volume was always corrected to standard conditions (1013 hPa, 273.15 K). The gas analyzer used was calibrated every month and cross checked with the micro-GC Inficon 3000 l-GC with two columns.

2.2. Substrate

Two sources of SBS were used for the experiments. The first one came from the agricultural research station "Heidfeldhof" located next to the University of Hohenheim, Stuttgart, in the south-west Germany. All sugar beets before ensiling in 60 l plastic barrels were cleaned manually and then shredded with a manual beet chopper.

The second silage used was from the agricultural research station Ihinger Hof (near Renningen, 50 km south west of Stuttgart). Directly after the harvest, the sugar beets were stored for about three months in a pile on a concrete floor at the Ihinger Hof. This time washing and shredding beets was performed with the help of a "Gazelle" type beet-washer from the Günter Schmihing GmbH Company (Melle, Germany). In order to describe the properties of the SBS, "Weender van Soest", dry matter/organic dry matter and chemical oxygen demand and pH analysis were conducted.

SBS from the 2014 harvest (Heidfeldhof) was used for experimental phases with the target pH of 5 and 5.5 and SBS from the 2015 harvest (Ihinger Hof) – for the phases with the target pH of 4.5 and 6. No high differences between used SBS were found in the COD-content ($266.75 \pm 5.3\ g\ l^{-1}$ and $277.38 \pm 7.95\ g\ l^{-1}$). Silages were comparable, relating to estimated theoretical biogas (755.28 Nl kg^{-1}oDM and 755.84 Nl kg^{-1}oDM) and methane yield (394.32 Nl kg^{-1}oDM and 395.41 Nl kg^{-1}oDM) according to Weißbach (2009). Comparing the most important factors, the COD and SMY, both silages are quite similar, so that the use of two silages should not have a high impact on the results of the pH comparison. The fact that two silages were used was taken into account in the statistical model for the evaluation of the experiments. Parameters of both SBS are presented in Table 1.

2.3. Experimental procedure

The experiments were conducted for four different target pH-values in the AR: 4.5, 5, 5.5 and 6. For each variant, the AR was restarted again to ensure similar starting conditions and to reduce the influence of the previous variant. For this purpose, the AR was filled with the mixture of 80 kg water, 20 kg separated liquid slurry from the "Unterer Lindenhof"

Table 1
The results of the "Weender van Soest" analyses, concentration of VFA, sugars and alcohols and the estimated theoretical biogas and methane yields in the SBS.

Parameter	Sugar beet 2014	Sugar beet 2015	Unit
DM	13.32 ± 1.79	16.4 ± 4.36	g
oDM	12.38 ± 0.75	10.59 ± 4.18	g
pH	3.52 ± 0.01	3.57 ± 0.11	–
COD solid	266.75 ± 5.30	277.38 ± 7.95	$g\ l^{-1}$
COD leachate	209.31 ± 6.80	220.51 ± 4.90	$g\ l^{-1}$
XA	0.69 ± 0.01	0.60 ± 0.06	% FM
XP	0.65 ± 0.14	1.45 ± 0.34	% FM
XL	< 0.60	< 0.60	% FM
XF	0.97 ± 0.17	1.22 ± 0.04	% FM
NDF	2.59 ± 0.43	3.50 ± 0.12	% FM
Acetic acid	14.00 ± 1.37	6.49 ± 0.45	$g\ kg^{-1}$ FM
Propionic acid	0.00	0.00	$g\ kg^{-1}$ FM
Lactic acid	10.32 ± 1.44	10.13 ± 1.58	$g\ kg^{-1}$ FM
Sucrose	0.00	0.00	$g\ kg^{-1}$ FM
Glucose	0.00	5.39 ± 3.65	$g\ kg^{-1}$ FM
Fructose	0.00	3.42 ± 0.69	$g\ kg^{-1}$ FM
Ethanol	53.51 ± 3.50	55.08 ± 7.46	$g\ kg^{-1}$ FM
Mannitol	19.01 ± 1.06	20.95 ± 8.95	$g\ kg^{-1}$ FM
Theoretical biogas yield*	755.28	755.84	Nl kg^{-1}oDM
Theoretical methane yield *	394.32	395.41	Nl kg^{-1}oDM

* Estimated according to Weißbach (2009).