Novel system for demand-oriented biogas production from sugar beet silage effluent in German practice scale biogas plants

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Abstract: In recent years, the concept of flexible electricity production from renewable energy sources has gained popularity in the field of renewable energy supply. This study investigated a new system for flexible biogas production in praxis scale biogas plants involving new sugar beet storage processes aiming on the use of produced sugar beet silage effluent. Both processes showed successful ensiling with moderate losses compared to conventional sugar beet storage processes. A clear advantage was found in the use of washed and chopped sugar beet for silage effluent production. Thanks to the high chemical oxygen demand-content and high digestibility, the produced silage effluent was applicable for point feeding. The system's response, observed as an increase in gas production, was noticed within a few minutes. The time required to obtain the maximum gas production rate was in the range of 1:42±0:47 h. The obtained average methane yield during point feeding was 0.38±0.08 m^3 kg^{-1} oDM. No volatile fatty acids accumulation or biological process disturbances of the full-scale biogas plant took place while point feeding.

Keywords: anaerobic digestion; biogas production; full-scale; demand-oriented; sugar beet silage effluent; point feeding

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1 Introduction

Over the last few years, there has been a trend in the world to increase the share of renewables in the total energy production (Hinrichs-Rahlwes, 2013). In this way, it is aimed at reducing the demand for fossil fuels and thus their greenhouse gas emission (European Environment Agency, 2017). Anaerobic digestion contributes greatly to this objective.

Germany is one of the leading countries in achieving this goal (Szarka et al., 2013). In 2017, Germany's share of biogas (incl. biomethane) in renewables-based electricity generation was 14.9%, the share of photovoltaics – 18.3% and share of wind energy – 48.9% (Federal Ministry for Economic Affairs and Energy, 2018). The electricity sector based on renewable resources in Germany is thus dominated by solar and wind power. However, the operation of wind and solar power plants is affected by the current weather conditions, and therefore they are characterized by strong fluctuations in time, which in turn

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cause variable electricity production.

Recently, flexible biomass-produced electricity has been gaining popularity in Germany's renewable energy supply policy (Laperrière et al., 2017). Biogas plants are a promising option for generating demand-driven energy in order to compensate for the differences between the electricity demand and supply caused by irregular sources (Barchmann et al., 2016).

Over 95% of the biogas in Germany is produced in single stage continuous stirred-tank reactor plants and used in combined heat and power plants (CHP) (Szarka et al., 2013). The flexible electricity production from biogas by a CHP unit can be achieved as a result of two main strategies: biogas storage and flexible biogas production, as well as a combination of both (Hahn et al., 2014).

The most common solution for obtaining flexible gas supplies is the storage of biogas, but its effectiveness is reduced by regulations that limit the on-site stored biogas quantity. Additional investment costs are also connected (Ahmed and Kazda, 2017; O'Shea et al., 2016).

The demand for additional gas storage volumes can be significantly reduced by flexible feeding in flexible biogas production (Barchmann et al., 2016). To obtain some peak-production periods, easy biodegradable substrates can be added to the system. On the other hand, variable feeding increases the problem of reactor response (Laperrière et al., 2017; Terboven et al., 2015). This also leads to variable biogas production rates, changes in volatile fatty acid (VFA) concentrations and the respective pH-value (Mauky et al., 2017). In the literature on flexibility, there are descriptions of experiments conducted at a lower constant organic loading rate (OLR) and only point overloads (Laperrière et al., 2017). Researchers have also checked the suitability of various substrates, such as maize and grass silage, cattle slurry or macroalgae (seaweed), with different degradation kinetics for flexible feeding (Mauky et al., 2015; O'Shea et al., 2016).

Sugar beet silage is often used as a substrate for flexible biogas production (Ahmed and Kazda, 2017; Mauky et al., 2015; Terboven et al., 2015). Sugar beet can compete with maize in respect of the methane hectare yield (Starke and Hofmann, 2014), specific methane yield (Lindner et al., 2016) and high degree of degradation (Krakat et al., 2010) due to its low proportion of structurants.

However, taking into account the production costs of the substrates and the impact of respective preparation and conservation procedures on the economics of a 500 kW biogas plant (Hartmann and Döhler, 2011), it must be stated that maize is economically a better choice. Therefore, the better-paid on-demand electricity production using sugar beet may be an interesting alternative.

The problem, however, is the storage of sugar beet. Various sugar beet storage methods for biogas production can be found in the literature (Dirks et al., 2017; Wagner et al., 2011; Weißbach et al., 2011). As a result of the anaerobic fermentation of the ensiling process of sugar beets, silage effluent is formed. According to Jones and Jones (1995), the amount of silage effluent produced during ensiling of wet crops, such as beet tops, can reach 500 L t^{-1} FM. Because of its high nutritive value, the silage effluent is practically as valuable as the sugar beet silage retained in the silo, and it should be collected for further use (Wagner et al., 2011; Weißbach et al., 2011). All existing sugar beet storage methods, however, do not take into account separate use of silage effluent.

The aim of this study is to examine the suitability of a new storage system for sugar beet with collection of the produced silage effluent for its use in flexible biogas production, and also to test the silage effluent in a praxis scale biogas plant for its suitability for gas peak production.

2 Material and methods

2.1 Ensiling experiments - flexible tanks

This research was carried out at the agricultural research station Ihinger Hof, near Renningen, 50 km south west of Stuttgart, Germany. The flexible tanks were placed on a plane concrete surface inclined by 2%.

For this research, three cylindrical shaped flexible tanks with a diameter of 5 m and height of 1 m (Baur Folien GmbH, Ettenstatt, Germany) made of polyvinyl chloridecoated polyester fabric were used (Figure 1). Mounted to the center of each tank's top surface was a 3 m length zipper for filling and emptying. The flexible tanks were oriented so that the outlet (plug valve) was located at the lowest point of the sidewall in order to facilitate the removal of silage effluent. A stainless steel sieve was installed inside the tank behind the plug valve to prevent clogging by sugar beet chips.

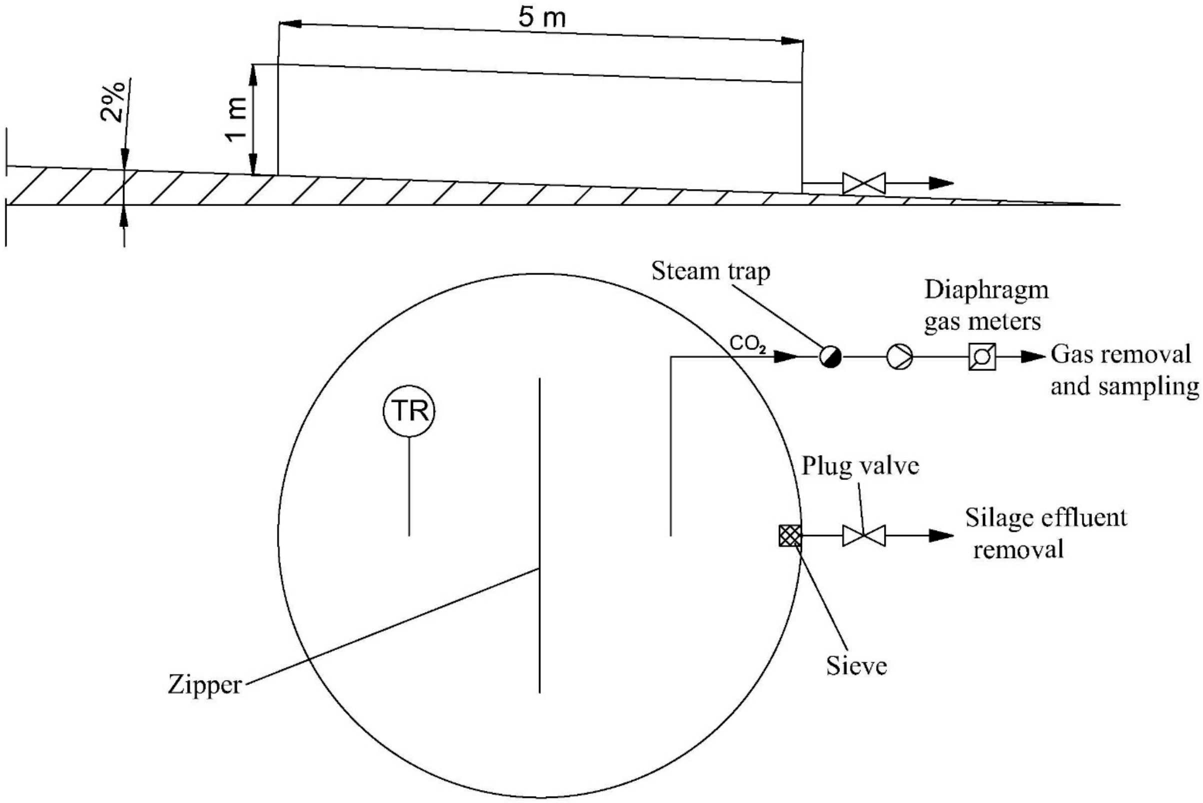


Figure 1 R&I-Scheme of the experimental flexible tanks

Gas volume and quality was recorded for each tank according to VDI 4630 standards (VDI - Society Energy and Environment, 2006). Gas volume was corrected to standard conditions. The temperature inside the flexible tanks was logged every 15 minutes.

The sugar beets from the agricultural research station Ihinger Hof were used. They were stored after the harvest for about three months in a fleece covered pile on a concrete floor at Ihinger Hof. The sugar beets were washed and shredded with the help of a “Gazelle” type beet-washer (Günter Schmihing GmbH, Melle, Germany). Each flexible tank was filled with over 12 tons of sugar beet chips taking into account the removed soil. After filling the tanks, they were sealed gas tight. The air was removed from their interior to achieve anaerobic conditions and compression.

The filling and removal of masses in the tanks, including silage, silage effluent and gas, were recorded. The experiment was conducted for 368 days. Thirty liters of the silage effluent was removed three times per week. This silage effluent collection strategy was chosen to demonstrate the possibility of a full year's silage effluent supply. The number of measurements was appropriately reduced as the silage effluent and the gas production decreased. Samples of the effluent and the produced gas were taken at each effluent removal and analyzed in the biogas laboratory of the State Institute of Agricultural Engineering and Bioenergy at the University of Hohenheim (Stuttgart) for volatile fatty acids, chemical oxygen demand, sugars and alcohols content. Sugar beets were collected for analysis while filling and emptying the flexible tanks. At the end of the experiments, the remaining effluent was removed from the tanks before the solid silage.

2.2 Ensiling experiment – The Hohenheim pit silo

This research was carried out at the agricultural research station Unterer Lindenhof in Eningen unter Achalm, 40 km south of Stuttgart.

The new silo system used for research (Figure 2) hit the following functions:

- Drive in silo for easy solid removal and multifunctional use (other substrates)
- Acid resistant surface, because of the silage effluent storage
- Collection of the silage effluent in the silo
- Removal of the silage effluent without opening the silo to maintain anaerobic conditions
- Gas tight cover to be able to:
  - evacuate the remaining air,
  - compress the material (sugar beets are not drivable),
  - pay attention to the reduced staple height while ensiling and
  - collect the produced gas for fully mass balance.

The silo system consists of three chambers, each 10 meters long and 3.5 meters wide. The concrete was acid resistant coated. The floor area drops at a 10% angle to the back towards the back wall. This set-up allows the resulting silage effluent to be collected and later to be pumped while the silo cover remains closed. The lowest point has an outlet for the silage effluent. A sieve was built out of a perforated sheet of stainless steel and installed behind the outlet to prevent clogging by the sugar beet. The silo system was covered by an airtight silo seal (Fritz Seeger OHG Siloverschlüsse, München, Germany).

The quantity of the effluent of each silo was separately measured by an electromagnetic-inductive flow sensor (SE56, Christian Bürkert GmbH & Co, Ingelfingen, Germany).

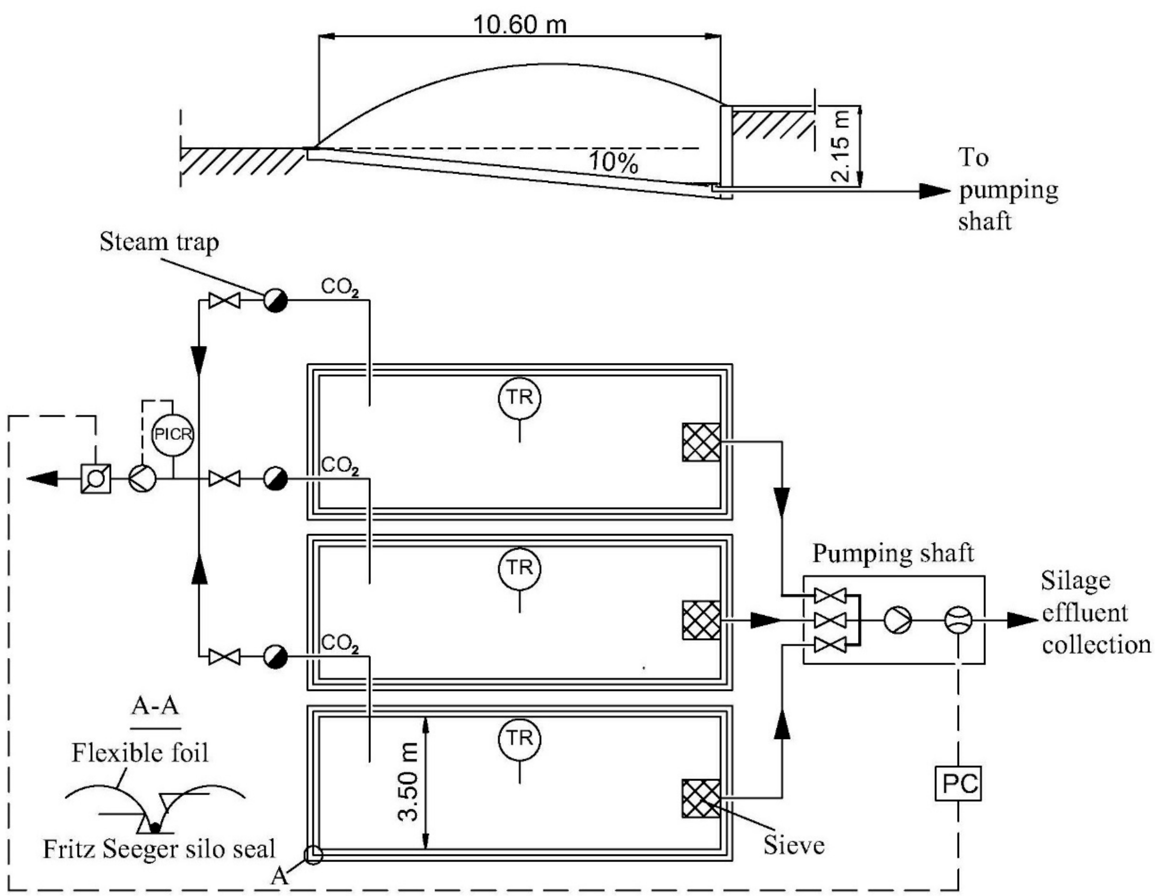


Figure 2 R&I-Scheme of the experimental Hohenheim pit silos

The volume of the produced gas was measured and calculated to norm volume according to VDI 4630 guidelines (VDI - Society Energy and Environment, 2006). The gas quality of the formed gas was measured by the gas analyzer Dräger (X-am 7000, Drägerwerk AG & Co. KGaA, Lübeck, Germany) equipped with an infrared sensor for CO_2 analysis and an electrochemical O_2 sensor. The temperature inside the silos was logged the same way as the flexible tanks.

For this experiment, sugar beets from the agricultural research station Ihinger Hof were used. The sugar beets were stored for technical reasons for about five months in a fleece covered pile at Ihinger Hof. Each Silo was filled with over 28 tons of unwashed, whole sugar beet to check the effect of chopped substrate on silage effluent production. After filling and sealing the silos, the air was removed from their interior, due to the fact that sugar beets are too soft to be compressed by driving on the material.

The experiment was conducted for 218 days. The gas collection was started two days after filling the silos, and the silage effluent was collected on experimental day 63 after the ensiling process took place. Thirty liters of the silage effluent was removed daily per silo. The measurements of the samples of silage effluent, sugar beets and gas were conducted in the same way as the ensiling experiments in flexible tanks.

2.3 Research biogas plant "Unterer Lindenhof"

The point feeding research was conducted at a full-scale research biogas plant at the agricultural experiment station "Unterer Lindenhof" of the University of Hohenheim. This research biogas plant is described in detail in the literature (Lemmer et al., 2013; Mönch-Tegeder et al., 2015; Nägele et al., 2014).

The daily substrate input of 8.8±2.0 t FM per day consisted of maize silage, grass silage, crushed grain, slurry from pig and cattle production and solid horse manure. The total amount of this mixture was properly divided into portions that were fed into the digester every two hours. The organic loading rate was 2.36±0.20 kg oDM m^{-3} d^{-1}, and only at the first and last point feeding repetition it was 3.45±0.71 kg oDM m^{-3} d^{-1} and 2.01±1.34 kg oDM m^{-3} d^{-1}, respectively. In this system, the online recording of the process parameters, such as temperature in the digester and gas quality, was conducted. The actual gas flow (gas flowmeter GD 300, Esters Elektronik GmbH, Rodgau, Germany) was also recorded every five minutes in the database. Each digester had an operating temperature of 40.5°C±1.0°C and contained liquid with an average pH-value of 7.8±0.19. The hydraulic retention time in the digester was about 70 days (post digester not included).

The experiment was repeated six times. Every few hours prior to point feeding, the digester agitators were switched to continuous operation to eliminate the influence of interval mixing on the gas production. Shortly prior to point feeding, the submersible motor mixer was set to the lowest position for effective mixing of the digester content and the colder silage effluent to achieve faster degradation of silage effluent and thus a faster peak in the gas production curve. The gas valves were adjusted so that the gas of the fermenter could flow freely through the gas meter into the empty gas storage of the post digester. The unused digester was connected directly to the CHP unit, so that the gas produced there did not affect the gas flow.

Approximately 2 tons of silage effluent was usually added to the digester as extra point feeding. The amount of silage effluent was pumped into the digester by the liquid substrate feeding system. At the end, the pipelines were flushed with 1000 kg of water to ensure that all the effluent was transferred from the pipeline into the digester.

The collected samples of the silage effluent and samples taken from the digester were analyzed for DM-content, organic dry matter (oDM), COD, pH, VFA, alcohols and sugars in the biogas laboratory of the Hohenheim University.

2.4 Laboratory analysis

Dry matter (DM)/organic dry matter (oDM)

The DM/oDM-content of sugar beet, sugar beet silage, silage effluent and of samples from the digester were determined by drying (predrying at 60°C for 48 h, final drying at 105°C for 3 h) and ashing (550°C, for 8 h). The content of the sugar beets, silage and silage effluent was analyzed before and after drying using gas chromatograph and high-pressure liquid chromatography for the correction of the DM-content. From the difference in the content of these components, the volatility coefficient was determined. These analyses were repeated for each used sugar beet, silage and silage effluent.

The DM/oDM-content in the samples taken from the digester was not corrected.

Chemical oxygen demand (COD)

The COD-concentration in the silage effluent was detected using the cuvette test from Hach Lange (Hach Lange Type LCK 014) with a high temperature thermostat (Hach Lange Type HT200 S) and a sensor array photometer (Hach Lange Type LASA 20).

Buffer capacity (FOS/TAC)

The determination of the buffer capacity (FOS/TAC) of samples from the digester was carried out according to VDLUFA standard methods (VDLUFA, 2007).

Intermediates

The content of **acetic, propionic, butyric, valeric** and **caproic acids** was determined with the gas chromatograph (GC, CP3800 type with the flame ionization detector, WCOT Fused Silica capillary column, Agilent Technologies Germany GmbH, Böblingen, Germany).

Lactic acid and ethanol were detected with high-pressure liquid chromatography (HPLC type with RI-detector, BioRadAminex HPX-87H HPLC column HPX-87H BioRad-precolumn, BISCHOFF Analysentechnik und –geräte GmbH, Leonberg, Germany). These analytical methods are described by Lindner et al. (2015).

The procedure for performing HPLC analysis of solids is described in Kumanowska et al. (2017).

The determination of sucrose, glucose, fructose and mannitol contents was carried out with the HPLC-Ca method (HPLC type with RI-detector and Hyperchrome HPLC Column Repro Gel Approx, BISCHOFF Analysentechnik und –geräte GmbH, Leonberg, Germany).

Solid samples

The methods that were used to determine the COD, sugar and mannitol concentrations in solids are described in Kumanowska et al. (2017), and the analysis procedure of the volatile fatty acids in solids is described in detail by Lindner et al. (2015).

Biomethane potential test (Hohenheimer Biogas Yield Test –HBT)

In order to determine the biogas and methane yield values, the silage effluent and produced sugar beet silage were tested with HBT. This is a high repetitive batch digestion test according to the VDI guideline 4630, and the performed method is described in detail in the literature (Helffrich and Oechsner, 2003; Mittweg et al., 2012; VDI - Society Energy and Environment, 2006).

2.5 Calculation

Conversion of the norm volume of produced **carbon dioxide to kg** was necessary to carry out the mass balance. Taking into account the molar volume of an ideal gas (22.414 L mol^{-1}) and knowing that the molar weight of CO_2 is 44.01 g mol^{-1}, the amount of produced carbon dioxide in kg was obtained.

Determination of the theoretical methane yield of silage effluent

The theoretical methane yield of the silage effluent was determined out of the COD content by the method described in VDI - Society Energy and Environment (2006).

The amount of biogas produced as a result of point feeding

To describe the dynamics of biogas production in the anaerobic digestion system, the first-order kinetics can be used if there was no inhibition in the system (Weinrich and Nelles, 2015). On the basis of the available data, a graph of gas flow in time was drawn up. The volume of produced biogas can be determined as the area under the curve, i.e. the sum of the area of all trapezoids that can be drawn beneath the curve. In order to separate the volume of gas produced as a result of the basic supply from the quantity of gas at the point supply, a baseline was determined for each case (Krümpel et al., 2016). Linear regression using the method of least squares has been fitted to the gas flow rate graph, starting from ten hours before point feeding. The baseline gas flow rate (B_i) has been described by:

$$B\ (t) = \alpha + \beta \cdot t \qquad (1)$$

B: baseline gas flow rate ($m^3\ h^{-1}$),

t: time (h); $t \in [-10, 0]$,

$t_0 = 0$, α: approximated intercept at t_0,

β: approximated rate of the respective gas flow.

In order to calculate the volume of gas formed only as a result of point feeding from the measured gas flow rate, the baseline was subtracted from the measured line.

$$\bar{Q}(t) = Q(t) - B(t) \quad (2)$$

$Q(t)$: measured gas flow rate ($m^3\ h^{-1}$),

$\bar{Q}(t)$: resulting gas flow rate from sugar beet silage effluent degradation.

Next, the total amount of gas produced from point feeding was calculated using the obtained function to determine the sum of the area of all trapezoids:

$$V(t) = \sum_{i=0}^{n} (t_{i+1} - t_i) \cdot \frac{(\bar{Q}_{i+1} + \bar{Q}_i)}{2} \quad (3)$$

$V(t)$: cumulative gas volume obtained from point feeding (m^3).

When calculating the sum of trapezoids, the first visible peak was omitted due to the assumption that this peak appeared because of the injected liquid volume and the displacement of dissolved carbon dioxide from the liquid caused by the sudden decrease in the pH-value in the digester (Chen et al., 2014; Krümpel et al., 2016; Mauky et al., 2017).

3 Results and discussion

3.1 Ensiling experiments in flexible tanks

During the storage experiment, the temperatures inside the flexible tanks were measured and then compared with ambient temperature. The temperatures recorded in the flexible tanks were, on average, 4°C higher (13.72°C±6.62°C) than ambient temperature (9.43°C±8.00°C), and fluctuations were lower than ambient temperature.

3.1.1 Mass balances in the ensiling process

After the end of the sugar beet storage process, mass balances of the process were carried out. The results are shown in Table 1. For possible direct comparison, the quantity of the ensiling products was set into relation to one kilogram of fresh mass.

The mass balance of the process showed that the final mass constituted 99.56%±5.62% of the initial mass. During the ensiling process in the flexible tanks, the average losses in organic dry matter were in the range of 15.28%±1.91%.

The average amount of produced silage effluent obtained in this experiment was 32.00%±2.00% of the sugar beet weight. The average production of carbon dioxide was only 0.003 kg per kilogram of sugar beet before ensiling. The obtained silage constituted 67.00%±4.00% of the total sugar beet weight.

Table 1 Results of the mass balances of the ensiling processes

	Flexible tanks	Hohenheim pit silos
mass balance		
Sugar beet (kg)	12101.25±458.60	28326.67±567.66
Silage (kg)	8088.37±162.38	23459.11±359.56
Silage effluent (kg)	3899.57±94.74	2131.41±132.71
CO_2 (kg)	42.34±24.84	892.84±190.27
organic dry matter balance		
Sugar beet (kg oDM)	3021.21±114.49	7139.37±143.07
Silage (kg oDM)	1823.95±82.28	4884.03±287.17
Silage effluent (kg oDM)	735.22±17.62	314.29±21.71
specific mass balance		
Silage (kg kg^{-1} FM)	0.67±0.04	0.83±0.01
Silage effluent (kg kg^{-1} FM)	0.32±0.02	0.08±0.00
CO_2 (kg kg^{-1} FM)	0.003±0.00	0.03±0.01

3.1.2 Composition of sugar beets before the ensiling process, sugar beet silage and silage effluent

In order to describe the properties of sugar beets prior to ensiling, obtained sugar beet silage and silage effluent, analyzes of DM / oDM-content, the COD, and the concentration of VFA, sugars, alcohols and pH analysis were carried out. In order to determine the specific methane yield (SMY) of fresh sugar beet and the obtained sugar beet silage, biomethane potential tests (HBT) were also carried out. The results are shown in Table 2.

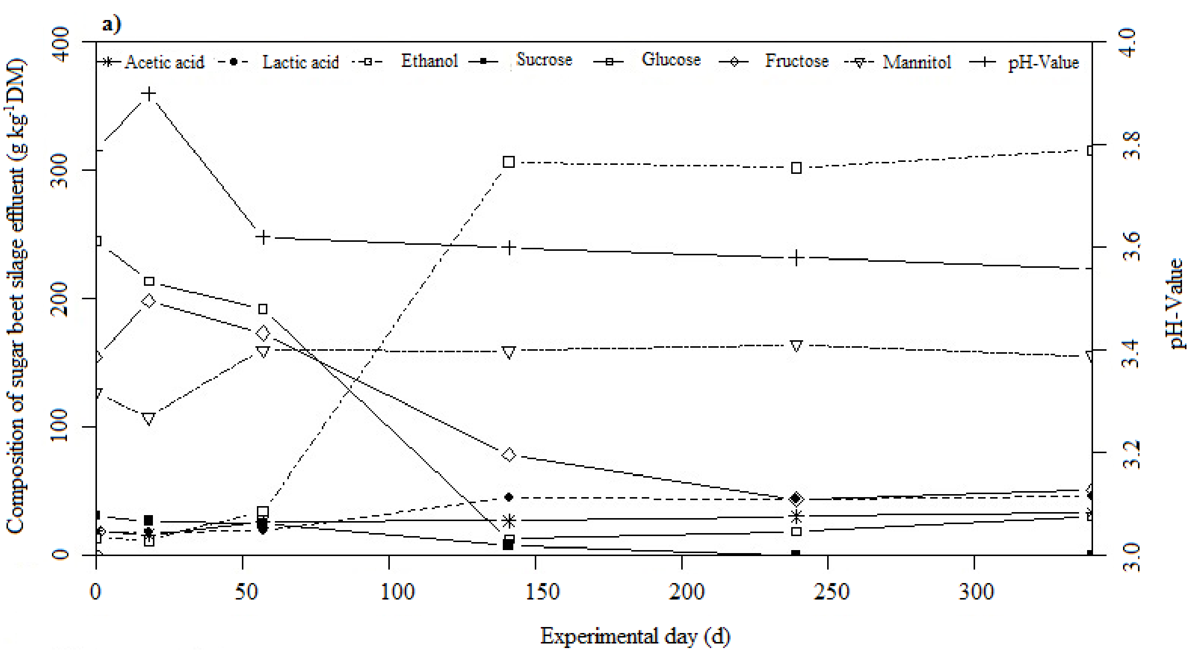
As a result of the ensiling process, the concentration of acetic, lactic acids and alcohols in the silage and in the silage effluent increased. The sucrose during this process was almost completely decomposed. The content of glucose and fructose in the silage decreased in comparison with fresh sugar beet.

Table 2 The DM/oDM-content, the COD, the concentrations of fermentation products and the specific methane yields in the sugar beets, the sugar beet silage and the sugar beet silage effluent from the flexible tanks

	Sugar beet before ensiling	Obtained silage	Silage effluent
DM (% FM)	25.46±0.41	23.98±1.45	20.26±0.57
oDM (% DM)	98.06±0.24	94.12±0.24	96.72±0.00
pH-value	4.01±0.10	3.72±0.16	3.66±0.11
COD (g L^{-1})	251.00±24.04	309.17±32.11	270.40±28.13
Acetic acid (g kg^{-1} DM)	12.07±0.06	21.97±12.26	25.04±6.94
Propionic acid (g kg^{-1} DM)	1.00±0.06	0.00	0.00
n-Butyric acid (g kg^{-1} DM)	4.96±0.01	0.00	0.00
n-Valeric acid (g kg^{-1} DM)	0.29±0.06	0.04±0.03	0.00
Lactic acid (g kg^{-1} DM)	9.82±1.11	25.86±10.77	31.48±14.70
Sucrose (g kg^{-1} DM)	55.36±0.41	0.00	14.57±13.62
Glucose (g kg^{-1} DM)	28.38±0.21	9.04±5.21	114.28±105.70
Fructose (g kg^{-1} DM)	17.42±0.04	11.00±2.88	111.69±67.01
Ethanol (g kg^{-1} DM)	51.45±3.33	280.90±85.18	163.95±152.27
1,2-Propanediol (g kg^{-1} DM)	0.00	0.00	0.00
Mannitol (g kg^{-1} DM)	15.54±0.26	44.72±17.35	147.88±23.33
SMY (N m^3 kg^{-1} oDM)	0.26±0.08	0.33±0.04	0.35±0.01

Sugar beet silage effluent was characterized by an extremely high and stable COD-value of 270.40±28.13 g L^{-1}. A higher specific methane yield in the silage and silage effluent referred to oDM substrate were recorded in comparison with fresh sugar beet. The pH-value of the sugar beet silage effluent was about 3.9 at first, and decreased with storage time to 3.55. Changes in the pH-value of the silage effluent were accompanied by changes in its composition. Figure 3a shows the changes of the pH-values and contents of acids, sugars and alcohols in the silage effluent from the flexible tanks.

At the beginning of the storage experiments in the flexible tanks, the generated effluent contained the most glucose, fructose and mannitol. During the course of the research, the content of sugars, due to its conversion into ethanol, mannitol, lactic acid and acetic acid, sharply dropped. Mannitol production ended after about 57 experimental days. Production of ethanol lasted more than twice as long. In this case, the content of ethanol was almost twice as large as the content of mannitol. During the ensiling process, the concentration of lactic acid and acetic acid in the silage effluent did not exceed 35 g kg^{-1} DM.



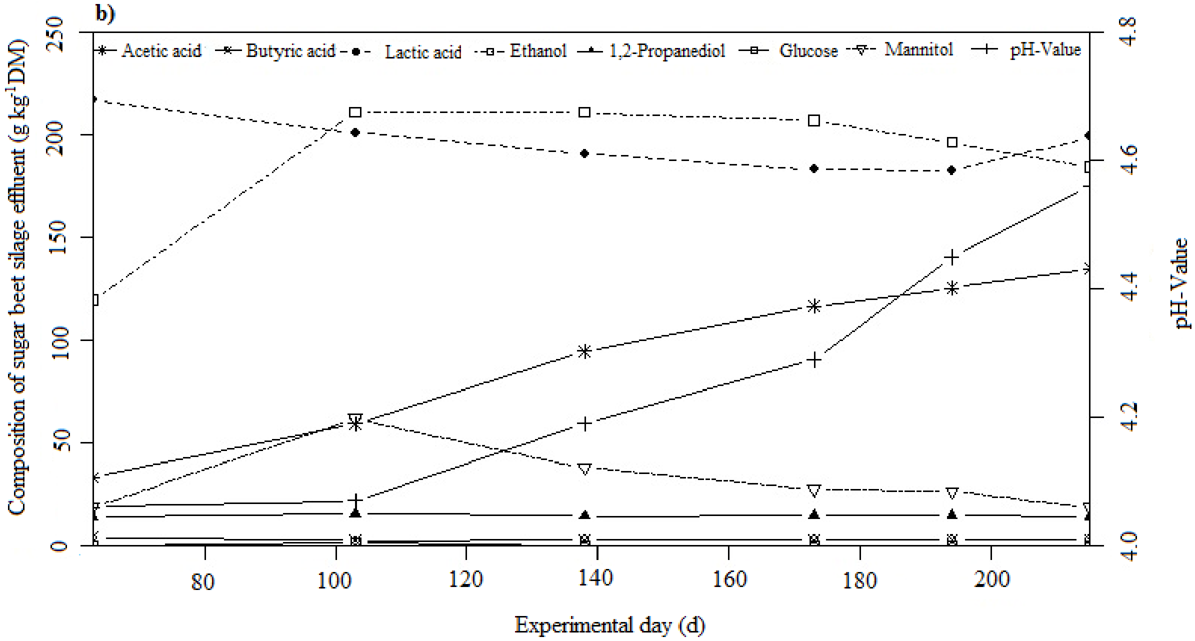


Figure 3 Changes in the composition and pH-value of the sugar beet silage effluent during storage in the flexible tanks (a) and in the Hohenheim pit silos (b)

3.2 Ensiling experiments in the Hohenheim pit silos

The temperatures recorded in the Hohenheim pit silos were generally an average of 2.25°C (18.41°C±3.31°C) higher than ambient temperature (15.43°C±6.59°C).

3.2.1 Mass balances in the ensiling process

The results for the mass and organic dry matter balance are shown above in Table 1.

The mass balance of the ensiling process in the Hohenheim pit silos showed an average difference between the input and output masses of 6.50%±0.42%. During the ensiling process, oDM-losses in the range of 27.17%±4.27% were noted. The obtained silage, produced silage effluent and CO_2 constituted, respectively, 0.83±0.01 kg, 0.08±0.00 kg and 0.03±0.01 kg per kilogram of input mass.

3.2.2 Composition of sugar beets before the ensiling process, sugar beet silage and silage effluent

In Table 3, the properties of sugar beet prior to ensiling, obtained sugar beet silage and silage effluent are shown. The average silage effluent COD-value of about 241.13±30.33 g L^{-1} was noted. The average pH-value of the silage effluent was 4.24±0.21. The pH-value of the silage effluent increased with storage time to almost 4.6.

Figure 3b shows the changes of the pH-values and concentration in the silage effluent from the new silo type. A trace amount of glucose was found in the silage effluent. During the process, the increase in acetic acid content was noted. High concentrations of lactic acid and ethanol were found.

Table 3 The DM/oDM-content, the COD, the concentrations of fermentation products and the specific methane yields in the sugar beets, the sugar beet silage and the sugar beet silage effluent from the Hohenheim pit silos

	Sugar beet before ensiling	Obtained silage	Silage effluent
DM (% FM)	25.65±0.09	25.34±0.88	18.54±1.00
oDM (% DM)	98.26±0.09	82.20±5.05	83.87±0.00
pH-value	4.22±0.12	3.68±0.13	4.24±0.21
COD (g L^{-1})	349.00±1.41	236.58±29.65	241.13±30.33
Acetic acid (g kg^{-1} DM)	0.00	41.98±10.26	94.03±40.19
Propionic acid (g kg^{-1} DM)	0.00	0.50±0.44	0.46±0.30
n-Butyric acid (g kg^{-1} DM)	0.00	0.42±0.14	2.96±0.54
n-Valeric acid (g kg^{-1} DM)	0.00	0.00	0.00
Lactic acid (g kg^{-1} DM)	0.00	77.87±12.61	195.67±13.04
Sucrose (g kg^{-1} DM)	604.05±61.75	1.84±1.65	0.00
Glucose (g kg^{-1} DM)	20.62±2.63	46.68±16.65	0.26±0.65
Fructose (g kg^{-1} DM)	6.44±0.47	13.37±3.42	0.00
Ethanol (g kg^{-1} DM)	0.00	143.78±19.23	188.32±35.27
1,2-Propanediol (g kg^{-1} DM)	0.00	16.77±8.65	14.47±0.54
Mannitol (g kg^{-1} DM)	0.00	105.51±21.77	31.83±16.40
SMY (N m^3 kg^{-1} oDM)	0.38±0.02	0.39±0.06	0.37±0.01

3.3 Discussion and comparison of the tested ensiling processes

After comparing the mass balances of both experiments, representing the two extreme cases unwashed whole beets and washed and chopped beets, it can be stated that during the process of ensiling in the flexible tanks, a larger share of the silage effluent was obtained. This is consistent with the data found in the literature (Wagner et al., 2011; Weißbach et al., 2011), according to which, chopped sugar beets release almost three times more silage effluent than whole beets. The amount of silage effluent produced in the flexible tanks (32.00%±3.00% of the fresh weight) was consistent with the literature (Jones and Jones, 1995).

In the case of the flexible tanks, the average losses in oDM during the ensiling process were 43.12%±9.10% lower than the average oDM-losses incurred during the ensiling process in the Hohenheim pit silos.

A higher content of acetic acid and alcohols in the silage from the flexible tanks (Table 2) could translate higher specific methane yields (Table 1) referred to oDM substrate (Herrmann et al., 2011) and an increase of 20% in COD-content. The specific methane yields of the obtained sugar beet silage from the Hohenheim pit silo were comparable with the specific methane yield of the fresh sugar beet. Kreuger et al. (2011) have supported this in stating that the ensiling process does not increase the methane yield of any tested crop materials

Compositional differences between the obtained silage and the silage effluent could have resulted from their different experimental conditions. According to Buxton et al. (2003), the range of temperature fluctuations in the silo and the pH-value affected the bacteria that became dominant during the fermentation of the silage. A higher inside temperature was recorded in the case of the Hohenheim pit silo, which could have resulted from covering the silos with gas tight black foil. It should also be taken into account that the research was conducted in different years, took place in two research stations with different weather conditions and used sugar beets from different harvests.

The influence of temperature and pH was also confirmed by the presence of 1,2-propanediol in the silage and silage effluent obtained from the Hohenheim pit silos, which was not found in the process using the flexible tanks. According to Elferink et al. (2001), 1,2-propanediol forms during anaerobic degradation of lactic acid by lactic acid bacteria (Lactobacillus buchneri), which caused the increase of oDM-losses incurred during ensiling due to the formation of CO_2.

In contrast to storage in the flexible tanks, the pH-value of the silage effluent increased during storage in the silos. This could only be explained by the negative impact of resign from cleaning the substrate before ensiling.

The obtained results confirm the assumption (Buxton et al., 2003; Herrmann et al., 2012) that reducing the size of the substrate improved the fermentation conditions by the additional release of easily fermentable substrates, leading to more extensive lactic acid formation, faster acidification and more effective inhibition of the development of undesirable microorganisms and ultimately to smaller losses of fermentation.

The technical aspects of the process in the Hohenheim pit silo was definitely less complicated, more mechanized and did not require much manual support. Filling and emptying the flexible tanks, however, did present problems, but this could possibly be solved by replacing sugar beet chips with sugar beet pulp. Regarding fermentation aspects of the ensiling of sugar beet chips in the flexible tanks, produced silage had a better quality and more silage effluent was obtained. The best solution would be a combination of technological and biological advantages, i.e. storage of sugar beet chips in the Hohenheim pit silo.

3.4 The volume of gas produced as a result of point feeding

The results show the effect of point feeding on the rate of gas production, and thus also the flexibility of the process itself. The reactions of the process, in the form of a peak in gas production, within a few minutes after point feeding were recorded (Figure). In this repetition, the agitator in the digester was switched to continuous work about 15 hours before point feeding. This was reflected in a noticeable reduction in the fluctuations in gas production. The biogas production curve declined before point feeding, reflecting the normal time of day fluctuations. The start of dosing the silage effluent to the digester was marked as point 0. Shortly after this, the peak relevant to the increase in gas production appeared. Subsequently, a steady decrease in the gas production rate was noted.

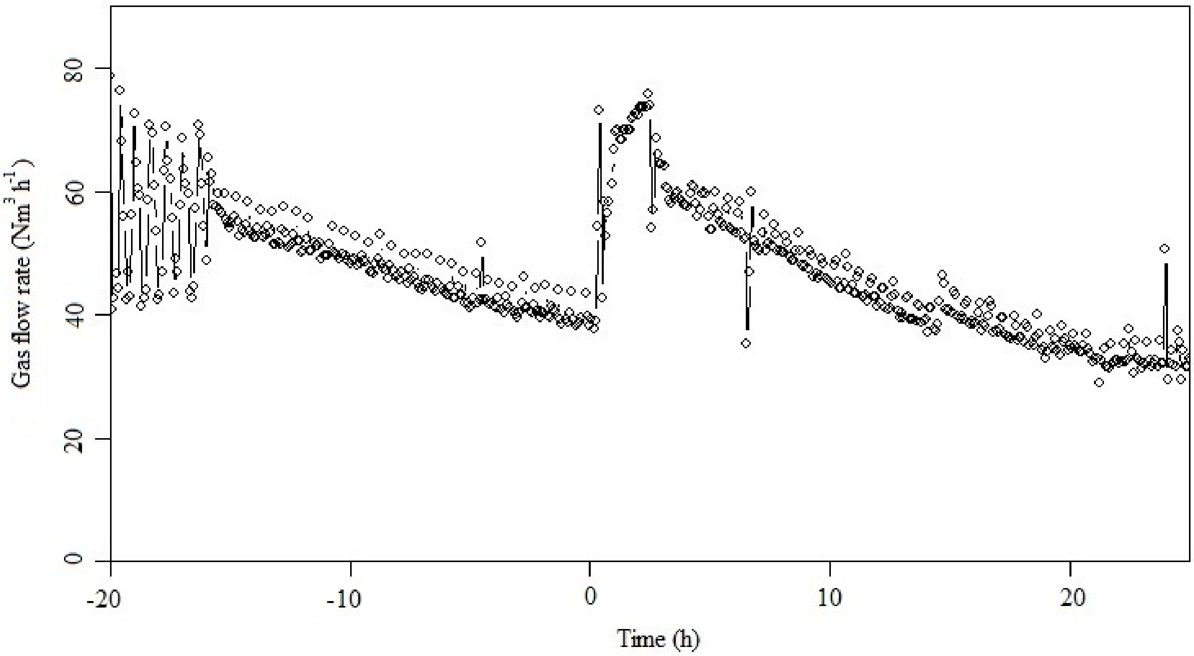


Figure 4 Example of gas flow rate in the biogas plant while point feeding (Time 0 – point feeding of 1860 kg of sugar beet silage effluent; repetition 4)

The cumulative gas production from point feeding with sugar beet silage effluent was determined using the method described in chapter 2.5.

Table 4 Characteristics of the point feeding, obtained gas and methane production (average value of six repetitions)

The amount of silage effluent added	kg	1930.83±68.73
Feeding COD-value	kg COD	483.16±74.03
Feeding oDM-value	kg oDM	380.80±13.56
Theoretical gas volume	Nm^3	328.41±68.48
Obtained gas volume	Nm^3	260.12±101.47
Obtained gas volume per kg silage effluent added	Nm^3 kg^{-1} FM	0.15±0.03
Obtained biogas yield	Nm^3 kg^{-1} oDM	0.75±0.18
Obtained methane yield	Nm^3 kg^{-1} oDM	0.38±0.08
Ratio of the obtained gas to the theoretical volume	%	86.92±10.10
Gas peak duration	h	24:34±4:42
Time needed to obtain maximum gas	h	1:42±0:47
Time to 15% of cumulated gas production	h	2:50±2:07
Time to 25% of cumulated gas production	h	3:40±2:18
Time to 50% of cumulated gas production	h	7:00± 2:51

In these studies, 1930.83±68.73 kg of sugar beet effluent was added to the biogas plant, and an average of 260.12±101.47 N m^3 of gas was obtained (Table 4). The average obtained methane yield was 0.38±0.08 N m^3 kg^{-1} oDM. The obtained gas constituted 86.92%±10.10% of the theoretical amount of gas produced for each COD-feeding. The maximum gas production rate was reached after 1:42±0:47 h. Within the first 10 hours after point feeding, 50% of cumulated produced gas was obtained.

After the point of feeding, a slight increase in the CO_2 concentration in the gas produced was observed, but ultimately, however, no significant changes in gas composition was observed. During this research, for all repetitions made, the average value of the ratio of CH_4 to CO_2 was 1.13±0.05.

3.5 Process dynamics and stability after point feeding

After point feeding, a drop in the pH-value in the effluent was observed. About 2.0 hours after feeding, the pH-value increased again and then fluctuated around a lower value as before feeding. Overall, however, the pH-value remained in a stable range. In the first hours after the point feeding, the increase in concentration of VFA, especially of acetic and propionic acid in the effluent, was noted. By comparing the experimental data from repetition 4 with the average values from the previous two months of biogas plant operation, it can be stated that the acetic acid concentration change was within the fluctuation during normal plant work (0.23±0.07 g kg^{-1}). The average pH-value within two months of normal installation operation was 7.86±0.11.

The ratio of propionic acid to acetic acid changed correspondingly with the change in VFA concentration in the effluent, but at all times did not exceed the value 0.29.

The average value of the buffer capacity (FOS/TAC) after point feeding (repetition 4) was 0.2±0.01.

By comparing the experimental data from repetition 4 with the average values from the previous two months of biogas plant operation, it can be stated that the average buffer capacity within two months of normal plant operation was 0.23±0.02.

In all replications carried out, an increase in FOS/TAC values with a decrease in the pH-value in the digester was noted within one hour after point feeding. The highest recorded value of this ratio in all repetitions was 0.30, and the lowest was 0.19. Finally, the FOS/TAC value usually reached a value similar to the initial value before point feeding. In two replications, an increase of approximately 0.05 was recorded in relation to the initial value.

3.6 Discussion of point feeding results

It was found that the average obtained methane yield (0.38±0.08 N m^3 kg^{-1} oDM) was 10.5% lower than the average theoretical methane yield (0.42±0.06 N m^3 kg^{-1} oDM), but was comparable to the methane yields of sugar beet silage and sugar beet silage effluent obtained from storage experiments, and was similar to the methane yield of other substrates, such as maize silage with DM-content of about 20% (0.35±0.03 N m^3 kg^{-1} oDM) (Oechsner et al., 2003). According to Mauky et al. (2017), the full-scale installation responded more slowly to changes in process conditions, so the response to feeding lasted longer. In contrast to this statement, after point feeding with sugar beet silage effluent, the system's response was observed within a few minutes.

Times needed to get 15%, 25% and 50% of cumulated total gas production from point feeding with sugar beet silage effluent (2:50±2:07 h, 3:40±2:18 h and 7:00±2:51 h, respectively) were shorter than the literature data for the full-scale for sugar beet silage (4.5 h, 8 h and 20.5 h, respectively), and more closely related to the time obtained for this silage in the laboratory scale (2 h, 4 h and 13.5 h, respectively) (Mauky et al., 2017). It has been proven that within 30 hours, the whole amount of biogas will be produced from point feeding. A temporary increase in CO_2 content in the gas was caused by the hydrolysis process of the silage effluent (Mauky et al., 2017). The progress of the hydrolysis process was also confirmed by a decrease in the pH-value. The release of gaseous carbon dioxide occurred as a result of the degradation of carbonic acid. This caused the increase of biogas production (Terboven et al., 2015).

After point feeding, no significant changes in the composition of the produced biogas were noted, because the produced gas is mixed with the huge volume of the digester's gas space (Mauky et al., 2015). This was advantageous, because CHP units are set to some specific methane concentration in biogas and if the methane concentration deviates from this value, biogas will not be efficiently burned, and the exhaust gas values and energy will be reduced.

According to the literature, an acetic acid concentration above 2500 mg L^{-1} can destabilize process biology (Mauky et al., 2017). The obtained average acetic acid concentrations in this study were much lower. The ratio of propionic acid to acetic acid in an anaerobic digestion system was a better indicator for disturbances caused by organic overload than changes in the composition of gas (ratio of methane to carbon dioxide) (Marchaim and Krause, 1993). Values of this ratio greater than 1.4 were critical for the anaerobic digestion system (Hill et al., 1987). In this study, the value of this ratio was only a half of the critical value.

According to Mauky et al. (2017), FOS/TAC values above 0.4 were limit values for a stable process operation. The FOS/TAC range obtained in the study was compatible with the literature values (Mauky et al., 2017).

Methane production, pH or the ratio of propionic acid to acetic acid cannot be used as a single reliable parameter indicating process imbalances in biogas plants (Nielsen et al., 2007). For this reason, the parameters commonly used to assess the stability of the biogas plant operation are summarized in this paper. However, no limit values were found in any case. Consequently, this study confirmed the claim that the anaerobic system can work stably even in conditions of high short-term organic load (Mauky et al., 2017; Mauky et al., 2016).

The results of the presented study confirmed the effectiveness of using sugar beet silage effluent for demand-driven biogas production. The presented point feeding did not affect the stability of the process. Differences in repetitions can be explained by the quite strong, but normal, fluctuations in gas production of praxis biogas plants, due to variation of raw materials (Nägele et al., 2012) and to daily temperature variation (Alvarez and Lidén, 2008). However, further research is necessary to check the maximum amount of silage effluent that can still be used for point feeding without achieving the critical process parameters. During this research nearly doubling of the gas flow rate was achieved.

4 Conclusion

The paper presented a new concept for the method of sugar beet storage, involving the collection of silage effluent produced during the ensiling process combined with its later use for demand-driven biogas production in a full-scale plant. The storage of the washed sugar beet chips in the Hohenheim pit silos is recommended, because silage effluent is produced in greater quantities, silage quality is improved and a fully automated process is possible.

Sugar beet silage effluent was added to a full-scale biogas plant for demand-oriented biogas production. There was an increase in gas production in a short time after point feeding, without endangering anaerobic system stability. The time required to achieve the maximum gas production rate was in the range of 1:42±0:47 h. Sugar beet silage effluent is applicable for point feeding, but future research should explore this process for a longer period of use. It is also interesting to what extent the energy demand can be covered by point feeding without the need for additional gas storage. Also, the kinetics of gas formation as a result of point feeding should be researched in more detail in order to obtain a faster and narrower peak, in other words, shorten the time needed to produce all gas, thanks to which additional gas storage would not be needed. For better control of the gas production, the combination of point feeding with other gas production influencing factors, such as mixing, should also be tested. Future research should seek to achieve more controlled gas production, which means on the one hand increasing gas production within a short time, but also on the other hand quick deceleration.

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References

Ahmed, S., and M. Kazda. 2017. Characteristics of on-demand biogas production by using sugar beet silage. *Anaerobe*, 46: 114–121.

Alvarez, R., and G. Lidén. 2008. The effect of temperature variation on biomethanation at high altitude. *Bioresource Technology*, 99(15): 7278–7284.

Barchmann, T., E. Mauky, M. Dotzauer, M. Stur, S. Weinrich, H. F. Jacobi, J. Liebetrau, and M. Nelles. 2016. Expanding the flexibility of biogas plants – substrate management, schedule synthesis and economic assessment. *Landtechnik*, 71(6): 233–251.

Buxton, D. R., R. E. Muck, and J. H. Harrison. 2003. *Silage Science and Technology*. Agronomy Monograph no. 42, Madison, Wisconsin: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.

Chen, Y., B. Rößler, S. Zielonka, A. Lemmer, A. M. Wonneberger, and T. Jungbluth. 2014. The pressure effects on two-phase anaerobic digestion. *Applied Energy*, 116: 409–415.

Dirks, S., D. Schaiper,W. Büscher, and P. S. Lammers. 2017. Conservation of sugar beet for substrate supply of biogas plants – procedure of ensiling and losses in 12 varieties. *Landtechnik*, 72(2): 61–75.

Elferink, S. J. W. H. O., J. Krooneman, J. C. Gottschal, S. F. Spoelstra, F. Faber, and F. Driehuis. 2001. Anaerobic conversion of lactic acid to acetic acid and 1,2-propanediol by Lactobacillus buchneri. *Applied Environmental Microbiology*, 67(1): 125–132.

European Environment Agency. 2017. Renewable energy in Europe - 2017 Update: Recent growth and knock-on effects. Available at: https://www.ipu.msu.eduwp-content/uploads/2018/o1/EEA-Renewable-Energy-in-Europe-2017.pdf. Accesssed 9 February 2018. 1

Federal Ministry for Economic Affairs and Energy. 2018. Development of Renewable Energy Sources in Germany 2017 Charts and figures based on statistical data from the Working Group on Renewable Energy-Statistics (AGEE-Stat), as at December 2017. Available at: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/development-of-renewable-energy-sources-in-germany-2017.pdf. Accessed 25 May 2018.

Hahn, H., B. Krautkremer, K. Hartmann, and M. Wachendorf. 2014. Review of concepts for a demand-driven biogas supply for flexible power generation. *Renewable Sustainable Energy Reviews*, 29: 383–393.

Hartmann, S., and H. Döhler. 2011. The economics of sugar beets in biogas production. *Landtechnik*, 66(4): 250–253.

Helffrich, D., and H. Oechsner. 2003. The Hohenheim biogas yield test comparison of different laboratory techniques for the digestion of biomass. *Landtechnik*, 58(3): 148–149.

Herrmann, C., M. Heiermann, and C. Idler. 2011. Effects of ensiling, silage additives and storage period on methane formation of biogas crops. *Bioresource Technol*ogy, 102(8): 5153–5161.

Herrmann, C., M. Heiermann, C. Idler, and A. Prochnow. 2012. Particle size reduction during harvesting of crop feedstock for biogas production i: effects on ensiling process and methane yields. *BioEnergy Research*, 5(4): 926–936.

Hill, D. T., S. A. Cobb, and J. P. Bolte. 1987. Using volatile fatty acid relationships to predict anaerobic digester failure. *Transactions of the ASAE*, 30(2): 496–501.

Hinrichs-Rahlwes, R. 2013. Renewable energy : Paving the way towards sustainable energy security: Lessons learnt from Germany. *Renewable Energy*, 49: 10–14.

Jones, D. I. H., and R. Jones. 1995. The effect of crop characteristics and ensiling methodology on grass silage effluent production. *Journal of Agricultural Engngineering Research*, 60(2): 73–81.

Krakat, N., S. Schmidt, and P. Scherer. 2010. Mesophilic fermentation of renewable biomass: does hydraulic retention time regulate methanogen diversity? *Applied Environmental Microbiology*, 76(18): 6322–6326.

Kreuger, E., I. A. Nges, and L. Björnsson. 2011. Ensiling of crops for biogas production: effects on methane yield and total solids determination. *Biotechnology for Biofuels*, 4, 44: 1–8.

Krümpel, J., F. Schäufele, J. Schneider, T. Jungbluth, S. Zielonka, and A. Lemmer. 2016. Kinetics of biogas production in anaerobic filters. *Bioresource Technology*, 200: 230–234.

Kumanowska, E., M. U. Saldaña, S. Zielonka, and H. Oechsner. 2017. Two-stage anaerobic digestion of sugar beet silage : The effect of the pH-value on process parameters and process efficiency. *Bioresource Technology*, 245: 876–883.

Laperrière, W., B. Barry, M. Torrijos, B. Pechiné, N. Bernet, and J. P. Steyer. 2017. Optimal conditions for flexible methane production in a demand-based operation of biogas plants. *Bioresource Technology*, 245: 698–705.

Lemmer, A., H. J. Nägele, and J. Sondermann. 2013. How efficient are agitators in biogas digesters? Determination of the efficiency of submersible motor mixers and incline agitators by measuring nutrient distribution in full-scale agricultural biogas digesters. *Energies*, 6(12): 6255–6273.

Lindner, J., S. Zielonka, H. Oechsner, and A. Lemmer. 2016. Is the continuous two-stage anaerobic digestion process well suited for all substrates? *Bioresource Technology*, 200: 470–476.

Lindner, J., S. Zielonka, H. Oechsner, and A. Lemmer. 2015. Effect of different pH-values on process parameters in two-phase anaerobic digestion of high-solid substrates. *Environmental Technology*, 36(2): 198–207.

Marchaim, U., and C. Krause. 1993. Propionic to acetic acid ratios in overloaded anaerobic digestion. *Bioresource Technology*, 43(3): 195–203.

Mauky, E., H. F. Jacobi, J. Liebetrau, and M. Nelles. 2015. Flexible biogas production for demand-driven energy supply - feeding strategies and types of substrates. *Bioresource Technology*, 178: 262–269.

Mauky, E., S. Weinrich, H. F. Jaccobi, H. J. Nägele, J. Liebetrau, and M. Nelles. 2017. Demand-driven biogas production by flexible feeding in full-scale - Process stability and flexibility potentials. *Anaerobe*, 46: 86–95.

Mauky, E., S. Weinrich, H. J. Nägele, H. F. Jacobi, J. Liebetrau, and M. Nelles. 2016. Model predictive control for demand-driven biogas production in full scale. *Chemical Engineering Technology*, 39(4): 652–664.

Mittweg, G., H. Oechsner, V. Hahn, L. Andreas, and A. Reinhardt-Hanisch. 2012. Repeatability of a laboratory batch method to determine the specific biogas and methane yields. *Engineering in Life Sciences*, 12(3): 270–278.

Mönch-Tegeder, M., A. Lemmer, J. Hinrichs, and H. Oechsner. 2015. Development of an in-line process viscometer for the full-scale biogas process. *Bioresource Technology*, 178: 278–284.

Nägele, H. J., A. Lemmer, H. Oechsner, and T. Jungbluth. 2012. Electric energy consumption of the full scale research biogas plant “Unterer Lindenhof”: Results of longterm and full detail measurements. *Energies*, 5(12): 5198–5214.

Nägele, H. J., M. Mönch-Tegeder, N. L. Haag, and H. Oechsner. 2014. Effect of substrate pretreatment on particle size distribution in a full-scale research biogas plant. *Bioresource Technology*, 172: 396–402.

Nielsen, H. B., H. Uellendahl, and B. K. Ahring. 2007. Regulation and optimization of the biogas process: Propionate as a key parameter. *Biomass and Bioenergy*, 31(11-12): 820–830.

Oechsner, H., A. Lemmer, and C. Neuberg. 2003. Crops as a digestion substrate in biogas plants. *Landtechnik*, 58(3): 146–147.

O'Shea, R., D. Wall, and J. D. Murphy. 2016. Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times. *Bioresource Technology*, 216: 238–249.

Starke, P., and C. M. Hofmann. 2014. Yield parameters of Beta beets as a basis to estimate the biogas yield. *Sugar Industry*, 139(3): 169–176.

Szarka, N., F. Scholwin, M. Trommler, H. F. Jacobi, M. Eichhorn, A. Ortwein, and D. Thrän. 2013. A novel role for bioenergy: A flexible, demand-oriented power supply. *Energy*, 61: 18–26.

Terboven, C., P. Ramm, and C. Herrmann. 2015. Demand-driven biogas production from sugar beet silage in a novel fixed bed disc reactor under mesophilic and thermophilic conditions. *Bioresource Technology*, 241: 582–592.

VDI - Society Energy and Environment. 2006. VDI 4630: Fermentation of organic Materials - Characterisation of the substrate, sampling, collection of material data, fermentation tests. VDI: VDI Richtlinien, 4, Berlin: Beuth

VDLUFA (Association of German Agricultural Analytic and Research Institutes). 2007. *Method book III - The Chemical Analysis of Feedstuffs*. 3nd ed. Darmstadt: VDLUFA-Verlag.

Wagner, A., H. Auerbach, C. Herbes, and F. Weißbach. 2011. Preservation of sugar beets for biogas production. FnBB e.V. 2011: Progress in *Biogas II - Biogas production from agricutural biomass and organic residues, Proceedings of the international congress Progress in Biogas 2011*. Stuttgart. 29 March- 01 April.

Weinrich, S., and M. Nelles. 2015. Critical comparison of different model structures for the applied simulation of the anaerobic digestion of agricultural energy crops. *Bioresource Technology*, 178: 306–312.

Weißbach, F., A. Wagner, M. Scholtissek, H. Auerbach, and C. Herbes. 2011. Conservation losses in the course of ensiling sugar beet for biogas production. *Landtechnik*, 66(4): 254–258.