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Anaerobic digestion of sugar beet pulp in Russia

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Russian agriculture generates approximately 250 Mio t dry matter of organic waste every year, which cannot be recycled usefully. Sugar beet pulp is one of this waste materials in some regions. The utilisation of these residues for biogas production can reduce negative environmental effects and can play an important role to achieve the Russian climate protection goals. Therefore, the aim of this study is to examine, if a substitution of corn silage with sugar beet pulp is possible. For this investigation a simple batch test was developed. Subsequently the degradation of the ingredients according to Weender, the biogas yields and the degradation kinetics were determined. A total degradation by approximately 40 % of the ingredients according to Weender was detected at both substrates. At the substrate sugar beet pulp a 35 % lower biogas yield was detected, because the pH-value in the reactor declined resulting in inhibition of the biogas production. This results show that a substitution of corn silage with sugar beet pulp is possible, but sugar beet pulp should only be used in co-fermentation with other substrates.

Keywords
Biogas, sugar beet pulp, corn silage, batch test, Russia

In Russian agriculture and agricultural processing industry approximately 250 Mio t dry matter (TM) of organic waste are produced every year, which represent a major challenge for the local agriculture (Delegation der Deutschen Wirtschaft in der Russischen Förderation 2010). One example is sugar beet pulp, a by-product from the sugar industry, especially in the regions Tatarstan, Krasnodar, Woronesch, Tambow, Kursk, Lipezk, Pensa and Belgorod (Maitah and Smutka 2016). The annual sugar production is approx. 0.3 Mio. t from 2 Mio. t sugar beet in the region Belgorod. In this processes approx. 1.6 Mio. t of sugar beet pulp is generated (Rogler 2006, Dega Market, 2014, Skripka 2014, Osetrov 2016). This sugar beet pulp is often used for cattle and pig feeding. A conservation by ensilage, drying or pelletization is necessary because of its perishability (Forschungsinstitut für Zuckerrüben und Zucker im Nord Kaukasus 2001). Furthermore, sugar beet pulp is used for the production of prebiotics in animal nutrition and of fungicides (Forschungsinstitut für Zuckerrüben und Zucker im Nord Kaukasus 2001, Holopkin 2013). However, a complete utilisation of sugar beet pulp in animal nutrition is not possible, because an increased use can lead to acidification of milk, to diarrhoea as well as to an over-acidification of the rumen from ruminant animals (Osetrov 2016). Therefore, sugar beet pulp is often recycled directly on the fields, with a maximum application rate of 60 t/ha on para black soils (Holopkin, 2013). A higher application rate will lead to a strong acidification of the soil (Dontschenko et al. 2006). This acidification is mainly undesirable on the slightly acid soils in the black soil area of Russia, i. e. 42 % of the cropland in the region Belgorod (Tschekmarev and Lukin 2013).

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Therefore, the biogas production is a good possibility to use these waste- and by-products and offers in addition to the energetic utilisation further positive synergy effects for agriculture, e. g. the substitution of mineral fertilizers (Geist 2013). In addition, biogas can play an important role contributing to the energy strategy of the Russian Federation which aims an electrical power production of 4.5 % from renewable energy sources until 2020 (Ministry of the Russian federation 2010). Currently, the amount is approximately 1 % (Makhovski 2013). In order to attain this objective the electrical power and heat production with biogas plays an important role because of the ability to produce base load as well as control energy to compensate weather-related fluctuations of other renewable energy sources like solar and wind power in the power grid. Another essential aspect is the possibility for a decentralised energy supply in regions without permanent gas and electrical power supply. In 2012, only 63 % of the Russian households were supplied with gas and only 47 % of the potential consumers in rural regions (70 % in the cities) were connected to the gas grid (Makhovski 2013).

Against this background, some agricultural biogas plants were constructed in Russia by German plant manufacturers such as, for example, "Farmatic Anlagenbau GmbH" or "Big Dutchman Agro" in recent years. The plant designs and the economic efficiency calculations were frequently performed according to German indexes, such as published from the KTBL (KTBL 2009). However, by this calculations regional differences of the substrate compositions, which occurs especially by agricultural residues, were often not considered. Thus, the predicted power output often was not achieved.

The aim of this study at the Belgorod State Agricultural University V. Gorin is to construct a simple anaerobic batch digestion test (BT) to determine the specific biogas yields of substrates in Russia. Subsequently, the possibilities of a substitution of corn silage with sugar beet pulp in the region Belgorod should be determined. In existing agricultural biogas plants renewable raw materials like corn silage are often used as substrate. However, the high potentials of organic residues are not considered (ffe solutions, 2015; AD AGRO systems, 2013). Furthermore, for an economical plant operation the use of cost-effective substrates like sugar beet pulp will be necessary because there is no government funding for biogas production in Russia. In the experiments the influence on the pH-value on the degradation of the ingredients according to Weender, on the biogas yields and on the degradation kinetics will be determined. Subsequently, the biogas yields will be also determined with the "Hohenheim Biogas Yield Test" (HBT) for validation of the results.

Material and Methods

The construction and the subsequent test of this batch system has been executed at the Belgorod State Agricultural University V. Gorin.

Set up of the test facility

The experimental plant consisted of four stainless steel batch reactors with a total volume of 30 l and a working volume of 28 l (Figure 1)

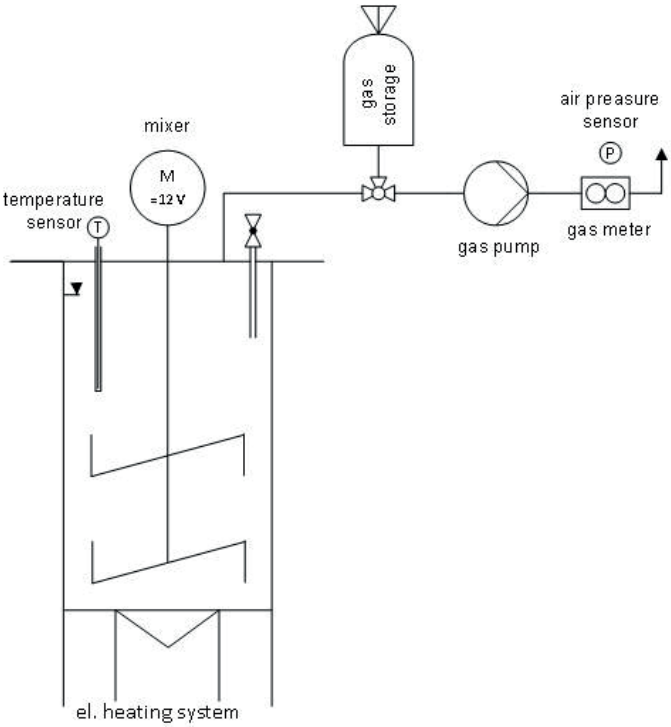

Figure 1: Piping and instrument diagram of the test facility with batch test as well as biogas storage and gas volume measurement

Each reactor was mixed with a vertical paddle agitator (four paddle). The working time was 2 min and the break time 14 min. Under each reactor an electrical heating plate which was controlled by a two-point controller was installed. The temperature was detected in a dip tube with a Pt 100 temperature sensor. The reactors were insulated with an aluminium insulating film. A dip tube was mounted in the lid of the reactor for sample taking. The produced gas was saved in 230 l gas storing bags made of polyethylene foil. The foils were welded at the edges and subsequently proofed for tightness. The gas amount was determined three times during the experimental period with a gas meter (ГРАНД 1.6, НПО "ТУРБУЛЕНТНОСТЬ ДОН", Russia). For correction to standard conditions (1,013 hPa, 273.15 K) the gas temperature was measured with a Pt 100 temperature sensor and the air pressure with a manometer (Figure 1).

Experimental procedure

Subsequently, the functionality of the experimental plant and the fermentability of corn silage (input 1.5 kg fresh mass FM; 33.0 % total solids TS; 95.1 % volatile solids VS) and sugar beet pulp (input 1.75 kg FM; 29.3 % TS; 94.9 % VS) were investigated. Both substrates were tested in two replicates. As inoculum (reactor corn silage 19.5 kg FM, reactor sugar beet pulp 20.0 kg FM) digestate (4.7 % TS; 82.2 % VS) from the biogas plant Lutschki (region Belgorod, Russia) was used. The relation of VS-inoculum to VS-substrate was approximately 1.6 : 1.

To ensure an optimal mixing of the added substrates, the experiments were started with an initial phase of three days at a temperature of 19.6–20.6 °C. Subsequently, the reactors were operated for 41 days at a temperature of 37 ± 2 °C. After three days a high foam generation started in the reactors with sugar beet pulp. As deformer 549.5 g sun flower oil was added in each reactor. The formed gas was measured at the 10^{th}, the 24^{th} and the 45^{th} day based on the degraded organic dry matter. The experimental procedure was based on the VDI-Guideline 4630 (VDI 2006).

Hohenheimer Biogas yield Test

For evaluation of the developed batch test, the biogas yields of the substrates were also detected with the "Hohenheimer Biogas yield Test" at the university of Hohenheim Germany. This is a high reproducible batch digestion test according to VDI-Guideline 4630 (Mittweg et al. 2012, VDI 2006; Helffrich and Oechsner 2003). As reactors, glass stirrings (volume 100 ml) were used and filled with 0.4 g sample material and 30.0 g inoculum. Each substrate was investigated in triplicates. The stirrings were mixed with a rotor mounted in a climate chamber. This test was carried out at a temperature of 37 ± 0.5 °C for a duration of 35 days. The produced gas was read directly from the stirrings, with an accuracy of 1 ml if at least 20 ml of gas was formed. Furthermore, the gas quality was detected with the gas transducer AGM 10 (Pronova Analysetechnik, Berlin, Germany). The gas volumes were corrected to standard conditions (1,013 hPa, 273.15 K). All gas yields were based on the degraded organic dry matter (Mittweg et al. 2012,VDI 2006, Helffrich and Oechsner 2003)

Laboratory analyses

From the substrates and the digestates the concentration of TS, VS, crude ash, crude fat, crude fibre, crude protein, and nitrogen free-extract (NfE) was measured. Every week a sample was taken from each reactor and the TS and VS concentration as well as the pH-value was detected

- The TS and VS contents of the substrate and the digestate were determined by drying (105 °C, 24 h) and ashing (550 °C, 8 h) according to VDI (2006). The pH-value was measured with a hand held pH meter. The nutrients were determined according to the following methods:
- Crude protein – according to Kjeldahl (ГОСТ 13496.4-93),
- Crude fat– by Soxhlet-Extraktion (ГОСТ 13979.2-94) and
- Crude fibre – according to Henneberg and Stohmann (ГОСТ 13496.2-91).

The NfE content was calculated according to equation 1.

$$NfE = 100\% - water - crude\ ash - crude\ fat - crude\ fibre - crude\ protein \quad \text{(Eq. 1)}$$

Degradation kinetics

The cumulative specific biogas yields were fitted to the modified Gompertz function (equation 2), for determination of degradation kinetics (Mönch-Tegeder et al. 2013, Nopharatana et al. 2007). This formula assumes that the cumulative biogas production is a function of bacterial grow:

$$M = P \times \exp\left\{-\exp\left[\frac{R_m \times e}{P}(\lambda - t) + 1\right]\right\} \quad \text{(Eq. 2)}$$

Thereby, M is the cumulative biogas production (l kg^{-1}), P the biogas production potential (l kg^{-1}), R_m is the maximum daily biogas production (l d^{-1}), λ is the duration of lag phase (d) and t is the duration of the assay (d). The constants P, R_m and λ were calculated by linear regression. For determination of the time and volume of the maximum daily biogas production, the first deviation of equation 2 was used.

Results and Discussion

Influence of the substrate on the pH-value

In Figure 2 the pH-value of corn silage and sugar beet pulp in the reactors is presented during the whole experimental phase. The pH-value in all reactors was pH 8.13 at the beginning of the experiment. Until the fourth day, the pH-value of both substrates decreased continuously (corn silage pH 7.4; sugar beet pulp pH 7.2). At the sixth day, the pH-value increased by 3.5 % to pH 7.6 in the reactors with corn silage. The pH-value fluctuated between pH 7.6 and 7.9 during the rest of the experimental period. In contrast, the pH-value decreased to pH 7.1 at the substrate sugar beet pulp until the tenth experimental day. At the tenth day, the pH-vale increased by 4.6 % to pH 7.4. Afterwards the pH-value decreased again continuously and reached the minimum of pH 6.5 at the 32th experimental day. During the rest of the experiment, the pH-value fluctuated between pH 6.5 and 6.7 (Figure 2).

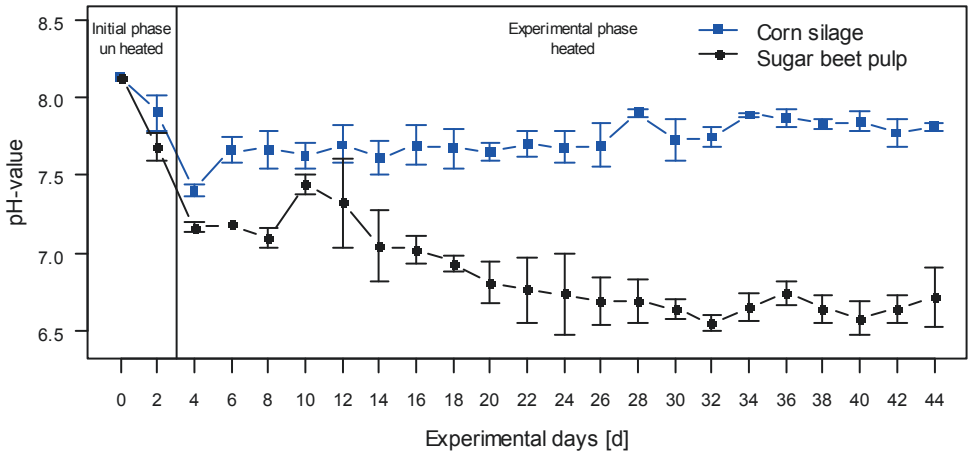

Figure 2: Influence of the substrates corn silage and sugar beet pulp on the pH-value in the developed batch system (BT)

Influence of the substrate on the degradation of the ingredients according to Weender

The degradation of ingredients according to Weender is presented in Table 1. In the reactors with corn silage 93.2 g crude fat was added. During the experiment 21.9 % (20.4 g) of the crude fat was degraded. At the substrate sugar beet pulp the amount of added crude fat was with 639.7 g much higher because of the use of sunflower oil for deformation. The crude fat degradation was 34.8 % and thereby 58.8 % higher than in the reactors with corn silage. The added crude protein amount was 324.6 g in the reactors with corn silage and 350.4 g in the reactors with sugar beet pulp. The crude protein degradation at the substrate corn silage (75.5 g) was 27.4 % higher than at the substrate sugar beet pulp (59.9 g).The concentration of crude fibre was 62.1 % lower than the crude protein concentration at the substrate corn silage and 65.6 % lower at the substrate sugar beet pulp. At the substrate corn silage (44.2 g) the degradation of crude fibre was 20 g higher than at the sugar beet pulp (25.0 g). The added amount of NfE was at both substrates approximately 638 g. The NfE degradation at the substrate sugar beet pulp (64.0 %) was approx. 10 % higher than at the substrate corn silage (54.1 %). The degradation of ingredients according to Weender was approximately 40 % at both substrates (Table 1).

Table 1: Degradation of the ingredients crude fat, crude protein, crude fibre and the nitrogen free-extracts (NfE) based on the volatile solids of the substrates corn silage and sugar beet pulp

		Crude fat	Crude protein	Crude fibre	NfE	Complete ingredients
				Input pro Reaktor in g		
Corn silage	Inoculum	72.15	278.85	25.35	302.25	678.60
	Substrate	21.00	45.75	97.80	335.85	500.40
	Total	**93.15**	**324.60**	**123.15**	**638.10**	**1.179.00**
Sugar beet pulp	Inoculum	74.00	286.00	26.00	310.00	696.00
	Substrate	16.28	64.40	94.50	328.83	504.00
	Sun flower oil[1)]	549.45	-	-	-	549.45
	Total	**639.73**	**350.40**	**120.50**	**638.83**	**1.749.45**
				Output per reactor in g		
Corn silage		72.78	249.08	78.93	293.15	693.93
Sugar beet pulp		417.30	290.55	95.55	230.10	1.033.50
				Degradation in g		
Corn silage		20.38	75.53	44.23	344.95	485.08
Sugar beet pulp		222.43	59.85	24.95	408.73	715.95
				Degradation in %		
Corn silage		21.87	23.27	35.91	54.06	41.14
Sugar beet pulp		34.77	17.08	20.71	63.98	40.92

[1)] Sun flower oil was used as deformer.

Influence of the substrate on the specific biogas yield and on the degradation kinetics

The specific biogas yield as well as the degradation kinetics calculated with the modified Gompertz equation of the substrates corn silage and sugar beet pulp are presented in Figure 3. The maximally calculated biogas yield (with the Gompertz equation) of the substrate corn silage was 770.6 l kg^{-1} in the "Hohenheim Biogas Yield Test" and 9.3 % (699.0 l kg^{-1}) lower in the batch test after 45 days. However, the difference between the last measured value in the batch test and the calculated value in the "Hohenheim Biogas Yield Test" after 45 days was only approximately 40 l kg^{-1}.

At the substrate sugar beet pulp significant differences between both test facilities could be detected. The calculated biogas yield was 757.0 l kg^{-1} in the "Hohenheim Biogas Yield Test" after 45 days. In the batch test a 36.4 % (481.6 l kg^{-1}) lower biogas yield was determined. This high difference can be explained by the decreasing of the pH-value. The optimum pH-value for one phase systems is between pH 6.8 und 8.0 according to Demirel and Yenigün (2002) because the methane formers are inhibited at pH-values below 6.8 which results in an accumulation of volatile fatty acids (Figure 3).

The detected substrate-specific methane yield in the HBT was 331 l kg^{-1} of the substrate corn silage and 342 l kg^{1} of the substrate sugar beet pulp based on volatile solid. In comparison, specific methane yields of 340 l kg^{-1} by corn silage and 350 l kg^{-1} by sugar beet pulp are described in literature (FNR, 2013).

The maximum daily biogas production of corn silage was 94.1 l kg^{-1} d^{-1} in the batch test (HBT 60.9 l kg^{1} d^{-1}) and was reached after 4.7 days (HBT 5.01 d). The process inhibition at the substrate sugar beet pulp led to a lower maximum daily biogas production of 32.1 l kg^{-1} d^{-1}. The maximum was reached 1.6 days later than by the substrate corn silage. In the HBT, the maximum daily biogas production of the substrate sugar beet pulp was 20 l kg^{-1} d^{-1} (time after 4.8 d) lower than of the substrate corn silage (Figure 3).

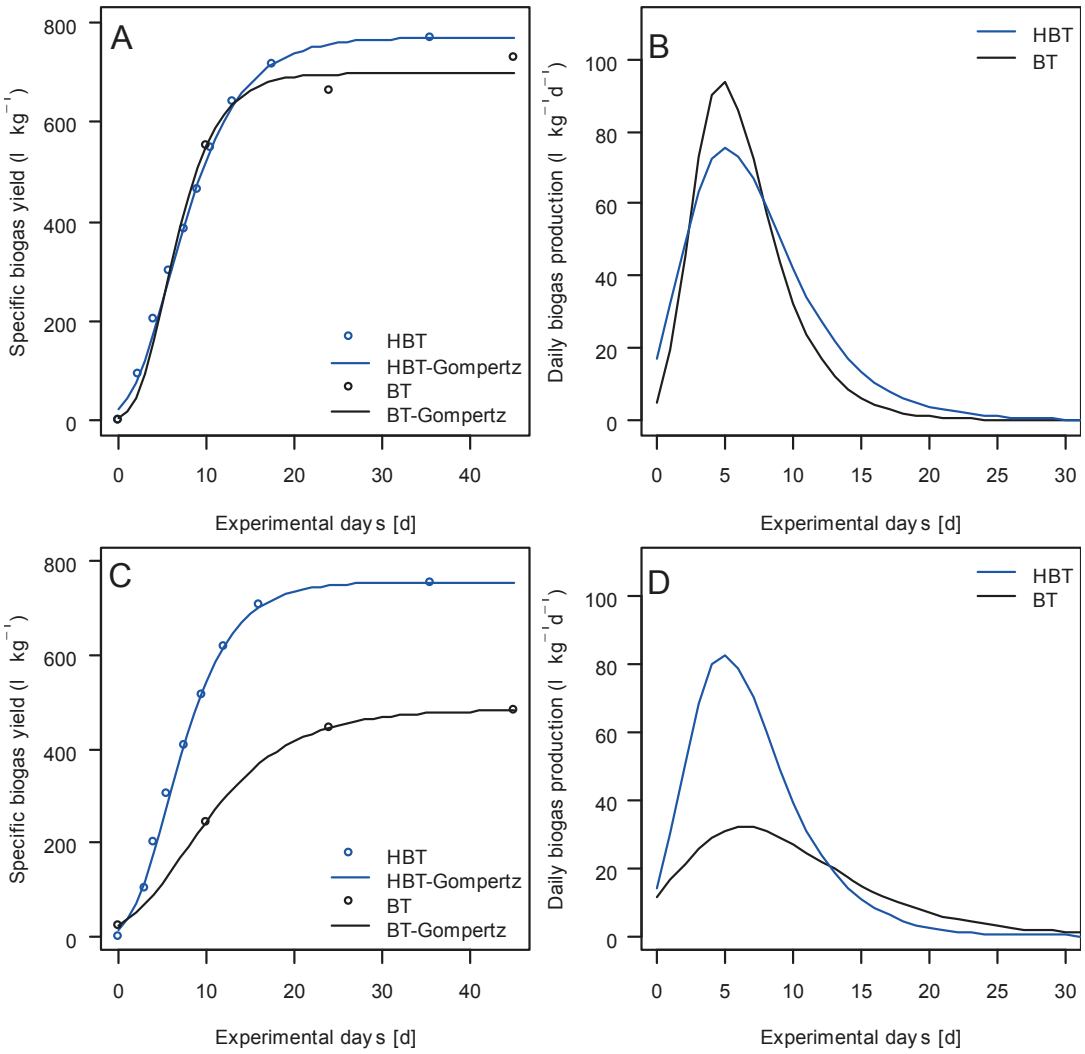

Figure 3: Sum curve of the specific biogas yields based on the degraded volatile solids of the substrates corn silage (A) and sugar beet pulp (C) as well as the daily biogas production of the substrates corn silage (B) and sugar beet pulp (D) in the developed batch test and in comparison to the “Hohenheim Biogas Yield Test” (HBT)

Conclusions

The experiments showed that it is possible to investigate important parameters of process stability such as the degree of degradation, the biogas yield as well as the degradation kinetics with the developed batch test because there was only a low difference in the specific biogas yield (40 l kg^{-1}) between the batch test and the "Hohenheim Biogas Yield Test" at the substrate corn silage. However, further optimisation of the experimental procedure will be necessary to improve the quality of results. A ratio of VS inoculum to VS substrate not less than 2 : 1 has to be obeyed (VDI 2006) in further experiments to avoid an overloading of the process. Furthermore, the biogas yield of the inoculum has to be measured and considered by the calculation of the specific biogas yield. For a further optimisation of the system, a gas quality detector will be purchased to detect also the specific methane yield of the substrates. Moreover, a standard substrate to compare different experimental trials should be used.

In this experiments a degree of degradation by approximately 40 % of the substrates corn silage and sugar beet pulp could be detected. The NfE degradation of the substrate sugar beet pulp was higher than of the substrate corn silage. In contrast, crude fibre and crude protein degraded better at the substrate corn silage. In the batch test, a significantly lower biogas yield could be detected at the substrate sugar beet pulp in comparison to the substrate corn silage because of the inhibition of the methane formers due to the decreasing of the pH value. Therefore, an adapted organic loading rate or co-fermentation with other substrates will be necessary in the use of sugar beet pulp. The formation of foam at the substrate sugar beet pulp could be suppressed by the addition of sun flower oil, however, in further experiments a nonbiodegradable oil should be used. To reduce the risk of process inhibition by volatile fatty acids accumulation, a two-stage biogas system as described from Lindner et al. (2016) could be used. This investigation showed that a substitution of corn silage with sugar beet pulp is possible and negative environmental aspects of the present recovery methods can be reduced.

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