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Two-Step Pilot-Scale Anaerobic Treatment of Sugar Beet Pulp

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Abstract

Sugar beet pulp is a very suitable material for anaerobic biodegradation. This work investigates anaerobic treatment of sugar beet pulp in a pilot plant. The pilot plant consisted of an acidogenic reactor (volume 5.3 m^3) and an methanogenic reactor (volume 3.5 m^3). It was found that designed technology was convenient for both, high degradation of beet pulp dry matter and sufficient specific biogas production. Recommended organic loading rate for the acidogenic reactor was 20 kg COD $m^{-3}d^{-1}$, hydraulic retention time 4 days, and maximum content of acidified pulp (dry matter) in this reactor - 6-7%. During the operation period, the organic loading of the methanogenic reactor achieved was 21 kg COD nr'd"[1]. Hydraulic retention time in this reactor varied from 27 days (at the loading 3 kg m^{-3} d^{-1}) to 3.9 days (at the loading 21 kg m^{-3} d^{-1}). An average value of specific biogas production was 0.391 m^3 per kg of dried beet pulp added. The average efficiency of dried pulp matter degradation was 91.5%.

Keywords: anaerobic digestion, acidogenesis, methanogenesis, sugar beet pulp

Introduction

According to work [1] dry sugar beet pulp composition is as follows: rhamnose 2.4%, fucose 0.2%, arabinose 20.9%, xylose 1.7%, mannose 1.1%, galactose 5.1%, glucose 21.1%, galacturonic acid 21.1%, methanol 1.8%, acetic acid 3.9%, ferulic acid 0.8%, diferulic acid 0.04%, protein 11.3%, and ash 3.6%. This composition creates wide possibilities for biological treatment. Research dealing with sugar beet pulp biodegradation is mostly dedicated to enzymatic hydrolysis [1, 2, 3] and to characterisation of products of the hydrolysis. Other works concern anaerobic treatment with biogas production [4, 5]. In this work [4] sugar beet pulp was treated in a ten liter stirred tank at loading rate of 4.06 kg $m^{-3}d^{-1}$ (kg of volatile solids -VS). VS reduction was 95.2% and methane yield was 0.263 m^3 per kg VS added. Weiland in his work [5] presented an anaerobic digestion of beet pulp in a one-stage and a two-stage pilot plant. In both plants 60-65% efficiency of COD removal 60-65 % was achieved. Methane yield was 0.210 m^3 per kg of COD added. Volume of the reactor used for a one-stage process was 6.5 m^3, and 2.5 m^3 (acidification) and 1.0 m^3 (methanisation), for a two-stage process, respectively. Weiland [5] suggested the addition of only the liquid fraction from an acidogenic reactor to a methanogenic reactor in a two-stage process.

Our previous study [6] dealt with laboratory investigations of optimal anaerobic treatment parameters of beet pulp for production of biogas. Beet pulp was treated in a two-stage laboratory model (volume of acidification - 1.6 liters, volume of methanisation 4 liters). The following findings were drawn from this study:

- two-stage treatment (acidogenesis and methanogenesis) was required for this anaerobic treatment
- optimal pH in the acidogenic phase was 4-5. It had to be adjusted by $NaHCO_3$ because pH in the course of acidogenesis decreased to 3.5

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- optimal hydraulic retention time for the acidogenesis was 4 days; optimal dried beet pulp content in acidogenesis was 6-7%
- specific beet pulp COD was 1.295 g per gram of dry beet pulp
- average specific production of biogas was 0.490 m^3 per kg of dry beet pulp, average content of methane in biogas was 72%
- the highest organic loading rate (OLR) in the labora tory methanogenesis reactor was 10 kg COD $m^{-3}d^{-1}$.

The quality of sludge water at this OLR was as follows:

- COD filtered 1000-3200 mg 1^{-1}
- COD nonfiltered 2600-5200 mg 1^{-1} (after 30 minutes sedimentation)
- NH_4 - N 60-190 mg 1^{-1}
- PO_4 - P 0.5-8 mg 1^{-1}

In our work [6] the beet pulp was semi-continuously dosed into a two-stage laboratory model equipment once a day. Due to technical reasons and the reactor's small volume, the laboratory experiments were conducted without stirring. In order to confirm our results and possible transfer to scale conditions, the measurements were carried out in a pilot-scale plant.

Materials and Methods

Based on our previous results [6], pilot-scale equipment was designed. It consisted of two-stage technology of anaerobic treatment of beet pulp. In the first stage, a proposed acidogenic reactor had 5.13 m^3 total volume. For the second stage, a methanogenic reactor with 3.5 m^3 total volume was designed. The scheme of pilot-scale equipment used is shown in Figure 1. Five sampling valves were installed along the height of the methanogenic reactor in regular intervals. The acidogenic reactor was mechanically stirred. The reactor was heated by recirculation stream heating (see Fig. 1). A modified UASB reactor was proposed for the methanogenic stage. Modification of the reactor included forced recirculation of the sludge from a three-phase (g-l-s) separator to the sludge bed. This forced recirculation also enabled mixing of the sludge bed. This was advantageous at low OLR, when mixing by generated biogas was insufficient. Heating of the methanogenic stage was similar as in the acidogenic reactor.

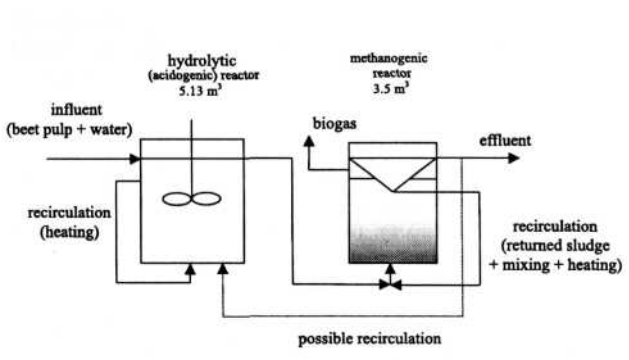

Fig. 1. Pilot-scale model of anaerobic treatment of sugar beet pulp.

Dried beet pulp from AGROTREND Trencin (Zemianske Podhradie, Slovak Republic) was used for the pilot experiments. Its composition is shown in Table 1 [6]. Originally, it was proposed that dilution of beet pulp with water will be conducted in a separate tank. However, later it was found that it was sufficient to dose beet pulp with water directly to the acidogenic stage. Based on the laboratory tests, it was proposed that a weight ratio of the mixture of beet pulp : water equal to 0.8:10 be used. That represented a still mixable body. Total daily dosage of beet pulp depended on OLR of the methanogenic reactor.

Table 1. Characteristics of used sugar beet pulp.

Parameter	Unit	Average value
TS	%	90
VS from TS	%	90
Specific COD	g g^{-1}	1.295
TKN	mg g^{-1}	110
TP	mg g^{-1}	20

Constant OLR of the acidogenic reactor approximately 20 kg COD $m^{-3}d^{-1}$ was proposed. Constant retention time of 4 days was used. Volume of the acidogenic reactor was chosen according to a load of the methanogenesis reactor.

The following parameters of the reactor operation were monitored, and if necessary adjusted:

- **operational parameters**
- temperature in acidogenic and methanogenic reactor
- pH in acidogenesis (optimum 4.0 - 4.4) and pH in methanogenesis (optimum 7)
- daily amount of biogas
- consumption of water, beet pulp, and Na_2CO_3 dos ages
- **analytic parameters**
- sludge water (COD filtered and COD nonfiltered after 30 minutes sedimentation, NH_4-N, PO_4-P, dissolved solids - DS, volatile dissolved solids - VDS)
- sludge (suspended solids - SS, volatile suspended solids - VSS)
- biogas (content of CO_2 and methane)

All analysis were performed according to standard methods [7].

33.8 kg of the dried beet (90% dry matter) was dosed into the acidogenic reactor together with 483.4 1 of water.

The reactor was heated to 37°C, Na_2CO_3 was added and mixture beet pulp-water was under acidification for 4 days. A dosage of Na_2CO_3 was adjusted in order to hold pH between 4.0-4.4 for the acidogenic reactor and at 7 for the methanogenic reactor. Unlike laboratory model [6] (where pH was adjusted by Na_2HCO_3) soda as a cheaper buffer medium in pilot scale model was used. At the start-up phase, it was necessary to add 1-3 kg of the soda per day. A digested sludge (of the municipal WWTP in Trencin) was used as inoculum into the methanogenic reactor in the amount of 1 m^3 of the sludge at the concentration of 34 g 1^{-1} (VSS - 54%). The reactor was filled up with water and heated to 37°C.

Operation of the pilot plant began after 4 days. 129.3 1 of the mixture from the acidogenesis stage was supplied daily into the methanogenic reactor (at the initial OLR of 3 kg $m^{-3}d^{-1}$). 8.5 kg of dried beet pulp and 120.8 1 of water were added into the acidogenic reactor. There was no possibility to apply reagents continually because pumps required a higher capacity. Therefore pumping of acidificated beet pulp to the methanogenic reactor was regulated by a timer. The pumping interval depended on the methanogenesis OLR.

Results and Discussion

A start-up of a pilot plant was carried out at OLR of the methanogenic reactor 3 kg $m^{-3}d^{-1}$. 33.8 kg of the dried beet pulp (90% dry matter) was dosed into the acidogenic reactor together with 483.4 1 of water. The reactor was heated to 37°C, Na_2CO_3 was added and mixture beet pulp-water was under acidification for 4 days. A dosage of Na_2CO_3 was adjusted in order to hold pH between 4.0 - 4.4 for the acidogenic reactor and at 7 for the methanogenic reactor. At the start-up phase it was necessary to add 1-3 kg of the soda per day. A digested sludge (of the municipal WWTP in Trencin) was used as inoculum into the methanogenic reactor in the amount of 1 m^3 of the sludge at the concentration of 34 g/1 (VSS - 54%).

A course of an increase of OLR in the methanogenic reactor and related hydraulic retention time are shown in Fig. 2. During the operation period, the maximum achieved OLR of the methanogenic reactor was 21 kg COD $m^{-3}d^{-1}$ and the hydraulic retention time varied from 27 days (at the loading of 3 kg $m^{-3}d^{-1}$) to 3.9 days (at loading of 21 kg $m^{-3}d^{-1}$).

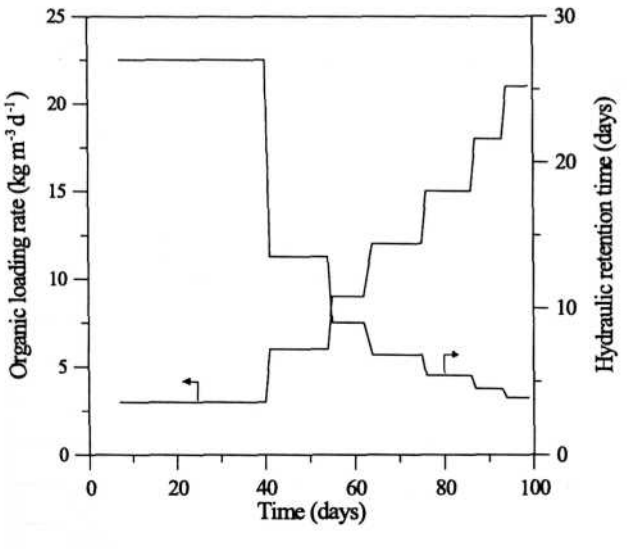

Fig. 2. Course of organic loading rate and hydraulic retention time in methanogenic reactor.

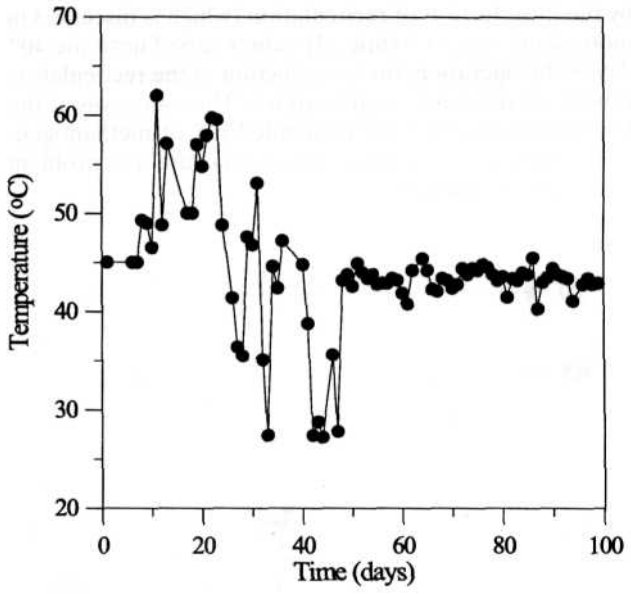

Fig. 3. Temperature in acidogenic reactor.

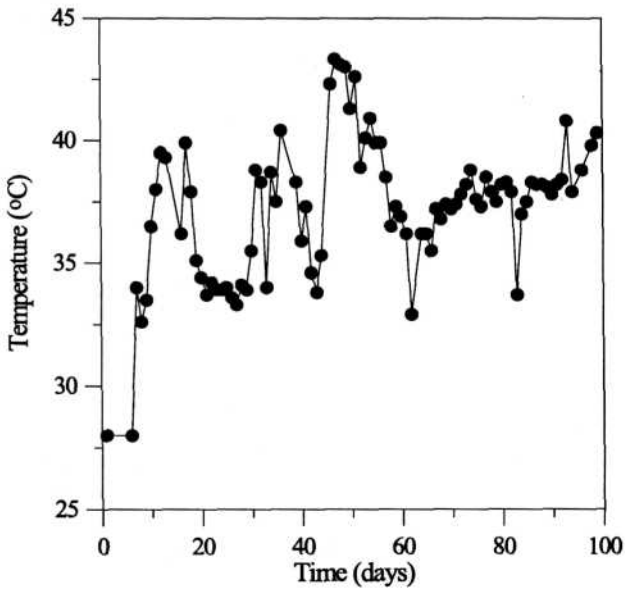

Fig. 4. Temperature in methanogenic reactor.

Figs. 3 and 4 show the course of the temperatures in the reactors throughout the study. An average temperature in the acidogenic reactor was 44°C. Sufficient temperature for the acidogenesis is 37°C. A higher temperature was reached because the heating of acidogenesis was designed for the total reactor volume of 5.13 m^3. During the operation, total reactor volume used was only 70% at the maximum OLR of 21 kg $m^{-3}d^{-1}$. An average temperature in the methanogenic reactor was 37.1°C.

Figs. 5 and 6 show the course of pH in the reactors during the study. The process allowed proper regulation of pH, thus it did not vary significantly. The pH value temporarily increased in the acidogenic reactor and the pH value in the methanogenic reactor permanently declined in the 47th day of the monitoring. This was caused by the introduction of recirculation (which is discussed in more detail below). While pH values varied until the 40th day of the operation, the introduction of the recirculation caused almost constant pH - of 6.6. This value was at the lower interval of the recommended pH of methanogenesis, however, this did not appear to cause any problem for biogas production.

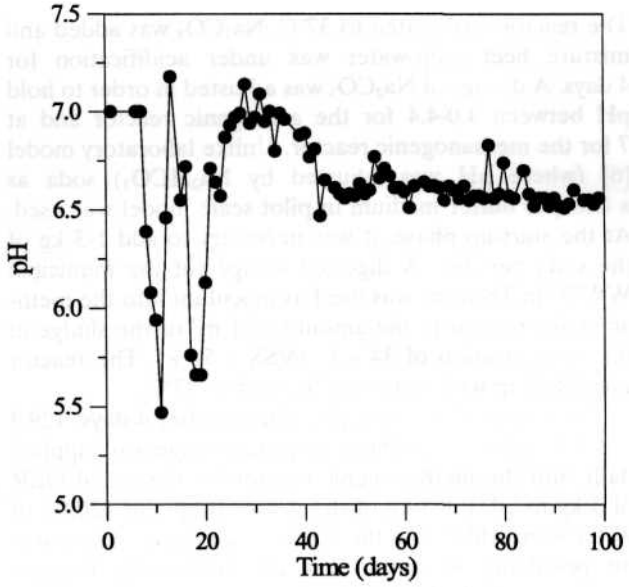

Fig. 6. pH in methanogenic reactor.

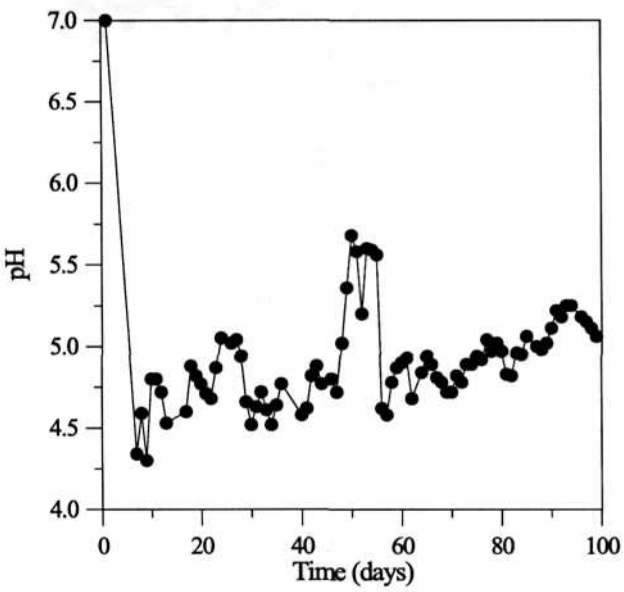

Fig. 5. pH in acidogenic reactor.

Results of the monitoring of the anaerobic sludge concentration in the methanogenic reactor are shown in Table 2. As can be seen from this table, in the beginning of the operation, a concentration gradient of the sludge over methanogenic reactor height was observed. It was suggested that a main cause for the existence of this gradient was the small amount of produced biogas. This amount was not sufficient to mix up the content of the reactor. Approximately, at the 20th day of the operation, heavier fractions of the sludge remained at the bottom of the reactor. Sludge concentration was only 3 g l^{-1} at the level of the third sampling valve, which resided at 120 cm from the bottom of the reactor. Between the 40th to 60th operation day, there was a partial flotation of the sludge in the methanogenic reactor. That resulted in higher sludge concentration in the samples from the V. valve (just under the surface) when compared with samples from the I. tap (at 40 cm from the bottom). When OLR of 9 kg $m^{-3}d^{-1}$ on the 60th day of operation was reached, a concentration of the anaerobic sludge became homogeneous, mainly due to the generation of biogas. The gas loading in the methanogenic reactor in this phase was 3 m^3 $m^{-3}d^{-1}$. Biogas production during pilot plant operation is shown in Fig. 7.

The quality of effluent from the methanogenic reactor is given in Table 3. The measured characteristics of the pilot plant effluent up to the 47th operation day were comparable with data from our previous study [6] using laboratory equipment. In order to maintain pH in the methanogenic and acidogenic reactors, it was necessary to add soda. At the 40th operation day, the dosage of soda was 0.5 kg. This represents a ratio of soda:

Table 2. Concentrations of anaerobic sludge in methanogenic reactor.

Day of operation	Concentrations of anaerobic sludge g l^{-1}		
	I. valve	III. valve	V. valve
16	19.0	12.4	3.5
23	21.2	2.9	3.0
37	15.1	14.1	22.4
63	25.8	20.2	20.3
73	28.6	29.0	28.3
84	39.9	36.2	39.2
90	44.9	43.2	42.7
99	50.2	51.4	50.5

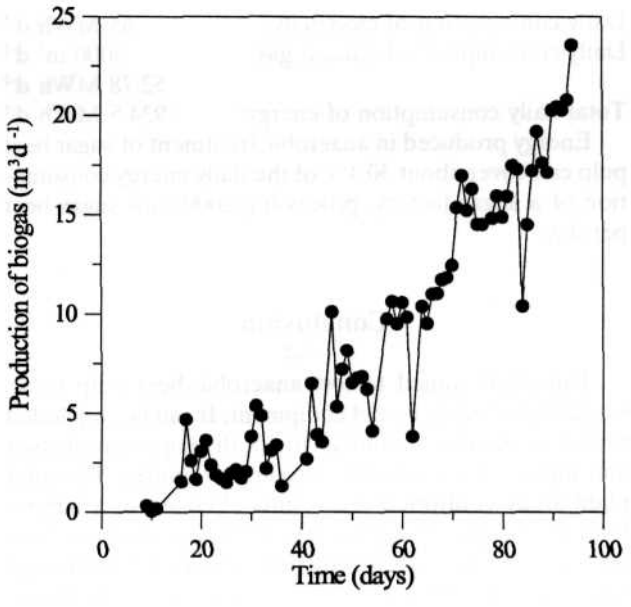

Fig. 7. Biogas production in methanogenic reactor.

beet pulp dry matter equal to 1:30. In order to utilize alkalinity of the effluent, to reduce soda consumption and sludge water production, on the 47th day of the operation the recirculation from the outlet of the methanogenic reactor to the input of the acidogenic reactor was introduced. If beet pulp was mixed with effluent from the methanogenic reactor instead of with clean water, the following problems were expected to arise:

- gradual equalizing of the pH in both reactors; higher pH in the acidogenesis and lower in the methanogenesis in compasison with optimum values, respectively, vs. that of optimum
- methanogenesis might prematurely appear in the acidogenesis due to recirculation of suspended solids which are present in the methanogenic effluent
- increase in the concentration of ammonium ions and dissolved solids in the methanogenic reactor; these substances might inhibit the process of the production of biogas.

None of these expectations occurred because of the introduction of recirculation. Introduction of recirculation caused pH in the acidogenesis to increase for the eight-day period (Fig. 5). Concentration of COD slightly increased and the concentration of ammonium nitrogen doubled at the outlet of the methanogenesis. A significant increase of nonfiltered COD was caused by a high concentration of sludge in the methanogenic reactor. This indicated that an internal separator was not able to sludge separate it. Figs. 5-7 show that recirculation of the sludge into the acidogenic reactor did not cause problems in the system. After the introduction of the recirculation, it was not necessary to add soda into the acidogenesis. Only a beet pulp supply into the system was required. Only biogas was produced. Water was added to the acidification in the volume sufficient to cover evaporation losses.

Based on the operation data, specific production of biogas was calculated. It ranged in interval from 0.102-0.624 m^3 per kg of dried beet pulp. An average value was 0.391 $m^{-3}d^{-1}$. This is a lower value in comparison with the value obtained in the laboratory experiment [6]. This could be explained by more unstable conditions in the operation of the pilot plant.

Fig. 8 shows specific production of biogas at individual OLR of the methanogenic reactor. Almost a constant specific production of biogas was achieved in the loading range of 12-18 kg $m^{-3}d^{-1}$. Due to a significant increase of the concentration of suspended solids at higher loadings, it is recommended to maintain the OLR for the methanogenic reactor at the bottom margin lower value of this interval. Also, the content of methane was lower in comparison with our previous laboratory experiments [6] (60% vs. 72%, respectively).

From total balance of suspended solids follows 91.5% degradation of dried beet pulp. This value of degradation efficiency was calculated based on:

- total amount of processed dried beet pulp,
- produced amount of sludge in the methanogenic reactor during the monitored period,
- concentration of suspended solids in effluent in the period until the 47th day (without recirculating the effluent from the methanogenesis into the acidogenesis).

The optimal process parameters resulting from a pilot-scale study are listed in Table 4.

Table 3. Quality of effluent from the methanogenic reactor.

Day of operation	COD filt mg l^{-1}	COD nonfilt mg l^{-1}	SS		DS		NH_4-N	PO_4-P
			g l^{-1}	VSS %	g l^{-1}	VDS %	mg l^{-1}	mg l^{-1}
23	2570	6580	2.7	–	–	–	106	6.1
37	840	4940	4.5	62.9	–	–	113	1.7
60	1490	5230	1.6	–	4.4	48.2	200	2.1
63	2090	5530	2.4	–	5.7	31.8	351	5.7
69	4782	6280	1.6	–	6.6	–	267	3.5
71	3650	7470	4.9	–	7.0	–	266	2.1
73	3650	38860	36.3	–	5.7	–	370	1.2
84	2930	34680	16.2	62	4.4	24.6	255	0.7

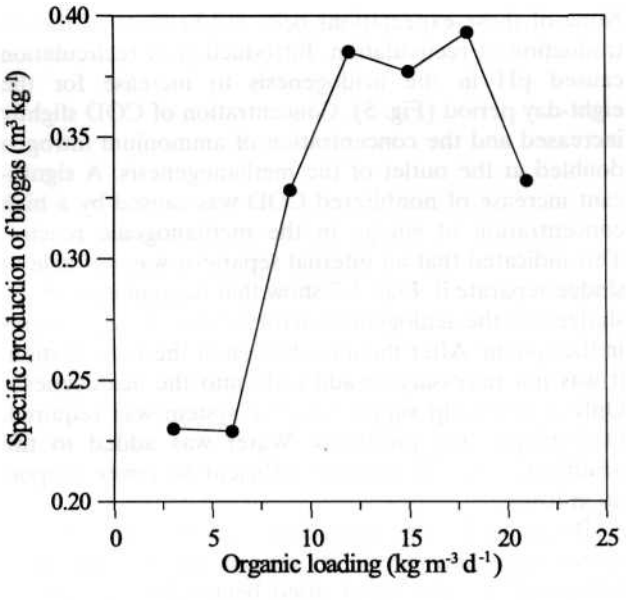

Fig. 8. Specific production of biogas at individual OLR of the methanogenic reactor.

Table 4. The optimal process parameters resulting from a pilot-scale study.

Parameter	Acidogenesis	Methanogenesis
Organic loading rate – COD kg m^{-3} d^{-1}	20	10-12
pH	4.0-5.0	6.5-7.5
SS in the reactor kg m^{-3}	60-70	30-35
Temperature °C	35-37	35-37
Production of biogas per kg of dried beet pulp m^3 kg^{-1}	–	0.4-0.5
Content of methane in biogas %	–	60-70
Removed COD of the beet pulp %	–	95
Removed dried beet pulp matter %	–	90

Utilization of sugar beet pulp can be illustrated by following energy balance.

Recovery of energy from sugar beet pulp in sugar factory (processing of 2000 tons of sugar beet pulp per day of sugar beet) Exhausted pressed sugar beet pulp production: 500 t d^{-1} (80% water content)

Dried beet pulp production: 100 t d^{-1}
Average production of biogas: 45000 m^3 d^{-1}
Average production of methane: 29250 m^3 d^{-1}
Energy content of produced methane: 1023.750 GJ d^{-1} ~ 284.4 MWh d^{-1}

Daily consumption of fuel-oil: 70 t d^{-1} (energy content 42 MJ kg^{-1}) 816.7 MWh d^{-1}

Daily consumption of electricity: 65 MWh d^{-1}
Daily consumption of natural gas: 5000 m^3 d^{-1} 52.78 MWh d^{-1}
Total daily consumption of energy: 934.5 MWh d^{-1}

Energy produced in anaerobic treatment of sugar beet pulp can cover about 30.4% of the daily energy consumption of a sugar factory, processing 2000 tons sugar beet per day.

Conclusion

This study aimed to test anaerobic beet pulp treatment in pilot-scale model equipment. It can be concluded that this process is suitable for both biogas production and high degradation of beet pulp dry matter. The pilot plant study confirmed our results obtained in a laboratory model [6]. The pilot model has worked without problems for a relatively long time, for more than 50 days with the recirculation of the effluent from the methanogenic reactor to the acidogenic reactor. In comparison with other studies [4, 5] related to anaerobic decomposition of sugar beet pulp, this study resulted in a higher organic load, lower retention time and a higher specific production of biogas and methane. Higher treatment efficiency (95% of COD removal efficiency) in comparison with the work [5] was achieved by processing homogenized content of an acidogenic reactor in a methanogenic reactor. In work [5] only a liquid fraction from an acidogenic reactor was added to a methanogenic reactor (60-65% of COD removal efficiency).

The treatment of beet pulp in the real industrial settings might be little different. In a full-scale operation, treatment of fresh beet pulp with high water content (about 80%) is expected. That can affect input-output relationships, and other parameters such as water supply, amount, and the quality of the effluent stream from the methanogenic reactor.

Anaerobic treatment of sugar beet pulp is a viable alternative for sugar beet pulp processing with production of biogas. Energy from biogas can be a significant contribution to the energy balance of a sugar beet factory. This study offers optimal technological parameters for realization of this technology.

Acknowledgments

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