Biogas from sugar beet press pulp as substitute of fossil fuel in sugar beet factories

L. Brooks, V. Parravicini, K. Svardal, H. Kroiss and L. Prendl

ABSTRACT

Sugar beet press pulp (SBP) accumulates as a by-product in sugar factories and it is generally silaged or dried to be used as animal food. Rising energy prices and the opening of the European Union sugar market has put pressure on the manufacturers to find alternatives for energy supply. The aim of this project was to develop a technology in the treatment of SBP that would lead to savings in energy consumption and would provide a more competitive sugar production from sugar beets. These goals were met by the anaerobic digestion of SBP for biogas production. Lab-scale experiments confirmed the suitability of SBP as substrate for anaerobic bacteria. Pilot-scale experiments focused on process optimization and procedures for a quick start up and operational control. Both single-stage and two-stage process configurations showed similar removal efficiency. A stable biogas production could be achieved in single-stage at a maximum volumetric loading rate of 10 kgCSB/(m^3·d). Degradation efficiency was 75% for VS and 72% for COD. Average specific gas production reached 530 NL/$kgCOD_{SBP}$ or 610 NL/$kgVS_{SBP}$. (CH_4: 50 to 53%). The first large-scale biogas plant was put into operation during the sugar processing period 2007 at a Hungarian sugar factory. Digesting approximately 50% of the SBP (800 t/d, 22%TS), the biogas produced could substitute about 40% of the natural gas required for the thermal energy supply within the sugar processing.

Key words | anaerobic digestion, biogas production, sugar beet pulp

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INTRODUCTION

Cane sugar production has become a serious competitor for sugar beet factories since the opening of the European Union sugar market. It is self-sustaining in energy supply by burning bagasse. Sugar beet factories in contrast need a high input of fossil energy, about 170 to 330 kWh to process one ton of beets – excluding drying of sugar beet press pulp (SBP). SBP, a by-product in the sugar beet production, has a lower heating value than bagasse and is generally silaged, dehydrated or dried to be used as animal food. The drying process takes up one third of the whole energy demand for sugar production. The idea of the research project was, to design a more cost effective treatment of the SBP, which would lead 1) to savings in energy consumption (reduction of CO_2 production), 2) reduction of treatment costs and consequently 3) to a more competitive sugar production from sugar beets. The challenge was to develop a technology for the anaerobic digestion of SBP, which would be easy to operate, ensured a stable biogas production during the whole sugar processing and could be started up within a short period of time just before each processing period.

At first lab-scale experiments were carried out to gain information about 1) the suitability of the anaerobic process to treat SBP, 2) favourable process conditions like temperature, pH-value, solid retention time (SRT), loading rate for a stable biogas production, 3) the most effective treatment configuration (single-stage or two-stage process) and 4) quality of the biogas and of the residual material.

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Based on these results, further experiments were conducted in pilot-scale aiming at the 1) optimisation of biogas production and evaluation of process stability with daily fresh SBP, 2) assessment of nutrients (N, P) and trace elements demand during long-term operating conditions and 3) development of an efficient process control. The results of the experiments at lab- and pilot-scale led to the implementation of the first large-scale biogas plant at a Hungarian sugar factory, processing 7,500 t sugar beets/d. Digesting approx. 50% of the SBP (800 t/d, 22%TS), the biogas produced could substitute about 40% of the natural gas required for thermal energy supply.

MATERIAL AND METHODS

Sugar beet pulp (SBP)

The sugar production at the Hungarian factory lasts from October until December. About 1,600 t of extracted and dewatered SBP (20–22% Total Solids) accumulate as by-product every day. SBP mainly consists of carbohydrates, like cellulose (22–30%), hemicellulose (24–32%), pectin (24–32%) and lignin (3–4%) (Spagnuolo *et al.* 1997). The residual sucrose is between 1% and 4% (Amon *et al.* 2006). Other constituents are proteins 8.5% and ash 4.2%. Lab-scale experiments started with silaged SBP in April 2006 and then continued with fresh SBP during the sugar processing period from October to December 2006. The pilot plants were started up with fresh SBP in 2006 and operated with silaged SBP till the successive processing period of 2007. Table 1 shows the composition of fresh and silaged SBP. In silaged SBP the amount of dissolved organic matter is higher (approx. 35 g COD/L), due to the conversion of the residual sugar to lactic acid. Anaerobic microorganisms need organic carbon (as COD), nitrogen (N) and phosphorus (P) for their growth. Analyses showed a balanced nutrient ratio of COD:N:P = 1,000:13.7:0.9, thus no additional co-substrate was considered at the beginning.

In order to ensure an unobstructed operation of the lab-scale plant and to increase the reactive surface for enzymes and bacteria, the SBP was mechanically cut with a masticator (pore size 3 mm). Particle size distribution in SBP prior to mincing was 40% between 6.3 and 4 mm, 37% between 4 and 2 mm and 7% between 2 and 0.63 mm. After cutting, particle fraction between 4 and 2 mm increased up to 63% and between 2 and 0.63 mm to 28%. In pilot-scale minced as well as not minced SBP were used for the operation.

Table 1 | Relevant parameters of silaged and fresh SBP (average values)

Parameter	SBP Silage	SBP Fresh	Parameter	SBP Silage	SBP Fresh
COD (g O_2/L)	265	230	P_{total} (g P/L)	0.2	0.2
COD_{diss} (g O_2/L)	45	10	TS (g TS/L)	195	200
TKN (g N/L)	3.1	3.2	VS (%TS)	94	94

COD: Chemical Oxygen Demand; COD_{diss}:dissolved COD; TKN: Total Kjeldahl Nitrogen; P_{total} phosphorus; TS: total solids; VS: volatile solids.

Design and operation of the lab-scale plant

Experiments in lab-scale were run in 3 litre cylindrical acrylic glass reactors from April 2006 to July 2007. The reactors were operated under mesophil conditions (37°C), continuously stirred and fed once a day with SBP (weighted amount). The produced gas was collected and measured in graduated cylinders dipped in acidified water. pH-value and temperature were daily monitored. Anaerobic digested sludge from an Austrian municipal wastewater treatment plant (WWTP) was used as seed sludge in the methane reactor. To allow adaptation of the anaerobic bacteria to the new substrate, the reactors had to be started at a low COD-volumetric load, which was then carefully increased. As a consequence, steady state process conditions at full loading could not be reached before several months of operation (at least 3 times the SRT).

Acidogenic bacteria grow faster than methane bacteria and reach their optimum under different process conditions. In order to optimize both acidification and methane production, the anaerobic process was at first operated in two separated stages. In some cases, separate pre-acidification of organic substrate at pH-value <7 turned out to be advantageous for a more stable methane production (in the second stage) by reducing the formation of the strong inhibiting propionic acid in favour of acetic and butyric acid (Kunst 1982).

Due to the high solid concentrations in the first stage, effluent sludge of the second stage (prior or after dewatering) had to be recycled into the pre-acidification stage for dilution to avoid problems with mixing devices. In the lab-scale experiments SBP was diluted with water to 6–7%TS. Ammonium concentration in the diluted SBP was increased to the value of the undiluted sludge in methane reactor by adding urea. Single-stage reactors were fed with undiluted SBP.

Design and operation of pilot scale

Two pilot plants were put up directly on the premises of the Hungarian sugar factory. Pilot plant No.1 was designed as a two-stage configuration with a pre-acidification reactor of 0.9 m^3 sludge reaction volume, a methane reactor of 4.1 m^3 sludge reaction volume and 0.9 m^3 gas expansion space (Figure 1). Pilot plant No. 2 was a single-stage configuration with the same methane reactor as in No. 1. At first SBP was supposed to be mixed with part of the effluent sludge of the methane reactor in a pulp preparation tank (0.5 m^3) so that it could be pumped automatically by an eccentric screw pump supplied by an auger. This proved to be impossible in practice, since the auger did not work properly with SBP. Therefore a second eccentric screw pump, feeding directly into the internal recirculation pipe, had to be installed and fed manually with SBP every 2 hours. Temperature was at 37°C, pH-value was measured three times a day to check process stability. Concentration of total VFA was daily checked by titration and used as control parameter. Biogas was measured by a gas flow meter. Samples of influent and effluent of each reactor were analysed once a week. Influent TS and VS of fresh SBP were daily measured to monitor fluctuations in SBP composition. The daily influent COD-load was calculated using the COD/VS-ratio of the weekly analyzed samples, which was 1.2 for fresh SBP and 1.4 for silaged SBP.

Analyses

COD, COD_{diss}, TKN, NH_4-N, P_{total}, PO_4-P, TS and VS of influent and effluent were regularly analyzed according to German Standard Methods for Water, Wastewater and Sludge Analysis (DIN, 1989). Samples for dissolved

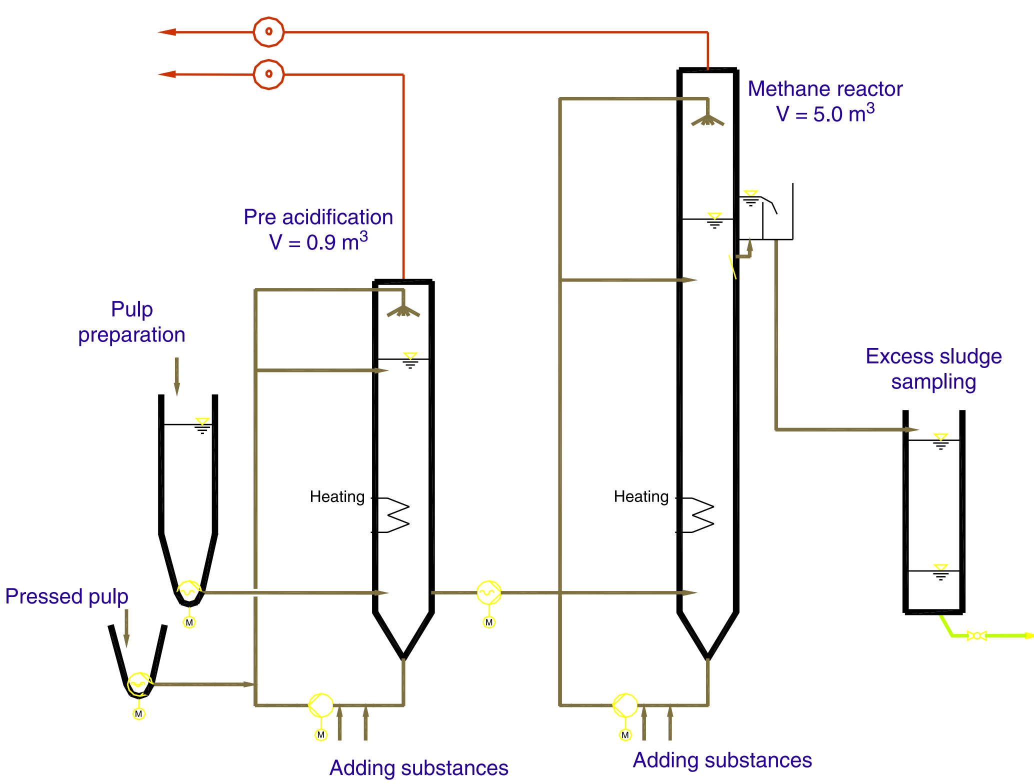

Figure 1 | Pilot plant No. 1, two-stage digestion process with pre-acidification.

parameters were centrifuged and filtered (0.45 μm) immediately after sampling and stored at 4°C no longer than 24 h until chemical analysis. Volatile fatty acids (VFA) were analysed with High Performance Liquid Chromatography. Total VFA were also measured using the titration method (Götzendorfer 1989). The concentration of the VFA was quantified as COD equivalents of acetic acid. Concentration of methane (CH_4), carbon dioxide (CO_2), oxygen (O_2) and hydrogen sulphide (H_2S) in the biogas were measured once a week by infrared method (model GFM 420, ISS): Additionally, at pilot-scale, CO_2 was measured daily in all reactors using short-term test tubes (Dräger).

Evaluation method of analytical results

Analytical results were checked by mass balances for appropriate parameters as COD and total phosphorus over periods with steady state conditions. COD indicates the amount of oxygen needed to completely oxidize the organic compounds in the analyzed sample. It represents the reduction equivalent of the organic matter and can be directly related to its energy content. The influent COD, which has been degraded in the anaerobic reactor, is converted to methane gas. Theoretically 350 NL of methane are produced per kilogram of degraded COD. When COD concentration, influent load (kg SBP/d) and methane production are correctly measured, the COD load (kgO_2/d) of the influent has to be equal to the sum of the COD of the effluent and the produced methane per day: $COD_{influent} = COD_{methane} + COD_{effluent}(kg\ O_2/d)$.

Due to the high COD concentration of SBP the percentage of dissolved methane lost via the effluent is negligible (<1%).

RESULTS AND DISSCUSION

Two-stage process configuration

Two-stage configuration was first tested at lab-scale in 2 parallel operated plants from April until July 2006. The SRT in the pre-acidification reactor was set to 5 days with a COD volumetric load (B_v) of 14 kgCOD/(m^3·d). pH-value was varied to optimize the process. At the beginning caustic soda (NaOH) was added to maintain a pH-value of 5. Under these process conditions approximately 55% of VS was converted into VFA, mainly acetic (46%), propionic acid (37%) and butyric acids (16%). This agrees with results of Stoppok & Buchholz (1985) indicating that acetic and propionic acids and not butyric acid are the end products of the mesophilic pre-acidification of SBP at 11–16 kgCOD/(m^3·d) and at a pH-value of 6.2–6.8. The COD of the VFA corresponded to 75% of the dissolved COD. Without NaOH addition the pH-value dropped to 4.2 and part of the effluent of the methane reactor had to be recycled (recycle ratio: 25%) to ensure a stable acidification process and a high buffer capacity (SRT 4d). Despite, the VS-degradation efficiency decreased to 45% (Table 2). Under these conditions butyric acid production ceased and propionic acid decreased significantly (16%). COD-removal in the mesophilic pre-acidification reactor was, depending on the pH-value, between 7 and 11%. Accuracy of COD mass balances was satisfying (92–98%), considering the heterogeneity of the SBP as well as of the anaerobic sludge, which made sampling and analysis difficult.

In a second acidification reactor temperature was increased from 38°C to 55°C to accelerate hydrolysis. VS-degradation declined to <20% at 14 kg COD/(m^3·d) and at pH-value of 4.8. To supply the reactor with active acidification bacteria, sludge from the second stage was inoculated several times. Thus no distinctive thermophilic biocenosis could develop within a period of 100 days and VS degradation stabilized at a value of only 35%. A COD mass balance could not be verified due to irregular loading and gas production.

The methanogenesis in the second-stage was efficient as long as the acidification process in the first stage remained stable. B_v in the methane reactor was 3 kgCOD/(m^3·d) (SRT 20 d) and pH value 7.4.Further VS-degradation referred to influent SBP accounted for 30%. The overall VS and COD-degradation of the two-stage process in lab-scale was 84% and 74% respectively (Figure 2). Total gas production averaged 430 NL per kg COD of influent SBP (or 520 NL/$kgVS_{SBP}$). CH_4 content in methane reactor was 60%. Pilot-scale experiments of Hutnan *et al.* (2001) achieved a specific biogas production in methane reactors of 400 to 500 NL/kg VS_{SBP} by treating sugar beet pulp in a two stage configuration at B_v of 10–12 kgCOD/(m^3·d) (CH_4 content: 65%).

Table 2 | VS- and COD-removal efficiency of the pre-acidification stage at different pH-values (results of mass balances for periods in steady state)

pH-value	B_v kgCOD/(m^3·d)	VS-removal (%)	COD-removal (%)	COD-Balance recovery (%)*	VFA (mgCOD/L)
5.2	14	55	11	92	21,450
4.7	15	47	8	93	20,200
4.2	17	45	7	98	13,100†

*($COD_{effluent} + COD_{CH_4+H_2}$)/$COD_{influent}$ × 100.
†VFA concentration at pH 4.2 without dilution due to recycled methanogenic sludge.

VFA concentrations were 80 mg/L acetic acid, 95 mg/L propionic acid and 45 mg/L butyric acid. COD-removal efficiency of the two-stage plant in pilot-scale could not be evaluated, because the process did not achieve steady conditions due to technical problems of mixing and pumping of silaged SBP. Municipal digested sludge showed to be suitable seed sludge for both pre-acidification and methane production.

Instability of pre-acidification in the first-stage caused accumulation of VFA in methane reactors. A similar case was observed by Moser (1982) by the anaerobic treatment of wastewater from the citric acid production (Svardal *et al.* 1993). This may be a result to the higher pH-value for acidification in the methane reactor as suggested by Kunst (1982) and Zötemeyer *et al.* (1982).

Single-stage process configuration

Starting in January 2007, the two lab-scale methane reactors were further operated in single-stage for a mesophile anaerobic digestion of SBP. In April 2007 a third mesophile methane reactor was started-up with a different seed sludge – anaerobically digested sludge from the

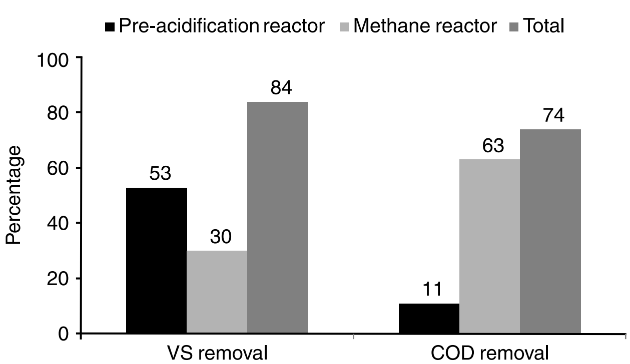

Figure 2 | Removal efficiency of VS and COD in the two-stage configuration.

municipal WWTP of Budapest – to prove whether this sludge would be a suitable inoculum for the large-scale biogas plant. After an acclimatisation of a couple of weeks, B_v was raised in lab-scale methane reactors stepwise from 1.4 (SRT 210d) to 10.3 kg COD/(m^3·d) (SRT 25 d), with a daily increase of 7% (Figure 3). At B_v higher than 5.5 kg COD/(m^3·d) foaming developed in the reactors, which could be controlled by adding anti-foam agents. Process stability deteriorated above 8.5 kg COD/(m^3·d) (SRT 28 d) with accumulation of VFA, mainly acetic and propionic acids. COD-loading was therefore reduced and kept below this level.

Anaerobically digested sludge from the WWTP of Budapest proved to be a suitable inoculum for the degradation of SBP in lab-scale, despite the high ammonium concentrations which fluctuate between 1,700 and 2,500 mg NH_4-N/L due to the co-digestion of slaughterhouse offals at the WWTP. No inhibition of the anaerobic process could be observed at an initial concentration of 1,800 mgNH_4-N/L corresponding to 50 mg NH_3-N/L at pH-value of 7.5. According to experiments of Kroiss (2005), ammoniac concentrations at this level could already affect acetate degrading methane bacteria. With the incorporation of nitrogen into the new developed biomass, the NH_4-N concentrations dropped to lower values of about 300–400 mgNH_4-N/L after the start-up, depending on B_v applied.

At single-stage in pilot-scale, B_v was also daily increased by 7% from 0.13 to 12.8 kgCOD/(m^3·d). The higher load achieved in pilot-scale as compared to lab-scale can be ascribed to the semi-continuously loading of SBP (every two hours) to the discontinuous feeding at lab-scale (once a day). Foaming could be controlled by pumping sludge from the bottom to the top of the reactor and by spraying it on the sludge surface. At B_v > 10 kg COD/(m^3·d) or in case of

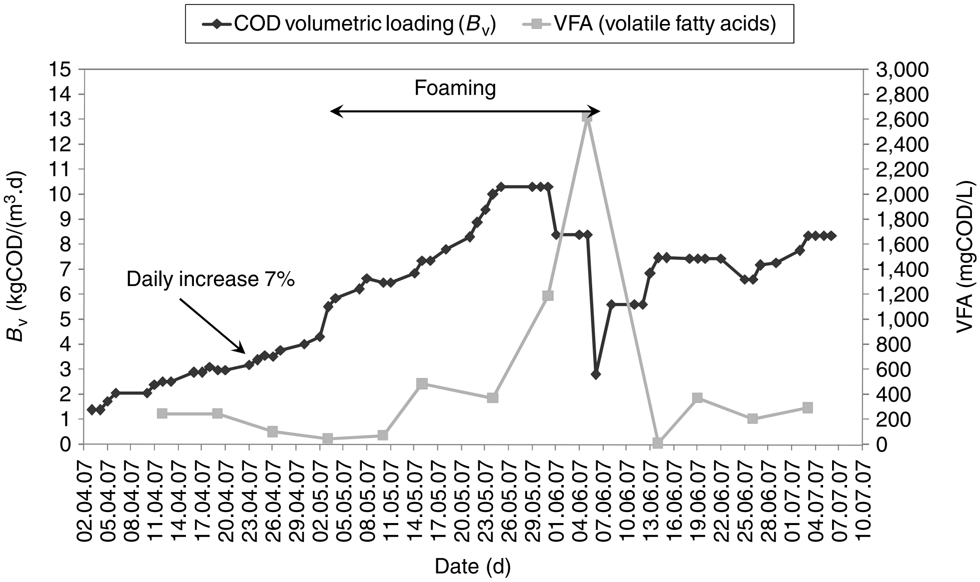

Figure 3 | B_v increase and VFA concentrations in the single-stage lab-scale methane reactor seeded with digested sludge from Budapest's WWTP and fed with silaged SBP.

process instability (e.g. by nutrients limitation) anti-foam agents had to be added. Maximum B_v achieved under stable methane production was 10 kg COD/(m^3·d) (SRT 22 d).

VS and COD removal efficiency at 8 kg COD/(m^3·d) in lab-scale reactors was 81% and 77% respectively. Table 3 shows average values of degradation efficiency for time intervals under different process conditions. Thus the single-stage configuration achieved degradation results comparable with the two-stage process (Figure 2). In Figure 4 degradation efficiency of VS in single-stage configuration (Table 3) is plotted in relation to B_v. A certain depletion of COD-degradation efficiency with rising B_v can be observed. In pilot-scale at higher B_v (11 kg COD/m^3·d) removal of VS (76%) and COD (72%) was slightly lower. It remains uncertain if the mincing of SBP also contributed to the higher degradation efficiency achieved at lab-scale.

Under stable process conditions VFA-concentrations in the effluent sludge were low in both scales with 20 to 50 mg/L acetic acid and 15 to 55 mg/L propionic acid. pH-value averaged 7.2, TS-concentration 5 to 6%.

Table 3 | Degradation efficiency of VS and COD in single-stage methane reactors in lab-scale as well as in pilot-scale under different process conditions (results of mass balances and average values for experimental periods in steady state conditions)

Single-stage configuration	B_v kgCSB/(m^3·d)	VS-removal (%)	COD-removal (%)	COD-Balance recovery (%)
Lab-scale, silaged minced SBP, SS-A	5.6	83	77	97
Lab-scale, silaged minced SBP, SS-A	8.2	79	76	96
Lab-scale, silaged minced SBP, SS-A	8	81	78	96
Lab-scale, silaged minced SBP, SS-B	7.4	83	77	95
Pilot-scale, silaged SBP, SS-A	14.2	73	72.4	92.5
Pilot-scale, silaged SBP, SS-A	12.5	76	73.5	93
Pilot-scale, silaged SBP, SS-A	11	74.5	72.2	94
Pilot-scale, silaged minced SBP, SS-B	11.4	78	74.9	93.5
Pilot-scale, fresh SBP, SS-B	10	76.2	71	92.5
Pilot-scale, fresh SBP and BTL, SS-B	10.2	74.7	72.3	92

SS-A: seed sludge from municipal WWTP Wiener Neustadt (A); SS-B: seed sludge from municipal WWTP of Budapest (U).

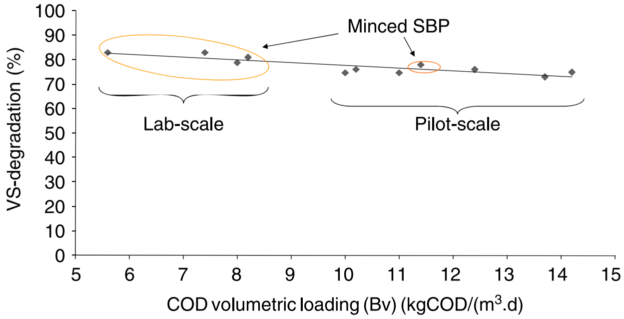

Figure 4 | TS degradation in correlation to COD volumetric load (Bv), single-stage configuration.

Average specific gas production with fresh SBP was 530 NL/kgCOD_{SBP} (or 610 NL/kgVS_{SBP}) in lab-scale and 510 NL/kgCOD_{SBP} (or 580 NL/kgVS_{SBP}) in pilot-scale (CH_4: 50–53%). Specific methane production per COD_{SBP} was the same as with silaged SBP. Due to the higher content of sugar in fresh SBP the shift from silaged to fresh SBP has to be performed gradually to allow adaptation of the micro-organisms to the new substrate. At pilot-scale foam developed when sugar was added to simulate a sudden change in substrate. With the co-digestion of beet tails and leaves (BTL) at pilot-scale, similar degradation efficiency and specific biogas production were achieved (Table 3). COD of BTL was about 20% of the total COD in the influent.

During the long-term operation of lab-scale and pilot-scale plants, a lack of nutrients and trace elements was observed in the SBP, which led to instability of the process and accumulation of VFA at higher B_v. Growth limitation of anaerobic bacteria first appeared when the pool available in the municipal seed sludge was depleted.

Implementation of the first large-scale plant

Although both process configurations achieved similar degradation results and biogas production, the two-stage treatment process showed certain disadvantages concerning the handling with the fermented SBP (mixing and pumping at TS $>$ 7%) and the costs for pH-control above 4.8 (NaOH addition). Additionally, investment costs would be higher with a pre-acidification tank, control and operation of the plant more complex.

According to the results of the research project, the biogas plant was designed as a single-stage configuration for 800 t SBP/d (22%TS), with 2 cylindrical reactors of 12,000 m^3 anaerobic sludge volume each and a volumetric COD-load of 8.5 kg COD/(m^3·d) each (SRT: 30 days). Under these conditions a stable biogas production of 4.3 Nm^3 biogas/m^3 digester volume per day can be expected (52% CH_4). The plant was put into operation at the beginning of October 2007 and met all the expectations derived from the experiments during the first sugar processing period. At the end of the production 2007 total SBP loading in the two reactors could be even raised above the design-value to 9.3 kg COD/(m^3·d), corresponding to 700 t SBP/d and 225 t BTL/d. Biogas production increased to 125,000 m^3/d (52% CH_4) and could substitute 44% of the natural gas demand of the sugar production process. Digester effluent was mixed and settled with the mud from beet washing; the separated wastewater was treated in the existing wastewater treatment plant system (aerated ponds) of the sugar factory.

CONCLUSIONS

Experiments at lab-scale as well as at pilot-scale proved that sugar beet press pulp is a suitable substrate for biogas production. Degradation efficiency in single-stage configuration was depending on the COD load 76–81% for VS and 72–77% for COD. Average specific gas production reached 530 NL/kgCOD_{SBP} or 610 NL/kgVS_{SBP}. (CH_4: 50 to 53%). Both single-stage and two-stage process configurations showed similar removal efficiency. Thus the single-stage process results in lower investment and operation costs and is easier to operate. Based on the experimental results, the first large-scale biogas plant (24,000 m^3 reactor volume) was built on the premises of a Hungarian sugar factory and put into operation during the sugar processing period of 2007, where the SBP load (9.5 kgCOD/m^3·d) of up to 900 t/d could be obtained. Maximum biogas production was 125,000 m^3/d (52% CH_4) and substituted 44% of the natural gas demand for sugar production. Biogas production of SBP enables savings in energy consumption and significant reduction of treatment costs for SBP and can therefore contribute to a more competitive sugar production from sugar beets.

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