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Continuous biogas production from sugarcane as sole substrate

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Abstract

A German–Brazilian research project investigates sugarcane as an energy plant in anaerobic digestion for biogas production. The aim of the project is a continuous, efficient, and stable biogas process with sugarcane as the substrate. Tests are carried out in a fermenter with a volume of 10 l.

In order to optimize the space–time load to achieve a stable process, a continuous process in laboratory scale has been devised. The daily feed in quantity and the harvest time of the substrate sugarcane has been varied. Analyses of the digester content were conducted twice per week to monitor the process: The ratio of inorganic carbon content to volatile organic acid content (VFA/TAC), the concentration of short-chain fatty acids, the organic dry matter, the pH value, and the total nitrogen, phosphate, and ammonium concentrations were monitored. In addition, the gas quality (the percentages of CO₂, CH₄, and H₂) and the quantity of the produced gas were analyzed.

The investigations have exhibited feasible and economical production of biogas in a continuous process with energy cane as substrate. With a daily feeding rate of 1.68 gVS /l*d the average specific gas formation rate was 0.5 m³/kgVS. The long-term study demonstrates a surprisingly fast metabolism of short-chain fatty acids. This indicates a stable and less susceptible process compared to other substrates.

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Keywords: Anaerobic digestion; Biogas production; Continuous tests; Space–time load; Sugarcane

1. Introduction

A shortage of fossil resources is expected in the near future, thus a switch to alternative, renewable raw materials is inevitable. Alternative energy sources must also be found in the future for synthesis gas (syngas), which is frequently utilized in the chemical industry and is produced by steam reforming of crude oil [1]. Currently, the

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largest producer of nickel and cobalt in Brazil requires more than 60,000 tons of syngas per year. This corresponds to a CO₂ equivalent of 190,000 tons per year from fossil sources. Biogas is one promising alternative renewable resource that could be implemented for syngas production. Due to its tropical climate, the partner country, Brazil, boasts high potential for biomass production [2]. In particular, sugarcane is cultivated in large quantities in Brazil and can be utilized as a raw material or for the provision of energy [3]. The overriding objective of this project is the sustainable production of syngas from the methane produced by the anaerobic fermentation of sugarcane.

The project, named “ProBioSyn-Provision of biogas for synthesis gas production by anaerobic digestion of energy cane”, was funded by the Federal Ministry of Education and Research [031B0172A] and addresses thematically an efficient and stable biogas production process based on energy cane. Previously implemented projects have approached biogas production from sugarcane waste [4] or utilization of pentoses from sugarcane biomass for biogas or butanol production [5]. They have shown that the straw from sugarcane has a specific methane production rate of 0.22 m³/kg_{Vs}, the bagasse 0.28 m³/kg_{Vs}, and the filter cake 0.25 m³/kg_{Vs} [6]. Continuous fermentation of sugarcane waste has resulted in a maximum space–time load of 2.5 g_{Vs}/l*d, at which a stable process is still possible [6].

The focus in this project is the consideration of the sugarcane species *Saccharum complex* (energy cane/*cana energia*), as it offers an above-average yield per area. In contrast to established applications for biogas production from residues of sugar or bioethanol production (bagasse), for this project, the whole plant was appropriated as a substrate. The aim of this research is the optimized production of biogas from the whole plant of the previously unknown substrate energy cane. This paper presents the results of continuous fermentation on a laboratory scale. On the basis of the results obtained, the existing biogas technology, which has, to this point, been primarily designed for European substrates such as maize silage or manure, may be adapted for operation with sugarcane.

2. Material and methods

The continuous fermentation in laboratory scale was performed in a reactor with a loading volume of 10 l. The reactor is a modified continuous stirred-tank reactor composed of stainless steel manufactured by Bioprocess Control AB, Sweden. The modification consists of an enlarged drain pipe with an inside diameter of 35.6 mm. The fermenter is heated by an external water bath, and the produced gas is collected in a gas bag. The amount of gas is measured with a MilliGascounter manufactured by RITTER.

To start the biogas processes, 4.5 liters of inoculum and 4.5 liters of water were added to the fermenter and mixed. The inoculum utilized was fermentation residue from a large plant operated with 30% liquid manure and 70% maize silage. Inside the fermenter, the mixture was continuously stirred and heated to 40 ° C. The feeding substrate (energy cane) was added with a space–time loading rate of 0.39 g_{Vs}/l*d. Subsequently, the space–time load was increased to 0.8 g_{Vs}/l*d. The start-up phase was completed within 40 days.

The substrate utilized for the continuous laboratory test in the start-up phase was fresh energy cane, which was cut into 1 cm pieces with scissors. During the continuous phase, ensiled energy cane was utilized, which was shredded into 3 mm pieces. The ensiling occurred in large canisters at 20 ° C. To ensure the absence of air the substrate was compressed and the canister was closed. The ensiling was carried out over a period of six months. The canister was opened only for the withdrawal of the quantities to be fed. During the later continuous phase, fresh energy cane was utilized, which was frozen for storage. This was also shredded into 3 mm pieces. The energy cane used has an average dry matter of 30.1% and organic dry substance of 28.1%.

During the continuous phase, the space–time load was constantly increased in order to achieve the load limit. After a three-week stable process, the space–time load was increased by 0.25 g_{Vs}/l*d. Regular process control was conducted to emphasize the stability or existing over-acidification. If acidification was present, the room time load was reduced or temporarily suspended.

The analyses performed included standard analyses, such as dry matter, organic dry matter, VFA/TAC by automatized titrator (HACH, Germany), pH, the gas quality in form of percentages of CO₂ and CH₄ (by Multitec 540 of SEWERIN) and short-chain fatty acids (acetate, propionate, isobutyrate, butyrate, isovalerate, valerate, hexanoic acid by the gas chromatograph). ammonium, total nitrogen, and total phosphate concentrations were measured photometric with a standard kit manufactured by Hach. Analyses of the digested residue were performed twice a week and gas composition was measured daily.

Table 1. Values of parameters of the inoculum.

Parameter	Average value
Dry matter [%]	7.36
Organic dry substance [%]	5.5
pH	7.9
NH ₄ -N [g/l]	1.7
Acetate [mg/l]	7

3. Results and discussion

3.1. Start-up phase

The average parameters of the inoculum utilized are provided in Table 1.

The start-up phase of the biogas building process is presented in Fig. 1. The graphs of the individual parameters describe a stable process. With a space–time load of 0.39 g_{VS}/l*d energy cane, the specific gas production rate differed between 0.5–1 m³/kg^{VS}. The daily gas production rate differed and decreased despite increasing feeding from test day 29 onward. The average values of the residue were: pH 7.8, FOS/TAC 0.16, dry matter 3 %, organic dry matter 2.9%, acetate 140 mg/l, and propionate 20 mg/l. The gas quality was measured as a percentage of CO₂ and CH₄. During the initial phase, the proportion of CO₂ was approximately 25–35 %, and CH₄ was approximately 50–60 %. After 39 days of the conversion phase, a lack of C-sources was suspected, because specific gas formation rate decreased although the feeding was increased; thus the start-up phase was terminated, and the space–time load was increased.

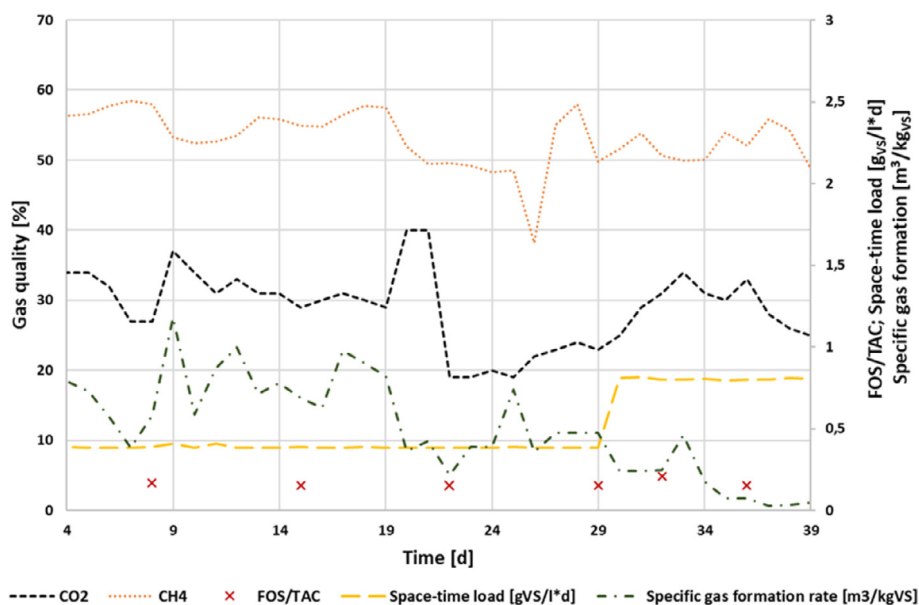


Fig. 1. Progression of the gas quality of CO₂ (black) and CH₄ (orange), the space–time load (yellow), and the specific gas formation rate (green) during the start-up phase. The FOS/TAC is represented by crosses on the respective analysis days.

The change of the previously utilized substrate of inoculum from corn and manure to sugarcane worked well. Due to the low space–time loads, the microorganisms were able to successfully adapt to the new nutrient composition. Gas was produced from the beginning. The production rate was low and subject to strong fluctuations. These factors may be explained by the different composition of the substrate supplied daily, which sometimes contained more wooded material. The FOS/TAC and the concentration of the fatty acids were low, thus creating a stable process in which the added carbon sources could be rapidly converted. The variations in gas quality were in the respective

percentage ranges. Over-acidification did not occur; therefore, the low space–time loads could be increased after 29 days.

3.2. Continuous phase

After the start-up phase, the continuous test phase could commence. Various factors were identified to ensure a stable process. Sufficient solids had to be removed during sampling to avoid an accumulation of solids which would lead to regular overloading of the process. This overloading manifests itself in over-acidification and lack of gas formation. In addition, it was necessary to grind the sugarcane fibers as small as possible, because longer fibers wrapped itself around the agitator shaft and prevented sufficient stirring. The accumulation of indigestible fibers inhibited the biogas production, presumably by hindering the microbial metabolism. If the substrate was overly dry, water had to be added during daily feeding to maintain an optimal process and avoid dehydration. If these conditions were met, and a sufficient and concurrently appropriate space–time load was chosen, then a stable fermentation process could be achieved and maintained in the long term. Fig. 2 illustrates a stable fermentation process based on energy cane.

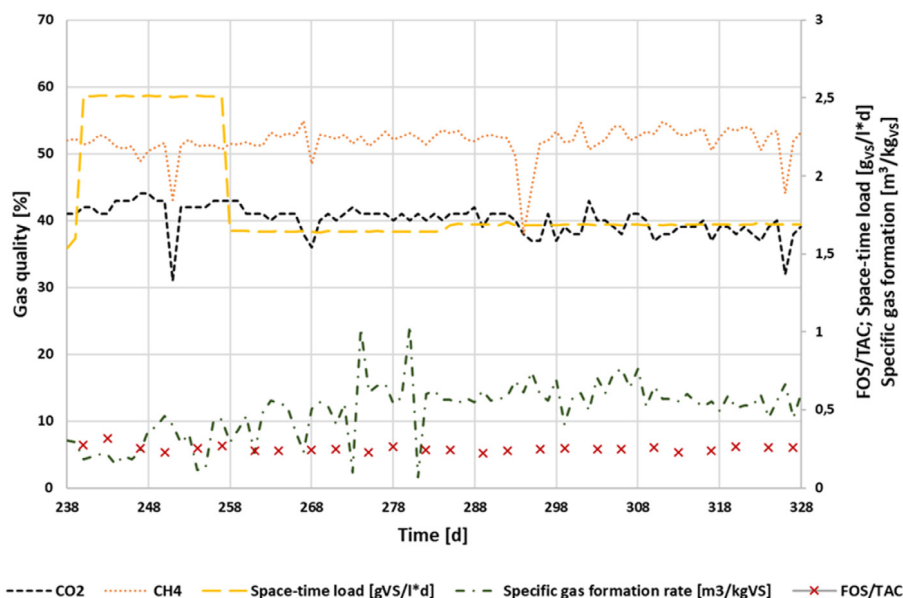


Fig. 2. Progression of the gas quality of CO₂ (black) and CH₄ (orange), the space–time load (yellow), and the specific gas formation rate (green) during the continuous phase without acidification. The FOS/TAC is represented by crosses on the respective analysis days.

With a space–time load of 2.51 g_{VS}/l*d, the process was permanently overloaded. The FOS/TAC was approximately 0.27, but the acetate concentration rose to 1364 mg/l (not pictured). The specific gas formation rate was below 0.5 m³/kg_{VS}. Since high acetate concentration would lead to acidification, the space–time load was reduced to 1.64 g_{VS}/l*d on day 258. At this value, the process maintained stability from trial days 258 to 328. The FOS/TAC was constant at 0.25, which indicates a stable process. The specific gas formation rate reached 1 m³/kg_{VS}, and the gas quality corresponded to a percentage of 40% CO₂ and 52% CH₄.

In order to investigate the maximum space–time load of the process, a daily space–time load of 1.8 g_{VS}/l*d was applied from test day 421, despite an already increasing FOS/TAC (Fig. 3).

After 20 days with a space–time load of 1.8 g_{VS}/l*d, the FOS/TAC rose to 1.08. After another eight days, the system was able to reduce this to 0.94 despite further daily feeding. The gas composition fluctuated strongly during the overfeeding phase: The CH₄ and CO₂ building rates decreased with increased FOS/TAC. The CH₄ differed daily between 35 % and 59 %, and CO₂ decreased from 40 % to 25 %. Fluctuations of this kind do not occur in a stable process. The specific gas formation rate was constantly below 0.5 m³/kg_{VS}.

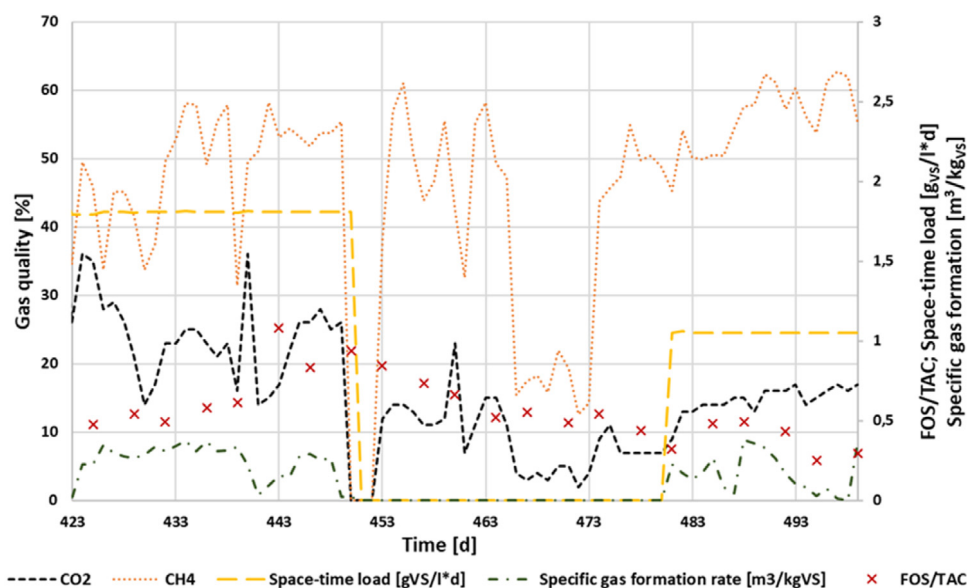


Fig. 3. Progression of the gas quality of CO₂ (black) and CH₄ (orange), the space–time load (yellow), and the specific gas formation rate (green) during the continuous phase with acidification. The FOS/TAC is represented by crosses on the respective analysis days.

In order to prevent a decline in the population of microorganism, feeding was terminated on trial day 450. After an interruption of feeding, the FOS/TAC normalized within 30 days to a value of 0.32. The specific gas formation rate during the feeding break is indicated with 0 m³/kg_{VS}. Since the specific gas formation rate refers to the feeding rate, and no feeding occurred from day 451 to 480, this is a constant zero in Fig. 3. Nevertheless, a daily gas formation transpired, so that the gas quality could still be measured. CH₄ ranged between 0 % and 61 %, and CO₂ ranged between 0 % and 22 %.

After stabilization of the process, the space–time load was increased to 1.05 g_{VS}/l*d. The continuation of the feeding led to an improvement of the biogas quality; its values were 10 %–20 % CO₂ and 50 %–63 % CH₄. The specific gas formation rate did not exceed 0.5 m³/kg_{VS}. A pH value of 7.7 was not undershot during the entire period. The quick regeneration after acidification and the constant pH value indicate a pleasing buffer capacity.

The maximum space–time load of the process at laboratory scale under stable conditions was determined by continuously increasing the feeding. This procedure has confirmed that a space–time load of 1.68 g_{VS}/l*d is optimal. It requires the previously described procedures, such as special sampling, water addition, and substrate grinding to be considered. The additional expense of sampling and grinding the substrate on a large scale would lead to low economic efficiency. However, the problem likely will not be present on a large scale, as the pipelines are sufficiently sized to remove larger fibers from the fermenter. Additionally, the size of the agitator shaft should prevent the sugarcane fibers from wrapping around it. The rapid system overload, which leads to a low gas formation rate, may be due to nutrient deficiency. Whether the nutrient deficiency is responsible for inhibition of the microorganisms will be confirmed by initial investigations.

4. Conclusion

The highest specific gas formation rate that was achieved with the space–time load of 1.68 g_{VS}/l*d was 1 m³/kg_{VS}. The average specific gas formation rate was 0.5 m³/kg_{VS}. Batch tests performed simultaneously with the same substrate demonstrated higher specific gas yields (0.55 m³/kg_{VS}). As previous investigations have confirmed, sugarcane waste can achieve specific gas formation rates of up to 0.28 m³/kg_{VS} [6]. By the fermentation of the entire energy cane plant, the same amount of methane is produced as by the fermentation of sugar cane waste. With regard to maize silage, which has a specific biogas production rate of 0.8 m³/kg_{VS}, the profitability of energy cane is lower.

The tests performed have proven that continuous fermentation of energy cane on a laboratory scale is possible with a maximum space–time load of 1.68 g_{VS}/l*d. A higher feeding rate is possible for only a short time and leads to acidification in the long term. After interrupting the additional feeding, rapid degradation of the fatty acids and normalization of the FOS/TACs could be observed; thus an optimal buffer capacity could be proven in this process. The reason for this finding has not yet been determined. Previous laboratory tests with sugarcane waste have achieved a maximum space–time load of 2.5 g_{VS}/l*d [6]. As it is a high caloric substrate with a high concentration of rapidly available sugars, a lower space–time load compared to sugar cane waste is plausible. Lower possible space–time loads with energy cane may be due to a lack of nutrients, thus tests are already being performed adding nitrogen, phosphate and trace elements to the fermenter.

Regular removal of solids and small fibers, as well as a sufficient supply of water, must be ensured on a laboratory scale. The existing laboratory scale problems, except the addition of water, will not be significant on a large scale. Therefore, the technical implementation of energy cane fermentation would be possible by shredding to a size of 0,5 - 3 cm.

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