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Year-round biogas production in sugarcane biorefineries: Process stability, optimization and performance of a two-stage reactor system

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ABSTRACT

The concept of year-round biogas production to increase the capacity factor of anaerobic digestion (AD) plants in sugarcane biorefineries was investigated for the first time in semi-continuous feeding mode. To simulate the use of sugarcane vinasse during the sugarcane season and sugarcane filter cake (SFC) during the off-season period, a two-stage reactor system based on an acidogenic continuous stirred-tank reactor (1st stage) followed by solid–liquid separation and an upflow anaerobic sludge blanket (UASB) reactor (2nd stage) to convert the COD-rich liquid fraction into biogas was operated. Additionally, to optimize the biogas production from SFC, the effects of its thermo-chemical pre-treatment on AD were investigated in a parallel reactor set-up. The saponification effect provided by autoclaving the substrate with sodium hydroxide improved the hydrolysis/fermentation of SFC in the acidogenic reactor, which in turn resulted in a 28% higher volumetric methane production in the methanogenic reactor ($p < 0.05$). However, the methane yields observed during operation of the two-stage reactor system were markedly lower than previously found in biochemical methane potential tests using SFC. In this case, the feed-in with low suspended solids required by UASB reactors prevented the utilization of the non-hydrolyzed/fermented solid fraction of SFC (> 60% of the substrate's methane potential). Nevertheless, the capacity factor of the AD plants in sugarcane biorefineries could be increased from 0.55 up to 0.69 when considering a 200 d a^{-1} sugarcane season (0.66–0.83 for a longer season of 240 d a^{-1}), representing an increase of 25.7%. The average capacity factor for biogas combined heat and power and upgrading units of around 0.91 (8000 h a^{-1}) would be reached if further developments could improve the solubilization of non-hydrolyzed/fermented solids or alternatively allow their direct use in the methanogenic reactor.

1. Introduction

The anaerobic digestion (AD) process has been proven to be an alternative biomass conversion pathway to diversify the product portfolio of sugarcane biorefineries by recovering methane-rich biogas, promoting sustainable waste management practices and reducing greenhouse gas emissions that usually occur during temporary storage, transportation and application of sugarcane waste to the soil for water and nutrient recycling [1–3].

Among the different types of waste generated during sugarcane processing, sugarcane vinasse (SCV) and filter cake (SFC) are the most suitable substrates for biogas production due to their high availability, relatively easy degradability and favorable balance of nutrients. In addition, no competition with the current practice of soil application would occur, since the AD process is able to maintain the mineral content of the biomass in form of digestate allowing its proper use as organic fertilizer [4].

However, the seasonal characteristic of sugarcane crop limits the availability of the substrate to around 200–240 days per year, which in turn results in an energy system with a low capacity factor if SCV and SFC would be used for biogas production only during the sugarcane season. The low incentives to produce bioenergy in countries like Brazil (major sugarcane producer) and the insufficient profitability of the biogas projects with such characteristics has not encouraged the adoption of the AD technology by the sugarcane biorefineries in the recent years.

In countries like Germany supporting the AD of energy crops, such as maize, sugar beet, and grass, the biomass naturally containing

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moisture is harvested and conserved/stored by ensiling to be used as substrate throughout the whole year. This concept allows the operation of AD plants at an average capacity factor of around 0.91 (8000 h per year) often achieved by biogas combined heat and power (CHP) and upgrading units [5]. Thus, the profitability of biogas projects is improved since a major share of the capital expenditures (20–45%) of an agricultural AD plant is derived from the post-biogas producing facilities [6].

The concept of using SCV during the sugarcane season and conserving/storing SFC to be used as substrate during the off-season period was previously assessed by our research group based on biochemical methane potential (BMP) tests [7]. Despite the differences in methane potential between SCV derived from annexed and autonomous biorefineries (4.1–5.7 $m^3\,CH_4\,t_{cane}^{-1}$), SFC could maintain during the off-season period up to 85.6% of the daily methane production of SCV, thus demonstrating the potential of this concept for increasing the capacity factor of an AD plant, especially when considering that some of the obligatory plant downtime for maintenance could be planned to occur during the period with less methane production [7].

However, several challenges to implement such a biogas production concept remain. Regardless of the influence that different ensiling techniques for conserving and storing SFC could have on the final methane potential, the reactor configuration plays a key role. On the one hand, for substrates with low solid content (*e.g.* SCV) usually high-rate anaerobic reactors are recommended, such as upflow anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB) or fixed bed. This is due to the fact that the immobilized biomass in form of biofilms allows shorter hydraulic retention times (HRT) resulting in lower reactor volumes. On the other hand, for substrates with high solid content (*e.g.* SFC), fully mixed anaerobic reactors are better suited, such as continuous stirred-tank reactors (CSTR), to allow a proper time to solubilize complex particulate organic matter [8].

The use of a different reactor type for each substrate in different periods of the year would simply transfer the idleness from the CHP/upgrading units to the biogas producing process, most likely not improving the profitability of the projects. One possible strategy to overcome the drawbacks of reactor configuration is the use of an UASB reactor as a high-rate anaerobic reactor for SCV during the sugarcane season and decouple the AD of SFC into two steps during the off-season period, where SFC would be initially hydrolyzed/fermented in an acidogenic CSTR at short HRT of 3–5 days followed by solid-liquid separation and the existing UASB reactor would be used as a methanogenic reactor for biogas production from the separated liquid fraction of fermented SFC.

Therefore, the concept of year-round biogas production in the sugarcane industry was experimentally assessed in the present study with the aims: (a) to investigate the process stability during gradual substrate substitution in the methanogenic UASB reactor; (b) to compare the methane potentials of different fractions of fermented SFC (liquid/solid) with values from previous studies based on BMP tests; (c) to optimize the methane production from SFC by a thermo-chemical pre-treatment method, and (d) to assess the increase of the capacity factor by using SFC as substrate during the sugarcane off-season. This approach can provide important inputs for an optimal process design leading to a more profitable utilization of these agricultural residues and thus facilitating the dissemination of the AD technology in the sugarcane sector.

2. Material and methods

2.1. Substrate and inoculum

Samples of SCV and SFC were obtained from a distillery plant in the state of Goiás (Brazil) during the 2014/2015 season, transported to Germany in sealed plastic containers and stored at 4 °C until its use. A large-scale biogas plant that uses maize silage and cattle manure as substrates provided fresh digestate, which was used as inoculum for the BMP tests and the acidogenic CSTRs. Lab-scale UASB reactors operated with SCV over 300 days provided adapted seed sludge used for the methanogenic UASB reactors [9].

2.2. Thermo-chemical pre-treatment

SFC pre-treatment was conducted in 500 mL glass flasks with an alkaline reagent concentration of 6 g NaOH/100 g SFC based on fresh matter (FM). The substrate's total solid (TS) content was 83 $g_{TS}\,L^{-1}$. SFC and NaOH solution were manually mixed and autoclaved for 30 min at 121 °C at 1 bar overpressure in a semi-automatic benchtop autoclave 2540 ML (Tuttnauer, Netherlands). After pre-treatment, SFC was neutralized with hydrochloric acid and stored at 4 °C until its use.

2.3. Semi-continuous experiment

Two lab-scale CSTRs with 5 L total volume (3 L working volume) were used as acidogenic reactors being continuously stirred (100 rpm) using a central stirrer with vertical shaped blades to reduce the formation of floating layers. Fresh digestate from the CSTRs was daily centrifuged at 17,700 × *g* for 10 min at 10 °C in a lab-scale centrifuge Sorvall RC 6 plus (ThermoFisher, USA) for solid-liquid separation. The liquid fraction (hereafter referred to as liquid SFC) was used as substrate in two lab-scale methanogenic UASB reactors with 1.5 L total volume each (1.3 L working volume). To improve the substrate contact with the granular biomass in the UASB reactors, digestate was continuously re-circulated (5 mL min^{-1}) by a peristaltic pump TU 200 (Medorex, Germany). The operation temperature in both CSTRs and in the UASB reactors was kept at mesophilic conditions (40 ± 1 °C) by recirculating hot water through the double-walled reactors. The schematic diagram of the two-stage reactor system is presented in Fig. 1.

The experiment was conducted over 75 consecutive days in three different phases to simulate the SCV substitution with liquid SFC until reaching a technical steady-state during the last phase of the experiment [10]. For comparison, both CSTRs were fed with the same feeding frequency (once per day), organic loading rate (OLR) and HRT, only differing on substrate pre-treatment (control versus experimental reactor). The UASB reactors were automatically fed (20 times per day) by using a peristaltic pump PD 5201 (Heidolph, Germany) with the same HRT of 3.4 d during the whole experiment, but differing in OLR due to the effect of organic matter solubilization provided by the substrate pre-treatment. For phase I of the experiment (days 0–12), the CSTRs were strategically fed with SFC to washout methanogens from the inoculum and to overload the reactors with organic acids. During this period, the UASB reactors were only fed with SCV to simulate the sugarcane season. For phase II (days 13–32) and phase III (days 33–75), the HRT was kept stable in the CSTRs (5 d), only differing in substrate input in UASB reactors. In this case, a gradual increase by 25% a week in SFC (fresh mass) was performed in phase II to avoid major disturbances in the microbial community due to the substrate substitution. Thus, during phase III only the liquid SFC was used as substrate in the methanogenic reactors to simulate the sugarcane offseason. For AD of SCV a combined supplementation of urea and trace elements was performed as described elsewhere [9]. The nutritional supplementation during AD of SFC was conducted in two steps: (a) during the CSTRs feeding a nutrients solution composed of 0.6 g S, 0.9 g Mn, 4.9 mg Co, 20.9 mg Cu, 16 mg Mo, 12 mg Ni, 5 mg W, 285 mg Ni and 2 mg Se per kg of TS was used and (b) during the UASBs feeding an urea solution of 2 g L^{-1} was applied. Detailed information about different feeding rates, OLR and HRT in each phase of the experiment is listed in Table 1.

2.4. Biochemical methane potential tests

The BMP of the solid digestate fraction from the acidogenic reactors (hereafter referred to as solid SFC) was determined according to VDI