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Diversifying the technological strategies for recovering bioenergy from the two-phase anaerobic digestion of sugarcane vinasse: An integrated techno-economic and environmental approach

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ABSTRACT

Technical, economic and environmental aspects of implementing two-phase anaerobic digestion (AD), i.e., acidogenic + methanogenic systems, in sugarcane biorefineries for the treatment of vinasse were assessed based on different strategies to using the hydrogen-rich biogas (biogas-H_2) generated via acidogenesis. Phase separation greatly enhanced the bioenergy recovered from vinasse AD compared with single-phase systems (methanogenic phase exclusively). The best results for generating electric energy were observed in combined cycle-based power plants that utilized biohythane (10.8 MW + 5.5 MW for the harvest and inter-harvest, respectively), which is the gaseous biofuel from blending biogas-H_2 with the methane-rich stream from the methanogenic phase (biogas-CH_4). Moreover, the results of this study indicated that scaling up two-phase AD systems is economically feasible for the treatment of sugarcane vinasse (net present value = USD 208.58–219.86 million) because a better or equivalent economic performance was attained compared with single-phase processes. Optimizing the alkalinization of methanogenic reactors strongly affected both the economic and environmental performance of the process, with better results observed with the use of low sodium hydroxide dosages (4 g NaOH kg^{-1}COD). In summary, our results highlighted that two-phase biodigestion may enhance energy production from vinasse by 20–30% without impairing the profitability of the biorefinery and could lead to slight improvements in the environmental performance of the ethanol production chain via the use of an optimized alkalinization strategy.

Abbreviations: AD, anaerobic digestion; ALO, agricultural land occupation; BFR, biogas flow rate; CB-0, reference scenario; CC, combined cycle; CE-1–CE-5, energy scenarios; CH, carbohydrate concentration; COD, chemical oxygen demand; COD_{acid}, COD of acidified vinasse; COD_{raw}, COD of raw vinasse; EC, carbohydrates; EC_{CH}, carbohydrate conversion; EEP, electric energy production; ER-COD, ER_{COD}, COD removal; EtOH, ethanol; FDP, fossil depletion potential; fCH_4, methane proportion in biogas; fH_2, hydrogen proportion in biogas; FWE, fresh water eutrophication; GHG, greenhouse gas; GTB, gas turbine; GWP, global warming potential; HTP, human toxicity potential; HY, hydrogen yield; ICE, internal combustion engine; IRR, internal rate of return; LCA, life cycle assessment; LHV, lower heating value; M, molar mass of sucrose; MARR, minimum acceptable rate of return; MY, methane yield; NPV, net present value; OLR, organic loading rate; OPEX, operational expenditure; R, ideal gas constant; STB, steam turbine; T, operating temperature; TAP, terrestrial acidification potential; TC, ton of sugarcane; TEP, thermal energy production; VFA, volatile fatty acid; VFR, vinasse flow rate; VSB, Virtual Sugarcane Biorefinery.

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1. Introduction

The concept of biorefining has recently attracted great interest in the agro-industrial sector because of the potential to expand the exploitation of raw materials by simultaneously producing different types of value-added products and/or recovering energy directly from residues [1]. Sugarcane-based sugar and ethanol plants are important examples of biorefineries based on the conversion of feedstock into sugar, ethanol, and even electricity because burning bagasse and straw in boilers may result in surplus electric energy sold to the grid [2]. Despite the efficient utilization of sugarcane in such facilities, a considerable fraction of the sugarcane energy content remains in the vinasse as residual organic matter from fermentation. Most of the organic content of vinasse is composed of easily degradable compounds, such as unconverted organic matter (residual fractions of reducing sugars and sucrose), compounds formed in competing fermentative metabolic pathways (glycerol and organic acids), and unrecovered fractions of ethanol [3].

In Brazil, sugarcane vinasse is commonly returned to the sugarcane fields via fertirrigation to recycle water and nutrients, predominantly potassium [4], to the crop. Although studies have associated beneficial results with fertirrigation [5,6], including reduced expenses from inorganic fertilizers, disposing vinasse on land may generate several negative impacts for the soil-water-plant system over the long term [4,7]. The biorefinery concept indicates that the direct land application of vinasse reflects the underuse of a highly energetic raw material because biotechnological approaches are potentially suitable for the processing of such wastewater, particularly via anaerobic processes.

Reference studies highlight the suitability of anaerobic digestion (AD) or biodigestion as the core technology for the treatment of vinasse, and they primarily focus on the reduction of organic polluting loads with bioenergy recovery through biogas production in single-phase anaerobic digesters [8–12]. Recently, research groups have also investigated the suitability of biohydrogen production from such wastewater [13–15] and proposed the operation of an acidogenic phase prior to methanogenesis. The high levels of residual sugars from vinasse may be directly fermented into hydrogen (H_2) and volatile fatty acids (VFAs) by acidogenic bacteria, which greatly increases the resource recovery efficiency in sugarcane biorefineries. In short, phase separation may be directed to the enhanced production of value-added biochemicals, which is primarily based on the recovery of VFAs, whereas bioenergy generation is maximized when the acidified effluent is applied to subsequent methanogenic reactors [1,16]. Particularly, phase separation provides a range of important benefits over methanogenic systems based on the marked improvements in the biodegradability of the wastewaters [17]. Higher process stability also leads to lower inputs of alkalizing compounds into digesters, which may directly affect the economic impact of the process [18].

Considering the suitability of two-phase AD for the treatment of vinasse, investigations are required to achieve a better understanding of the energetic potential of the H_2– and methane (CH_4)-rich biogas streams, i.e., biogas-H_2 and biogas-CH_4, respectively, resulting from vinasse biodigestion by providing the conditions for simulating scenarios in large-scale plants. The production of electricity is one of the potential uses of biogas that can maximize energy recovery [19] based mainly on the availability of consolidated efficient conversion technologies, such as engines and turbines [20]. Particularly in AD systems with phase separation, the biogas-H_2 resulting from the acidogenic step could play a key role in improving the generation of energy based on different technological approaches. Biogas-H_2 may be blended with the biogas collected from the methanogenic phase (biogas-CH_4) to form biohythane, which can improve the methane fuel properties, such as flame speed, range of flammability, and quenching distance [21]. A few recent studies have addressed the production of biohythane for bioenergy recovery from AD [22,23]. However, the energetic potential of biohythane is not addressed in detail in such cases. Another option includes the injection of biogas-H_2 into the methanogenic reactor, which represents an in situ biogas-CH_4 upgrade by increasing the CH_4 content via the conversion of H_2 and carbon dioxide (CO_2) by hydrogenotrophic methanogenesis [24,25].

In this context, this paper aims to assess different technological routes for bioenergy recovery from vinasse two-phase AD in first-generation sugarcane biorefineries based on the use of biogas-H_2 for different purposes: blending with biogas-CH_4 for biohythane production, injecting into methanogenic digesters for upgraded biogas-CH_4 production, and selling as a value-added product. Scenarios with two-phase AD without biogas-H_2 recovery and single-phase AD were also considered to assess the energy generation capacity of different prime movers, i.e., internal combustion engines (ICEs), gas turbines (GTBs) and GTBs followed by steam turbines (STBs). The influence of different alkalizing strategies in the methanogenic phase over the economic and environmental performance of the biorefinery was also assessed based on different approaches, such as the use of sodium bicarbonate ($NaHCO_3$) and sodium hydroxide (NaOH). The integration of vinasse biodigestion was compared with the usual scheme of sugarcane biorefineries in Brazil, in which vinasse is directed to fertirrigation without any processing. Experimental data from the literature [15,17,26] were used to simulate the performance of single- and two-phase AD systems, and the Virtual Sugarcane Biorefinery (VSB) methodological framework was used to compare the scenarios in terms of their techno-economic and environmental performance. The VSB is a tool developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) used to assess the technical, economic, environmental and social impacts by integrating the entire sugarcane production chain [27]. In particular, this is the first study presenting a holistic technological assessment for recovering and using H_2 in full-scale sugarcane vinasse-fed biodigestion systems, in order to investigate the competitiveness of applying phase separation compared to conventional single-phase AD layouts.

2. Methods

2.1. Scenario description and inputs for the technological assessment

The reference scenario (CB-0) considered an annexed optimized biorefinery producing sugar, first-generation ethanol and electricity from conventional sugarcane during the harvesting season. This scenario also considered the use of energy cane during the inter-harvesting period of the conventional sugarcane. The recovery of lignocellulosic material from sugarcane fields (trash) was set to 50% and 100% (the leaves and tops of energy cane are harvested together with the stalks) for the harvesting and inter-harvesting periods, respectively [28]. Table 1 presents the input parameters and production data for the optimized biorefinery, which constitutes an improved standard plant characterized by a more efficient use of steam and, consequently, lower energy consumption levels [29]. Sugar (50% of the juice), ethanol (50% of the juice + molasses) and electric energy (100% of the bagasse + 50% of the straw) are the products obtained during the harvest season. Because the higher content of reducing sugars in energy cane hinders the crystallization of sucrose, only ethanol (100% of the juice) and electric energy (from energy cane lignocellulosic material) are obtained during the inter-harvest period (Table 1).

Performance data from both single- and two-phase AD