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Designing full-scale biodigestion plants for the treatment of vinasse in sugarcane biorefineries: How phase separation and alkalinization impact biogas and electricity production costs?

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ABSTRACT

Anaerobic digestion (AD) is the most suitable approach for the management of vinasse in sugarcane distilleries because both environmental adequacy and bioenergy recovery could be achieved through biogas production. Because the literature lacks data on the implementation and operation of full-scale AD plants for enhanced energy recovery from vinasse, this study presents different designs for AD plants applied to vinasse in large-scale distilleries, considering both single- and two-phase schemes and different alkalizing strategies. Investment and operating costs and biogas and electricity production costs were obtained for each case. The results indicate that phase separation is economically feasible when scaling up AD plants in biorefineries. Despite the higher capital and operating costs in such schemes, the estimated biogas and electricity production costs reached equivalent or lower values compared with those of single-phase AD layouts, depending on the alkalizing strategy used. With respect to the alkalizing strategy, the best results were associated with sodium hydroxide dosing and/or effluent recirculation, with electricity costs reaching values 1.8- to 2.3-fold lower than grid electricity. In contrast, the competitive use of sodium bicarbonate in AD plants for treating vinasse requires further dosing optimization.

1. Introduction

The proper management of vinasse is one of the major issues facing sugarcane-based ethanol biorefineries due to environmental concerns associated with fertirrigation, the main technological approach used in the sucro-alcohol industry (Fuess and Garcia, 2014). The process constitutes the direct land application of in natura vinasse into sugarcane fields to recycle nutrients and water to the crop (Dias et al., 2015). Although such a practice reduces the input of mineral fertilizers, which also enhances economic benefits, the continuous, long-term land application of vinasse has been frequently associated with the lack of proper technical expertise and tends to reduce crop yields, the productive capacity of soils, and even the quality of surrounding water bodies (Fuess and Garcia, 2014). Additional drawbacks from fertirrigation include bioenergy losses due to the uncontrolled conversion of organic matter by soil microbial populations, which also enhances the

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emission of greenhouse gases, such as nitrogen oxides and methane (Oliveira et al., 2013).

Anaerobic digestion (AD), or biodigestion, is considered one of the most suitable technological approaches to the management of vinasse in biorefineries because both environmental adequacy and bioenergy recovery could be achieved through the controlled conversion of organic matter into biogas without significant losses in the fertilizing potential of vinasse (Fuess and Garcia, 2015; Moraes et al., 2015; Ryan et al., 2009). A large number of studies have investigated the application of AD to sugarcane vinasse (Bories et al., 1988; Costa et al., 1986; Craveiro et al., 1986; Ferraz et al., 2016; Fuess et al., 2017; Kumar et al., 2007; Siqueira et al., 2013; Souza et al., 1992) in an effort to optimize treatment performances by applying different reactor configurations and operating strategies. However, most studies have been based on lab-scale conditions; few have addressed pilot- to full-scale systems. The scale-up of efficient anaerobic systems is imperative for identifying operating drawbacks and for precisely assessing the energetic potential of the biogas from sugarcane vinasse.

Due to the expected increased demand for ethanol, decision makers in the sucro-energetic sector should be supplied with detailed technical and economic information on the implementation of full-scale AD systems in biorefineries for the efficient exploitation of vinasse as fertilizer and feedstock for bioenergy recovery. In this context, the design of biodigestion plants for ethanol biorefineries should be highlighted due to various means for enhanced bioenergy extraction from vinasse. Two major aspects are addressed in this study: phase separation applications in AD plants, i.e., uncoupling acidogenesis from methanogenesis, and assessments of different alkalizing strategies for stable conversion processes.

Regarding phase separation, studies have indicated that the pre-acidification of organic matter-rich effluents may lead to several advantages in methane production and treatment performance. Hydrolysis steps could be enhanced during the acidogenic phase by applying sufficient residence times in digesters (Hallenbeck, 2009). This would improve the biodegradability of complex organic matrices, such as vinasse, in the methanogenic phase (Ke et al., 2005). Greater process stability and energy yields would also result from phase separation, because methanogens would be less exposed to the negative effects of acid accumulation (Ferraz et al., 2016; Yu et al., 2015). This would also lead to lower alkalizing compound input requirements for digesters. Although phase separation would reduce chemical costs, this practice would require additional tanks and equipment and thereby increase capital and maintenance costs.

With respect to alkalizing strategies, the application of chemicals to raw vinasse is a key factor for obtaining high treatment performances, and specific composition characteristics, such as high carbohydrate concentrations, low pH and absence of alkalinity, provide favorable conditions for rapid vinasse acidification (Boncz et al., 2012). Sodium bicarbonate ($NaHCO_3$) has been frequently applied as an alkalizing compound in bench-scale AD systems for vinasse treatments (Döll and Foresti, 2010; Ferraz et al., 2016; Fuess et al., 2017; Harada et al., 1996; Siqueira et al., 2013). These adjustments usually enable reactors to deal with high organic loading rates (OLRs). Sodium hydroxide (NaOH) (Souza et al., 1992) and calcium carbonate (or limestone—$CaCO_3$) (Goyal et al., 1996; Seth et al., 1995) have also been commonly used in treating vinasse prior to methane production. Despite the added reactor stability, the use of high chemical doses negatively affects the economic favorability of scaling-up AD plants. Studies have proposed the recycling of treated effluent because the bicarbonate produced from methanogen metabolism can be used to neutralize influent wastewaters (Barrera et al., 2016; Nandy et al., 2002; van Haandel, 2005). Urea (CH_4N_2O) application has also been tested (Boncz et al., 2012) to provide alkalinity to methanogens and increase nitrogen levels in the treated vinasse and thereby improve its fertilization potential (van Haandel, 2005). However, the potential accumulation of ammonia within the reactors could lead to inhibitory effects over the methanogenic populations and thus impair the bioenergy recovery from vinasse (Boncz et al., 2012).

Overall, the various methods for full-scale AD systems in treating sugarcane vinasse require careful assessments of their benefits and drawbacks to determine their appropriate implementation in distilleries. This study aims to evaluate single- and two-phase schemes for AD plants and different alkalizing strategies for digesting vinasse in large-scale sugarcane-based distilleries. These alkalizing strategies include the application of chemicals ($NaHCO_3$ or NaOH) and/or effluent recirculation. Detailed investment costs were calculated for the AD plants, as well as biogas production costs for each case. Electricity production costs from biogas were also estimated for power plants with internal combustion engines (ICEs). Performance data for AD systems and alkalizing compound dosages were obtained from experimental data. Ethanol and vinasse flow rates were estimated based on the typical characteristics of the Brazilian sucro-energetic sector.

2. Methods

2.1. *Basic input data: sugarcane biorefinery and AD systems*

A large-scale, annexed, sugarcane-based biorefinery with a milling capacity of 4×10^6 tons of sugarcane (TC) per harvest was used as the baseline for calculations. Table 1 shows the input data for the biorefinery, including ethanol yield and ethanol and vinasse flow rates. The harvesting period was set at 232 days, i.e., the average duration of the sugarcane season in Brazil (Table 1; CONAB, 2011).

Reference data for the single- and two-phase biodigestion systems are also presented in Table 1. Performance data for the single-phase AD system were obtained from Ferraz et al. (2016). Data for the acidogenic and methanogenic steps of the two-phase AD system were collected from Fuess et al. (2016) and (2017), respectively. Biohydrogen production/collection was not considered in this study, i.e., the acidogenic phase was considered only for the enhancement of the vinasse biodegradability (Ferraz et al., 2016). The AD performance data refers to the thermophilic temperature conditions (55 °C).

2.2. *Design criteria for AD systems: reactors and alkalinization*

The design of the AD plants was based on reactor configurations reported by Fuess et al. (2016) and (2017) for fixed-film digesters. Such systems are advantageous compared with suspended-biomass reactors because immobilized cells are less sensitive to environmental variations (e.g., pH, temperature, and organic loading) and have higher substrate consumption rates (Chan et al., 2009). For the acidogenic phase, a set of conventional packed-bed reactors (APBRs) was designed using low-density polyethylene (LDPE) as the support material. The OLR was set at 84.2 kg-COD m^{-3} d^{-1} (Fuess et al., 2016), excluding chemicals used to adjust the pH of the raw sugarcane vinasse. With respect to the methanogenic phase, structured-bed reactors (ASTBRs) were designed for an OLR of 25 kg-COD m^{-3} day^{-1}, regardless of the phase separation. The ASTBRs, as alternatives to the random arrangement of support materials in packed-bed systems (Fig. 1), combine the advantages of immobilized-cell growth with high bed porosity to prevent the accumulation of extracellular polymeric substances and suspended solids (Camiloti et al., 2014). Polyurethane was considered the support material in methanogenic reactors (Fuess et al., 2017). The vinasse pH and alkalinity were adjusted as further presented. No cooling system was designed because vinasse might naturally reach the required temperature (from 85–90 °C to 55 °C) in intermediate storage tanks or in thermal exchangers prior to reaching the treatment plant.