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Research paper

Alkaline sulfite pretreatment for integrated first and second generation ethanol production: A techno-economic assessment of sugarcane hybrids

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ABSTRACT

Sugarcane hybrids have been developed through genetic engineering and plant breeding to produce lignocellulosic crops that are more susceptible for second generation biofuels production. Adequate evaluation of these plants requires process development combined with proper economic assessment. In this study, alkaline sulfite pretreatment of sugarcane biomass derived from four selected sugarcane hybrids was assessed for second generation ethanol production integrated with a first generation biorefinery. Process simulation and economic analysis were used to evaluate 32 biorefinery scenarios including different pretreatment conditions (high and low severity), enzymatic hydrolysis time (24 and 72 h) and pentoses destination (fermentation to ethanol or discard). Results indicated that high field productivity and low recalcitrance after pretreatment were critical characteristics for a selected sugarcane hybrid. High sodium sulfite loads were useful to increase ethanol production in the 1G2G biorefinery. However, sodium sulfite cost was relevant in the 1G2G ethanol cost. Sensitivity analysis applied to the best biorefinery scenarios indicated that maximum sodium sulfite prices to reach minimum acceptable rate of return (12%) were US$ 0.66/kg and US$ 0.47/kg for severe and mild pretreatments, respectively.

1. Introduction

Computer-aided process simulation and economic evaluation of several biorefinery schemes have been used to assess their techno-economic viability according to the feedstock or proposed processing route [1-4]. This kind of analysis helps to identify persistent bottlenecks hindering industrial implementation of technological developments reached last years, many of those concerning second generation (2G) ethanol production [2,3].

Techno-economic evaluation of a proposed 2G biorefinery is fundamental to guide researchers and investors. Such type of process simulation requires reliable databases. In the case of sugarcane feedstock, the Brazilian Bioethanol Science and Technology Laboratory (CTBE) developed a robust tool named Virtual Sugarcane Biorefinery (VSB), which allows evaluation of technical, economic, social and environmental impacts of different processing technologies regarding the production of bioethanol, sugar, bioelectricity and other products [2].

Sugarcane bagasse is a particularly valuable source of lignocellulose generated in first-generation (1G) sugar and ethanol mills. Processing of sugarcane bagasse into 2G ethanol could share part of the mill available facilities, such as juice concentration, fermentation, distillation, cogeneration of electricity and storage units, resulting in an integrated 1G2G biorefinery [5].

Considering the current development of 2G ethanol technology, lignocellulose recalcitrance has been overcome by using different pretreatment options and, in spite of the great number of reported works in this topic, this step remains as a relevant bottleneck in the process. For sugarcane bagasse, alkaline-sulfite chemothermomechanical (CTM) pretreatment is efficient to enhance polysaccharide enzymatic hydrolysis rate and sugars yield. The degree of removal of each lignocellulose component during pretreatment depends on the reaction severity, but optimized processes can provide glucose yields as high as 90% after enzymatic digestion of the pretreated material [6,7]. This CTM pretreatment is based on industrially developed CTM pulping processes

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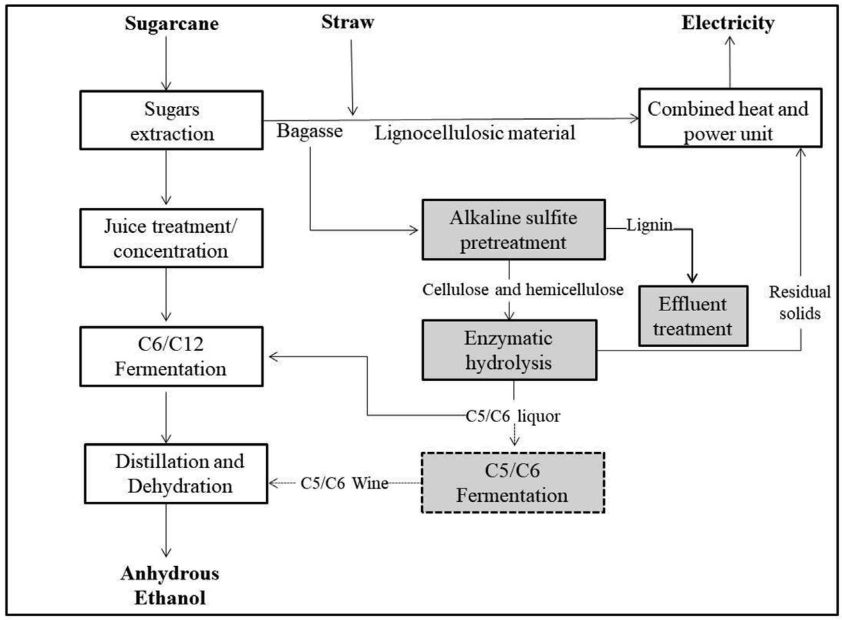

Fig. 1. Block flow diagram for integrated 1G2G process. Process steps in 1G autonomous distilleries (white blocks) and 2G process (gray blocks). Dotted line represents the scenarios in which C5 and C6 fractions were fermented separated from sugarcane juice.

currently used in the pulp and paper industry [7].

Along with biomass pretreatment, the development of plants with low recalcitrance helps to decrease biorefinery costs [2,8-10]. For example, sugarcane breeding programs provided hybrids with improved field productivity and varied biomass composition [11-13]. Studies with selected hybrids indicated that high sucrose and fiber contents are useful for 1G ethanol production [10], whereas genotypes with low lignin content require less severe pretreatment for 2G ethanol production [6].

The techno-economic impacts for using these new sugarcane hybrids require integrated evaluation of the 1G2G sugarcane biorefinery, which can be achieved through computer simulation tools. In a previous work, several new sugarcane hybrids were evaluated in the VSB context to estimate production of electricity, sugar and ethanol in a 1G biorefinery model [10]. Only high field productivity, and high sucrose and fiber contents fulfill plant characteristics to provide high internal rate of return for the process. In the present study, selected sugarcane hybrids were used for detailed techno-economic evaluation of an integrated 1G2G biorefinery. Process options included: different chemical loads in the alkaline-sulfite CTM pretreatment; varied enzymatic hydrolysis periods; and C6 fermentation or C5−C6 co-fermentation. These varied scenarios resulted in 32 individual techno-economic runs for processes comparison. All scenarios were evaluated regarding ethanol and electricity production, and the economic perspective considering metrics such as internal rate of return (IRR) and net present value (NPV). Conclusions were drawn to highlight sugarcane hybrid characteristics and processing conditions enabling profitable 1G2G sugarcane biorefineries.

2. Materials and methods

2.1. Raw material and data sources

Raw materials described in this work corresponded to four experimental sugarcane hybrids selected from previous work [6,7,10,12]. Data related to chemical compositions [12], field productivity, sucrose and fiber contents [10], and pretreatment and enzymatic digestibility [6] of sugarcane hybrids were obtained from previous reports. Those data can be found in the Supplementary material. Data for mill operational conditions, both 1G and integrated 1G2G sugarcane biorefineries, were based on VSB platform and databases [2,3].

2.2. Process description

The biorefinery was modeled for a sugarcane input of 500 metric tons of cane (TC) per hour. An optimized 1G2G ethanol production facility, which uses efficient cogeneration systems with high-pressure boilers (65 bar), ethanol dehydration by adsorption on molecular sieves, and reduced process steam consumption was assumed [3]. Sugarcane bagasse and a fraction of the sugarcane straw (50% of the amount produced in the field) were considered as fuels for production of steam and electricity in combined heat and power (CHP) units, supplying the entire thermal and electrical requirements of the 1G2G processes. Surplus bagasse (the fraction which exceeds the amount required for steam production after using all available straw) was destined for 2G ethanol production, and subjected to pretreatment, hydrolysis of carbohydrate polymers and fermentation of the resulting sugars. In this case, bagasse is pretreated in alkaline-sulfite CTM process [6]. After pretreatment, two fractions are obtained: a solid fraction enriched with cellulose and hemicellulose, and a liquid fraction containing mainly sulfonated lignin. The solid fraction is hydrolyzed by enzymes, where cellulose and hemicellulose are converted into glucose (C6 sugar) and xylose (C5 sugar), respectively. In some scenarios, this liquor is mixed with sugarcane juice in the 1G ethanol process for C6/C12 fermentation; in the other scenarios, C5 and C6 fractions were fermented in a mixture, separately from the sugarcane juice (C12 sugar). Residual solids from enzymatic hydrolysis containing lignin and unreacted cellulose and hemicellulose are burnt in the combined heat and power (CHP) units as supplementary fuel. After fermentation, alcoholic streams were sent to a series of distillation columns and dehydration processes where anhydrous ethanol (99.6 wt % purity) is obtained. A simplified block flow diagram of the process is shown in Fig. 1.

The unit operations of sugars extraction, juice treatment and concentration, fermentation, distillation and dehydration were simulated as described by Bonomi et al. [2].

Process Simulation Diagram (PSD) for pretreatment step was built in the Aspen Plus® software and is shown in Fig. 2. As can be observed, a stream containing surplus sugarcane bagasse (BAGASSE) from combined heat and power generation unit is inserted in the pretreatment