TECHNOECONOMIC ANALYSIS OF SUGARCANE RESIDUES CONVERSION VIA COTREATMENT CONSOLIDATED BIOPROCESSING

Isabela Uematsu Zambello[1]*, Luisa Pires Vaz[1], Tassia Lopes Junqueira[2] & Lee Lynd[3]

[1] *Advanced Second-Generation Biofuel (A2G) Laboratory, Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil.*
[2] *Brazilian Biorenewables National Laboratory (LNBR), Brazilian Center for Research in Energy and Materials (CNPEM), Campinas, Brazil.*
[3] *Thayer School of Engineering, Dartmouth College, Hanover, USA*
** Corresponding author's email i263671@dac.unicamp.br*

ABSTRACT

Biofuels and its production process are important features to be considered when meeting the requirements for a circular bioeconomy: replacing fossil fuels, reducing carbon emissions, and therefore endorsing climate change mitigation. Cellulosic ethanol production from sugarcane residues is impaired by its high operational costs and low efficiency. To overcome this, consolidated bioprocessing using thermophilic bacteria combined with milling during fermentation (cotreatment) can be an alternative. In this work, process simulation and technoeconomic analysis was used to compare both cotreatment and the current process that applies hydrothermal pretreatment and fungal cellulases for cellulosic ethanol production from sugarcane bagasse and straw. A significant reduction in capital and operational costs were observed when using cotreatment consolidated bioprocessing to convert residues from the sugarcane industry in lieu of the current applied process.

Keywords: Consolidate bioprocessing. Sugarcane bagasse. Sugarcane straw. Cellulosic ethanol

1 INTRODUCTION

In Brazil, the production of ethanol by sugarcane juice generates around 165 million ton of bagasse per year, and the use of this lignocellulosic biomass for second-generation ethanol (E2G) can increase in 50% the ethanol productivity regarding the same planted area [1–3]. The use of low-cost carbon sources, such as sugarcane straw and bagasse are great options being available near or on-site in first generation ethanol plants, reducing costs with transportation [4,5]. However lignocellulosic biomass requires methods to overcome its recalcitrance, such as hydrothermal or diluted acid pretreatments and saccharification by enzymatic hydrolysis. [6–8] The current applied process designs presents high installation and operational costs[6,9].

Cotreatment consolidated bioprocessing (C-CBP), an innovative technology proposed to produce cellulosic ethanol, combines milling while direct microbial conversion takes place, all in a single unit operation [10,11]. This approach has the potential to eliminate pretreatment and the need of added fungal enzymes, increasing ethanol productivity of non-treated biomass [10–12]. Studies evaluating cellulosic ethanol production via C-CBP at thermophilic conditions, considering bioconversion yields projected through future research and development, having corn stover as feedstock, and showcase the potential of this technology when compared to E2G[13,14]. In this work we build upon previous work to evaluate through technoeconomic analysis the differences between the E2G process using hydrothermal pretreatment and enzymatic hydrolysis and C-CBP cellulosic ethanol production using a blend of sugarcane bagasse and straw as feedstocks.

2 MATERIAL & METHODS

This study builds on the previous report that evaluated performance and cost of a simulated standalone cellulosic corn stover ethanol biorefinery using C-CBP as conversion platform[14]. Here we assume a 50/50 percent blend of sugarcane bagasse and straw as feedstock and assume financial parameters compatible with the Brazilian market. We present two scenarios: Scenario I is based on the conventional E2G process featuring hydrothermal pretreatment, fungal cellulase enzymatic hydrolysis and fermentation mediated by yeast (*Saccharomyces cerevisiae*)[15]. And Scenario II uses reported simulation assumptions for C-CBP[13,14], mediated by thermophilic bacteria (*Clostridium thermocellum* and *Thermoanaerobacterium thermosaccharolyticum*), considering optimistic yields and intending to represent long-term potential of this technology. The defined parameters of the evaluated scenarios are presented in Table 1.

Material and energy flows were modeled using ASPEN PLUS (V10), economic analysis was adapted from the NREL report for lignocellulosic ethanol [8], considering 2019 CEPCI as adjustment factor. All scenarios were normalized to generate the same amount of ethanol (230 million liters year), operating 8410 hours/year. Operational costs were calculated based on Brazilian prices and costs[15], considering exchange rate of 4.11 R$/US$.

Table 1. Scenario parameters

		Scenario	
Parameter	Unit	I	II
Conversion Platform		Pretreatment + Enzymatic Hydrolysis	Cotreatment Consolidated Bioprocessing
Feedstock inlet	Million ton/year	1.08	0.88
Sugar Yield*	%	77	85
Electricity demand	MW/year	218,774	179,463

*Sugar yield refers to the total amount of carbohydrates from the initial biomass converted to monomeric sugars (glucose and xylose) during pretreatment + hydrolysis or C-CBP.

3 RESULTS & DISCUSSION

Carbon and energy balances are presented in Figure 1. Scenario I presented higher carbon recovery in the electricity and steam cogeneration area (Figure 1A) but has lower electricity production (Figure 1B). The lower recovery is due to the demand of steam for pretreatment, not needed in the C-CBP scenario. Scenario II presented a higher mass recovery for ethanol, which was expected once it considers higher conversion yields (Figure 1A). Same was observed for the energy recovered for ethanol (Figure 1B).

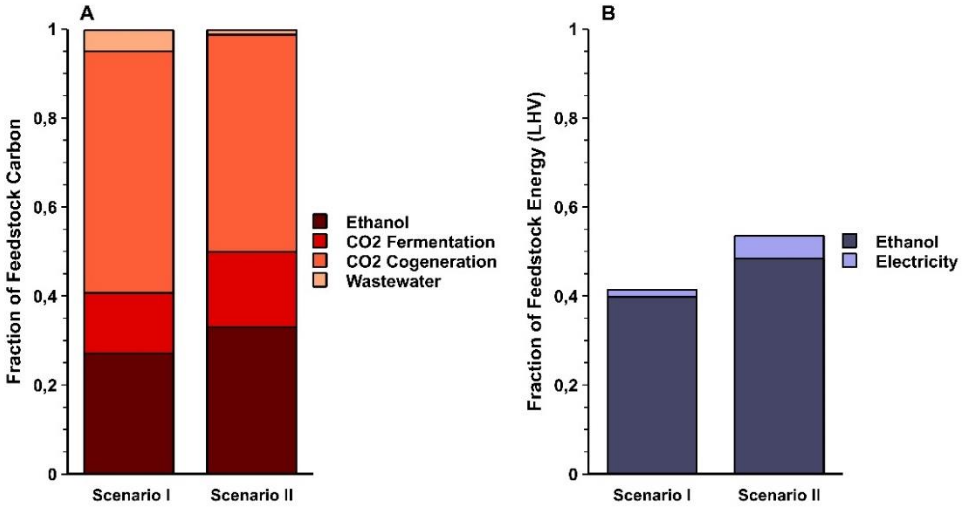

Figure 1. (A) Carbon balance, represented as fraction of the carbon present in the feedstock. (B) Energy balance represented as fraction of the lower heating valued (LHV) of the feedstock.

The total capital investment for the scenarios is shown in Figure 2A, being 431 MM$ and 353 MM$ for scenarios I and II, respectively. The main contributor to the higher price in Scenario I is the pretreatment step, responsible for around 14% of the capital cost. All the other features required mostly the same investment for all scenarios. The only exception is for the hydrolysis and fermentation area in scenarios II, due to the higher cost for cotreatment equipment and a higher amount of fermentation vessels needed. Figure 2B presents revenues, costs and the annual earnings before interest, taxes depreciation and amortization (EBITDA). Considering the feedstock cost 0.13 US$/ kg and ethanol selling price 0.47 US$/L. Due to the lower conversion and hydrolysis yields assumed for scenario I (conventional E2G), a higher amount of biomass is required, resulting in elevated operational costs for all other areas. In scenario I enzymes are produced off-site which is reflected in the operational costs of the process, being the main contributor for the elevated cost. For all scenarios the revenue for ethanol is equal. Discount flow rate analysis shows that the minimum ethanol selling price (MESP) is 0.55 US$/L and 0.39 US$/L for scenarios I and II respectively.

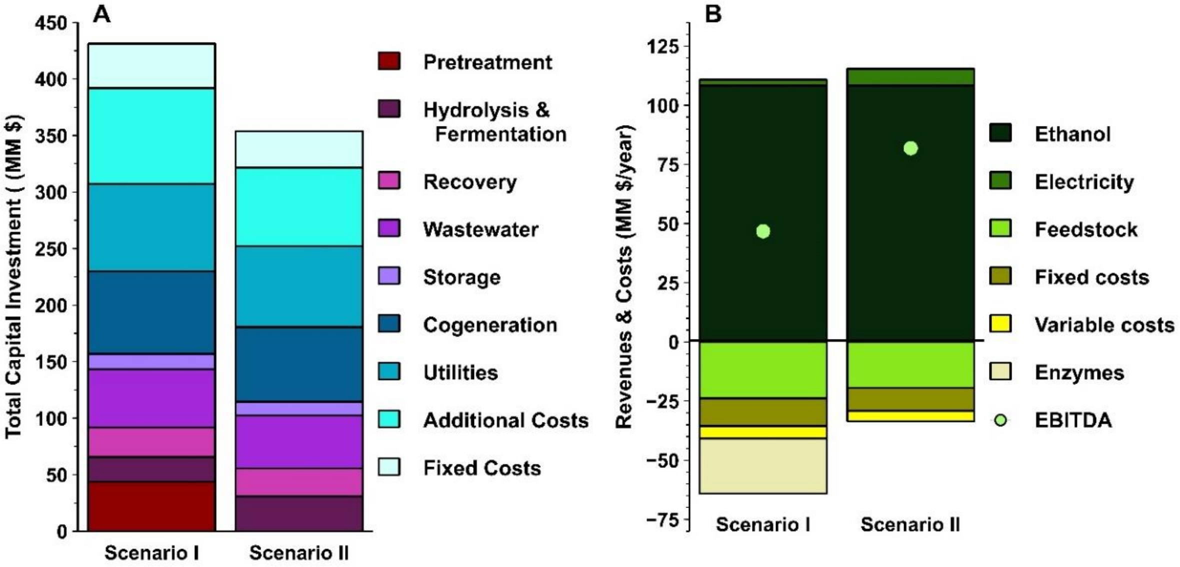

Figure 2. Capital and Operational Costs. (A) Total capital investmernt. Values showed are installed costs. (B) Revenue, costs and EBITDA. Other variable costs include chemicals used in neutralization and nutrients for microbial growth.

4 CONCLUSION

Cotreatment consolidated bioprocessing shows great potential over the conventional E2G process utilized for existing second-generation ethanol plants. This outcome is primarily attributable to its reduced capital expenditure due to removal of the pretreatment step and lower operational costs, as there is no need to purchase enzymes. The C-CBP scenario presented lower MESP than the assumed selling price, while E2G presented a higher value, which indicates that the technology is not yet economically competitive in the current Brazilian market without premium prices.

REFERENCES

1. De Souza Abud, A. K. & De Farias Silva, C. E. Bioethanol Production From Food Crops Challenges and Perspectives to Improve the Production. (2019) doi:10.1016/B978-0-12-813766-6.00021-7.
2. Dias, M. O. S. *et al.* Improving second generation ethanol production through optimization of first generation production process from sugarcane. (2012) doi:10.1016/j.energy.2012.04.034.
3. Kumar, S., Singh, S. P., Mishra, I. M. & Adhikari, D. K. Recent Advances in Production of Bioethanol from Lignocellulosic Biomass. *Chem Eng Technol* **32**, 517–526 (2009).
4. Dias, M. O. S. *et al.* Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. *Bioresour Technol* **103**, 152–161 (2012).
5. Bonomi, A., Cavalett, O., Pereira, M., Cunha, D. & Lima Editors, M. A. P. *Green Energy and Technology Virtual Biorefinery An Optimization Strategy for Renewable Carbon Valorization*. (2016).
6. Chandel, A. K. *et al.* Brazilian biorefineries from second generation biomass: critical insights from industry and future perspectives. *Biofuels, Bioproducts and Biorefining* **15**, 1190–1208 (2021).
7. Lynd, L. R., Cushman, J. H., Nichols, R. J. & Wyman, C. E. Fuel Ethanol from Cellulosic Biomass. *Science (1979)* **251**, 1318–1323 (1991).
8. Humbird, D. *et al.* Process design and economics for conversion of lignocellulosic biomass to ethanol. *NREL technical report NREL/TP-5100-51400* **303**, 275–3000 (2011).
9. Vandenberghe, L. P. S. *et al.* Beyond sugar and ethanol: The future of sugarcane biorefineries in Brazil. *Renewable and Sustainable Energy Reviews* **167**, 112721 (2022).
10. Paye, J. M. D. *et al.* Biological lignocellulose solubilization: comparative evaluation of biocatalysts and enhancement via cotreatment. *Biotechnology for Biofuels 2016 9:1* **9**, 1–13 (2016).
11. Balch, M. L. *et al.* Lignocellulose fermentation and residual solids characterization for senescent switchgrass fermentation by Clostridium thermocellum in the presence and absence of continuous in situ ball-milling †. *Energy Environ. Sci* **10**, 1252–1261 (2017).
12. Balch, M. L., Chamberlain, M. B., Worthen, R. S., Holwerda, E. K. & Lynd, L. R. Fermentation with continuous ball milling: Effectiveness at enhancing solubilization for several cellulosic feedstocks and comparative tolerance of several microorganisms. *Biomass Bioenergy* **134**, 105468 (2020).
13. Lynd, L. R. *et al.* Cellulosic ethanol: status and innovation. *Curr Opin Biotechnol* **45**, 202–211 (2017).
14. Kubis, M. R. & Lynd, L. R. Carbon capture from corn stover ethanol production via mature consolidated bioprocessing enables large negative biorefinery GHG emissions and fossil fuel-competitive economics. *Sustain Energy Fuels* (2023) doi:10.1039/d3se00353a.
15. Junqueira, T. L. *et al.* Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons. *Biotechnol Biofuels* **10**, 50 (2017).

ACKNOWLEDGEMENTS

Isabela Uematsu Zambello was financially supported by São Paulo Research Foundation (FAPESP) process number 2021/05398-9. Luisa Pires Vaz was financially supported by the Brazilian Coordination of Improvement of Higher Education Personnel (CAPES) grant numbers 88887.372463/2019-00. Lee R. Lynd was supported by the Center for Bioenergy Innovation (CBI), U.S. Department of Energy, Office of Science, Biological and Environmental Research Program under Award Number ERKP886. This work was also supported by São Paulo Research Foundation (FAPESP) process number 18/25682-0.