Bioresource Technology 208 (2016) 42–48

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Techno-economic analysis of ethanol production from sugarcane bagasse using a Liquefaction plus Simultaneous Saccharification and co-Fermentation process

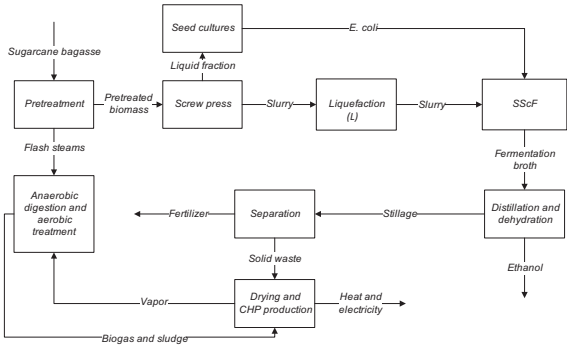
Krisztina Gubicza [a], Ismael U. Nieves [b], William J. Sagues [b], Zsolt Barta [a], K.T. Shanmugam [b,c], Lonnie O. Ingram [b,c,*]

[a] Department of Applied Biotechnology and Food Science, Faculty of Chemical Technology and Biotechnology, Budapest University of Technology and Economics, H-1111 Budapest, Muegyetem rkp. 3, Hungary
[b] Stan Mayfield Biorefinery, University of Florida, Perry, FL 32348, United States
[c] Microbiology & Cell Science, University of Florida, Gainesville, FL 32611-0700, United States

HIGHLIGHTS

- A simplified (L + SScF) process with phosphoric acid was modelled using Aspen.
- A $10 mil savings in capital cost was achieved by using phosphoric acid.
- Capital investment ranged from $169 to $197 mil for various scenarios.
- Ethanol production cost varied between 50 and 63 cents per liter.
- Overall ethanol yield had the biggest impact on production cost.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 22 January 2016
Accepted 25 January 2016
Available online 1 February 2016

Keywords:
Lignocellulose
Xylose
Ethanol
Hemicellulose
L + SScF

ABSTRACT

A techno-economic analysis was conducted for a simplified lignocellulosic ethanol production process developed and proven by the University of Florida at laboratory, pilot, and demonstration scales. Data obtained from all three scales of development were used with Aspen Plus to create models for an experimentally-proven base-case and 5 hypothetical scenarios. The model input parameters that differed among the hypothetical scenarios were fermentation time, enzyme loading, enzymatic conversion, solids loading, and overall process yield. The minimum ethanol selling price (MESP) varied between 50.38 and 62.72 US cents/L. The feedstock and the capital cost were the main contributors to the production cost, comprising between 23–28% and 40–49% of the MESP, respectively. A sensitivity analysis showed that overall ethanol yield had the greatest effect on the MESP. These findings suggest that future efforts to increase the economic feasibility of a cellulosic ethanol process should focus on optimization for highest ethanol yield.

1. Introduction

Due to the volatile nature of oil prices and environmental concerns, a great deal of attention has been placed on renewable lignocellulose-based fuels and chemicals to replace current

* Corresponding author at: Department of Microbiology and Cell Science, Bldg 981, University of Florida, Gainesville, FL 32611-0700, United States. Tel.: +1 352 392 8176; fax: +1 352 846 0969.
E-mail address: Ingram@UFL.edu (L.O. Ingram).

http://dx.doi.org/10.1016/j.biortech.2016.01.093
0960-8524/

petroleum-based products. Initial economic analyses performed on cellulosic fuel ethanol production cited conversion economics as the main issue to be addressed (Lynd et al., 1991), while other techno-economic models focused on optimization of operational costs (Nguyen and Saddler, 1991; von Sivers and Zacchi, 1995; Wyman, 1994). However, significant progress has been made since these earlier studies, and recent techno-economic analyses provide a more favorable view for lignocellulosic ethanol production (Chovau et al., 2013).

The National Renewable Energy Laboratory (NREL) published in 1999 a detailed analysis for lignocellulosic ethanol production and reported an ethanol production cost of 0.38 US$/L (1.44 US$/gal) (Wooley et al., 1999). A second report by NREL in 2002 with revised figures for equipment and installation costs, projected the required advances needed in key research areas with the aim to reach a MESP of 0.28 US$/L (1.07 US$/gal) in 2010 (Aden et al., 2002). Subsequent techno-economic analyses have made use of some of the parameters from the NREL report on the operation of an *n*th plant. Nevertheless, the reported MESP values have varied considerably from one study to the next based on the assumptions and process configurations (Aden and Foust, 2009; Chovau et al., 2013; Eggeman and Elander, 2005; Foust et al., 2009; Galbe et al., 2007; Hamelinck et al., 2005; Han et al., 2015; Kumar and Murthy, 2011; Macrelli et al., 2012; Sassner et al.). These differences have made it difficult to compare these studies (Chovau et al., 2013; Galbe et al., 2007; Sassner et al., 2008). The NREL report (Wright et al., 2010) was further revised with more representative values in 2011 and resulted in a MESP of 0.57 US$/L (2.15 US$/gal) (Humbird et al., 2011).

Some of the significant contributors to the MESP of lignocellulosic ethanol include the cost of the feedstock, the ethanol yield, and the cost of cellulase enzymes (Chovau et al., 2013). However, the main contributor to the MESP in almost all cases seems to be the capital cost (Galbe et al., 2007). From various studies, it is clear that one way to lower the MESP is to simplify the process in order to reduce the capital cost of a lignocellulose-to-ethanol facility. With this in mind, five research advances were identified that are required for process simplification:

1. development of biocatalysts with improved resistance to hemicellulose toxins (eliminates the need for separate detoxification steps);
2. replacement of sulfuric acid with the less aggressive phosphoric acid (eliminates the need for expensive metals or alloys);
3. solving the mixing and pumping issues related to high fiber solids loading (simplifies material handling, reduces opportunities for contamination, and improves product yields);
4. limiting the use of chemicals to those that are nutrients for the biocatalyst and for ultimate use as a high nitrogen fertilizer (partial recovery of chemical cost through multiple usage);
5. co-fermentation of hexose and pentose sugars in the same vessel (eliminates early liquid solid separation, fiber washing and detoxification of hemicellulose hydrolysate).

In recent years, significant progress has been made in this area with the development of a process termed Liquefaction plus Simultaneous Saccharification and co-Fermentation (L + SScF) that is analogous to corn ethanol (Geddes et al., 2011). This process uses a dilute-phosphoric-acid-steam-explosion pretreatment and meets target criteria for process simplification. In addition, the engineered *Escherichia coli* as the microbial biocatalyst is able to co-ferment all sugars derived from the lignocellulosic biomass while maintaining high conversion yields (Geddes et al., 2013). The L + SScF process was successfully scaled up to 80-L using a unit operation pilot plant (Nieves et al., 2011). Information gained from these studies was used to design the Stan Mayfield Biorefinery, a state-funded facility with the purpose of proving the feasibility of this lignocellulosic ethanol technology in a larger, fully integrated, continuous process that resembles a commercial-scale plant.

In this present study, data from the biorefinery pilot plant, and laboratories were used to develop a techno-economic model for the construction of a 83 million liters per year (22 million gallons of ethanol per year) commercial plant in order to determine the economic feasibility of the process and to identify areas for further improvement. An experimentally proven case and 5 hypothetical scenarios were evaluated in which enzyme loading, enzymatic glucan hydrolysis, overall biomass-to-ethanol conversion, solids loading, and incubation time are varied. Scenarios were also compared in terms of heat demand, electricity, fertilizer production, and cost of ethanol production.

2. Methods

2.1. Bagasse to ethanol plant

The proposed ethanol plant is assumed to be located in the United States and to convert 300,000 dry US tons of sugarcane bagasse into ethanol annually. It is assumed to be in operation for 8000 h/year. Live steam is assumed to be available at 20 and 4 bar. Whenever possible, secondary steam is used to replace live steam. The process model was obtained by modifying previous models reported by Barta et al. (2010) using a process design based on Nieves et al. (2011). Description of the process steps will focus primarily on modifications made to the model.

2.1.1. Feedstock

The dry matter (DM) of sugarcane bagasse contains approximately 43% glucan, 23% xylan, 2% arabinan, 2% galactan and 27% lignin (Nieves et al., 2011). The remaining portion is acetyl groups, ash and other compounds. The moisture content of bagasse as received is typically 50%.

2.1.2. Pretreatment

In the modelled process (Fig. 1) the conversion of carbohydrates is carried out after dilute-acid steam explosion pretreatment and in L + SScF. Additional details of compositions, energy, flows, etc. are provided as Supplemental tables and figures. The sugarcane bagasse is pretreated using dilute phosphoric acid (the conversion factors for some reactions are the following: glucan to glucose 0.021, xylan to xylose 0.727, xylan to furfural 0.099, arabinan to furfural 0.500, water-insoluble lignin to water-soluble lignin 0.148), after which a small part of the liquid fraction is separated from the pretreated biomass slurry (30% dry weight; DW) and used for seed propagation (ethanologenic *E. coli* SL100).

2.1.3. Enzymatic liquefaction and ethanol fermentation

The liquid fraction (6.2% of the DW flow from the pretreatment reactor, 10% DW content) is used for propagating the fermenting organism *E. coli* SL100. This genetically modified strain ferments both hexoses and pentoses into ethanol. The solid fraction (34% DW) is liquefied by Novozymes (Franklinton, NC, USA) CTec3® cellulase enzyme-preparation (50 °C, 6 h, enzyme loading: 2.5% of the DW in the Base Case) and then Simultaneous Saccharification and co-Fermentation is carried out (pH 6.3, 37 °C, 48 h in the Base Case), in which both the hexoses and pentoses are fermented into ethanol (conversion factors for some reactions in the Base Case: glucan to glucose 0.68, galactan to galactose 1.000, xylan to xylose 0.500, glucose to ethanol 0.950, galactose to ethanol 0.950, xylose to ethanol 0.900). For pH control during liquefaction and fermentation, ammonia is used. The *E. coli*-concentration in the fermentation broth is 2.6% (w/w), and the solids loading for the Base Case was 15% (w/w).