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Parametric analysis of total costs and energy efficiency of 2G enzymatic ethanol production

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HIGHLIGHTS

- Total costs and energy efficiency production are calculated for 2G ethanol.
- Calculations are parameterized function of feedstock composition and plant capacity.
- Major cost contributions are detailed and quantified for relevant cases.
- Energy duties were calculated for all plant capacity and feedstock compositions.
- TPC results were compared with updated and normalized values from published works.

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ABSTRACT

This paper presents an analysis of total costs (TPC) and energy efficiency of enzymatic ethanol production. The analysis is parametrized with respect to plant capacity and polysaccharides content (*pc*) of lignocellulosic feedstock.

The feedstock is based on wheat straw whose price is proportional to its *pc* ranging from new straw with high *pc* and high cost to agro-wastes with limited *pc* but lower cost. The plant flowsheet was built using a conventional biochemical platform with co-saccharification and fermentation (SHF) technologies. A parametric analysis of TPC as a function of plant capacity (100–2100 ton DB/day) and *pc* (i.e. feedstock price) (80% (75 USD/ton DB)–35% (6 USD/ton DB)) was performed with *Net Present Value* (*NPV*) techniques. Current data from Mexican economics and the agro-industrial sector were used as an illustrative case.

A quasi-linear section of the TCP surface was identified delimited by (300–1100 ton DB/day) and (80–55% *pc*) with increments no larger than 21% of the minimum TPC obtained (0.99 USD/l etOH for 2100 ton DB/day and 80% *pc*). Major cost contributions are detailed and quantified for boundary cases of this surface. Energy consumption and production were also calculated for all the plant capacity and feedstock *pc* cases, taking into consideration the *Maximum Energy Recovery* (MER) obtained from a *Pinch* analysis. The *end-use energy index eer* was less than 0.82 for all cases, thus stressing the need to use process equipment with lower energy requirements. TPC are compared against previously published results for SHF technology between 500 and 2100 ton DB/day plant capacities. These values were updated and normalized with respect to feedstock and enzyme costs employed in this work. Differences among TPC and recently published normalized results are within a ±5% range, thus confirming the dependence of TPC from feedstock and enzyme prices, regardless of flowsheet technology and economic conditions.

1. Introduction

Lignocellulosic materials are currently considered an alternative for the production of second generation (2G) biofuels that may alleviate the expected demands of the vehicular fuel markets and contribute to the mitigation of the negative impacts caused by the production and use of first generation biofuels worldwide (e.g. [1,2]). Guidelines have been established by some local and international bodies for the production and use of 2G biofuels that may favor the environment and local communities involved in the production chain (e.g. [3]). These guidelines are also intended to discourage the production and marketing models which are based largely on public subsidy [2]. Criteria besides economics, such as land-use change, carbon footprint, process water usage, net energy value (NEV) contributions, etc. will be fundamental in assessing the fulfillment of these guidelines. Pilot-scale plants are already in operation (e.g. Inbicon at Kalenborg, Denmark and Abengoa at

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Salamanca, Spain with a design capacity of 8–10 ton DB/h) and, at the time of writing this paper, the commercial production of lignocellulosic ethanol is expected to be competitive after 2020 (e.g. [3]).

Comprehensive accounts of the state-of-the-art research and technology can be found in the available literature (e.g. [4–8]). They include descriptions and challenges of each process stage involved. Among them, biochemical (i.e. enzymatic) conversion platforms have received considerable attention due to their technological maturity. Different strategies have been explored for this technology platform in order to improve yields and production costs from sequential saccharification stages followed by a fermentation process (SHF) to simultaneous hydrolysis and fermentation techniques (SSF or SCSF) (e.g. [6,9]). Energy consumption, mainly in the separation stage, is another issue being considered (e.g. [10,11]).

Regarding biofuel economics, most studies have been carried out on the assumption that polysaccharides-rich feedstock will be available for the production of 2G bioethanol. This may prove unrealistic in the medium term. This is relevant since it is well accepted that total production costs (TPC) of enzymatic ethanol are highly dependent on raw material (i.e. feedstock and enzymes) prices, regardless of the great differences of TCP values obtained in previous works. Plant capacity and technological platforms are other factors influencing TCP. However, most published works consider only a specific raw material at a fixed plant capacity for a particular technology platform (e.g. [9,11–14]). Added to these factors, inflation and technology change become relevant issues since the large time-span in which TCP values have been produced. Therefore, previous results are difficult to compare on equal basis.

This paper presents a parametric study of the impact of feedstock cost and plant capacity in TPC and in energy efficiency of the enzymatic ethanol production process with limited feedstock availability and using SHF technologies. The use of lower quality (i.e. lower *polysaccharides content* (*pc*)) feedstock is considered as an alternative to the unlimited feedstock supply usually employed in other works. The conceptual plant design (including energy integration) as well and economic analysis are thoroughly documented. The results of the parametric analysis shed some light on previous claims of TCP-dependency on feedstock cost and plant capacity as well as for explaining the differences on results of most previous works. Other important contributors to TPC and energy efficiency are also identified and quantified. Current data from the Mexican economy and agro-industrial sector are employed as an illustration case.

The paper starts by introducing the chosen feedstock to study the impact on TPC and energy efficiency. Based on wheat straw, the feedstock cost is calculated as a linear function of its (*pc*) adjusted to local pricing. The maximum cost-maximum *pc* corresponds to wheat straw, whilst the minimum cost-minimum *pc* feedstock is based on agro-industrial residues composed mainly of wheat straw that are available in sufficient amounts in central Mexico. Values of *pc* were collected in two different agricultural regions during a 4-years period. Section 3 then presents the plant flowsheet, which is based on conventional process technologies that could be suitable for deployment in the short term. The only exception was the pretreatment reactor, which employs patented technology for the feed and discharge of feedstock. Therefore, royalty fees were explored as a contributor upon TPC. Section 4 explains the construction of mass and energy balances of each process stage using standard models of a commercial simulator (i.e. SuperPro Designer 8.5 (SPD)). Operation and kinetic parameters were taken from the open literature dealing with pilot facilities and pretreatment. Pretreatment and enzymatic hydrolysis yields were corroborated experimentally at laboratory scale. A *Pinch* analysis was carried out to determine the *Maximum Energy Recovery* (MER) [15] and the *end-use energy ratio* (*eer*) definition [16] was introduced to evaluate the energy efficiency of the production facilities under consideration. The tools for calculating TPC are presented in Section 5. These are based on *Net Present Value* (*NPV*) techniques. Equipment size and cost were calculated using SPD based on plant capacity. All cost and financial parameters correspond to the current conditions (c. 2012) of the Mexican economy. TPC was then calculated for $NPV = 0$ as a function of plant capacity versus feedstock *pc* (i.e. price) for fixed financial and production conditions. The economic assessment considers the standard direct and indirect costs including total capital investment, royalty fees, heating and cooling duties after MER and electricity credit among others. Section 6 shows the results for the parametric Pinch and TPC analyses considering plant capacities from 100 to 2100 ton dry-weight basis (ton DB/day) with feedstock prices from 6 USD/ton DB with a maximum of 35% *pc* for the agro-residue to 75 USD/ton DB with approximately 80% *pc* for new straw. A region of plant capacities and feedstock *pc* (i.e. price) is identified with a maximum variation of 21% with respect to the minimum calculated TCP. The role of cost contributions (e.g. feedstock, enzymes, capital, financial and operation costs) is discussed for the boundary cases. Since most previous works (e.g. [6,11,13,14,17–19]) recognize that raw material (i.e. feedstock and enzymes) costs are the most important single contributing parameters to TPC, Section 7 presents a comparison of TPC values calculated in this paper with those previously published whose original sources considered similar SHF technologies and reported purchasing prices for feedstock and enzymes. These production costs were updated and normalized considering feedstock and enzyme prices. The comparison reinforces the impact of feedstock and enzyme costs on TPC and sheds some light on the differences of reported TCP values. Energy consumption is also compared with those results available in the open literature. Finally, Section 8 summarizes the results and discusses some factors that may help to reduce TPC and to improve the end-use energy ratio (*eer*).

2. Feedstock characterization

The feedstock employed in this study is a mixture of wheat straw (i.e. *ns*) with an agro-residue (i.e. *ws*) based on wheat straw available in central Mexico and usually employed as a soil enricher. Measurements of polysaccharides and lignin contents in wheat straw and the agro-waste samples from two different agriculture regions in Mexico were carried out during a 4-year period starting in 2008. Sample analyses were commissioned to three independent laboratories [20–22], each result being obtained at least twice, with the exception of result 5 as shown in Table 1. A wide span of *pc* values were reported, thus stressing the importance of considering this issue in TCP calculations.

Local prices for new wheat straw with the highest *pc* and the agro-waste are also provided. Based on this data, feedstock price and *pc* is calculated as a linear function of the proportional

Table 1
Feedstock composition.

Description	Composition (%DB)			Price p_i; $i = ns,ws$
	Lignin	Glucans	Pentoses	USD/kg DB
1. Wheat straw, *ns*	18.26 ± 0.28	68.65 ± 3.86	12.21 ± 0.27	0.075
2. Wheat straw, *ns*	5.61 ± 0.88	53.11 ± 2.84	19.23 ± 2.31	
3. Wheat straw, *ns*	5.39 ± 0.23	51.05 ± 3.25	14.88 ± 3.46	
4. Wheat straw, *ns*	3.49 ± 0.42	31.57 ± 0.44	22.20 ± 0.33	
5. Agro-waste, *ws*	5.63 ± 0.00	36.00 ± 0.00	11.90 ± 0.00	
6. Agro-waste, *ws*	19.91 ± 0.66	30.01 ± 1.51	5.37 ± 0.22	0.006