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Exergy analysis of pretreatment processes of bioethanol production based on sugarcane bagasse

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ABSTRACT

Bioethanol produced from LB (lignocellulosic biomass) is a renewable option to decrease fossil fuel demand. LB is considered the future feedstock for bioethanol production because of its low cost and availability. The production of bioethanol from LB involves different steps: pretreatment, hydrolysis, fermentation, and bioethanol recovery. Some pretreatments such as SE (steam explosion), LHW (liquid hot water), ammonia fiber explosion and acid hydrolysis treatment have been used frequently to remove lignin and to improve the saccharification of cell wall carbohydrates. In this work via exergy analysis biomass pretreatment methods to prepare LB for bioethanol production using two typical chemical compositions of sugarcane bagasse are evaluated. Four case studies for the following pretreatment technologies (A) SE, (B) Organosolv, (C) LHW and (D) SE + LHW are studied. Although high exergy values are obtained in all cases of this study (A) 93.2%, (B) 85.4%, (C) 94.1%, and (D) 95.1%, the values of destroyed exergy rate found for the cases analyzed using the raw material 2 are high compared to the input bagasse exergy rate, (A) 7.2%, (B) 24.8%, (C) 6.0%, and (D) 5.5%, highlighting the relevance of such processes in the overall exergy efficiency of second-generation bioethanol production routes.

1. Introduction

Among the potential bioenergy resources, lignocellulosic biomass has been identified as a cheap and effective feedstock for producing biofuels including bioethanol, biobutanol, and biogas. In general, biomass can be divided into first-generation crops as sugars from sugarcane or sugar beets, and starch from corn, rice, wheat, and on second-generation energy sources including various lignocelluloses. Hence, lignocellulosic biomass for the production of biofuels includes forest residues like wood; agricultural residues of sugarcane bagasse, corn cob, corn stover, wheat, and rice straws; industrial residue such as pulp and paper processing waste; municipal solid wastes; and energy crops like switch grass [1].

In the present work, sugarcane bagasse feedstock is analyzed. The annual world production in 2011 for this resource was 1.6 billion tons and it generated 279 million tons of biomass residues of bagasse and leaves. Theoretically, one ton of bagasse could yield up to 300 L of bioethanol [2]. For the past three decades, bagasse and leaves have been explored for use in lignocellulosic bioconversion.

Second-generation ethanol production has not yet reached commercial maturity. Nowadays, different process configurations have been investigated in order to apply and to develop efficient conversion processes using this technology [3–5]. Dias et al. [3] evaluated different configurations of the second-generation ethanol production process (e.g. pretreatment with steam explosion coupled or not with delignification, pentose biodigestion or fermentation to ethanol, solids loading on hydrolysis), integrated with first-generation bioethanol production from sugarcane, while Dias et al. [4] assessed second-generation ethanol production processes improvements in the first-generation autonomous distillery processing sugarcane. Moreover, Dias et al. [5] have compared a stand-alone second-generation ethanol production from surplus sugarcane bagasse and trash with conventional first-generation ethanol production from sugarcane and with integrated first- and second-generation.

In this context, pretreatment is one of the most expensive and least technologically mature steps in the process of converting the biomass into fermentable sugars. Hence, it offers a great potential for improvement in efficiency and the reduction of costs through

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Nomenclature

b	specific exergy (kJ/kg)
B_{tot}	exergy rate or flow rate (kW)
h	specific enthalpy (kJ/kg)
LHW	liquid hot water
LIG2-TP	lignin fraction at reference conditions
LFRAC-TP	lignocellulose fraction at reference conditions
T	temperature (°C, K)
P	pressure (MPa, kPa)
Rt	Reaction time (min)
SE	steam explosion
SFRAC-TP	solid fraction at reference conditions
Sl	solids loading (%)
w/w	weight/weight (%)

research and development. Indeed, pretreatment as a first step is the most costly operation and accounts for approximately 33% of the total cost with respect to the economic feasibility of each step [6].

Recently, using an exergy analysis several articles have been published on this topic on studies of pretreatments and biochemical routes [7–9] and for bioethanol production from lignocellulosic materials.

Ofori-Boateng and Lee [7] performed a comparative thermodynamic sustainability assessment of steam explosion, Organosolv and microbial pretreatment methods for bioethanol production via exergy analysis. Ojeda et al. [8] compared via exergy analysis sustainable ethanol production topologies from lignocellulosic biomass using steam explosion, diluted acid and Organosolv process for pretreatment stage of sugarcane bagasse. Moreover, Ojeda et al. [9] analyzed, also via exergy analysis, the bioethanol production from acid-pretreated bagasse using different process configurations that include SHF (sequential hydrolysis and fermentation), SSF (simultaneous saccharification and fermentation), and SSCF (simultaneous saccharification and co-fermentation).

Another interesting application was the production of bioethanol from bananas and their residues using energy, exergy and renewability analyses [10–12].

Velásquez et al. [10] evaluated the effect of chemical and biochemical stages involved in liquid biofuels production processes, while Velásquez et al. [11] applied the exergy analysis method to evaluate the renewability of anhydrous ethanol production from surplus banana fruit production and its lignocellulosic residues. These authors also apply an energy analysis to the production process of anhydrous ethanol obtained from the hydrolysis of starch and cellulosic and hemicellulosic material present in the banana fruit and its residual biomass [12].

In this paper, based on exergy analysis, the following biomass pretreatment methods for second-generation bioethanol production are evaluated: (A) Steam explosion, (B) Organosolv, (C) LHW and (D) SE + LHW, looking for implementation in the production process and to determine the effect of irreversibilities on the overall efficiency of lignocellulosic bioethanol production. Two typical chemical compositions of sugarcane bagasse were considered in the simulations performed to determine the variation of bagasse constituents and the ranges of efficiency for each pretreatment process.

Exergy efficiencies are calculated for the individual process steps. Furthermore, a performance comparison in terms of exergy efficiency and destroyed exergy rate of the cases studied were determined. Based on the outcomes, the impact of pretreatment methods on the average exergy efficiency of the ethanol production is discussed.

1.1. Biomass pretreatment methods for second-generation biofuels

An important step towards the production of biofuels from lignocellulosic biomass is the pretreatment method. Pretreatment affords the separation of the major biomass components; these being cellulose, hemicellulose and lignin which render the digestibility of lignocellulosic materials. Pretreatments for lignocellulosic biomass are classified in Fig. 1, including: biological, physical (mechanical), chemical methods and various combinations of these (physicochemical).

During the last decades, pretreatment research has been focused on identifying, evaluating, developing, and demonstrating approaches that support the enzymatic hydrolysis of the pretreated biomass with lower enzyme dosages and shorter conversion times. Several pretreatment methods have been investigated with a wide variety of feedstock, and there are recent review articles which provide a general overview of the field [13–15].

Cardona et al. [13] reported the status and perspectives in the production of bioethanol from sugarcane bagasse based on the potential transformation to sugars and ethanol, considering pretreatment technologies, detoxification methods and biological transformation. Menon and Rao [14] described the trends in bioconversion of lignocellulose describing the advancement in recent pretreatment techniques, current global scenario of bioethanol pilot plants and biorefinery concept for the production of biofuels and bioproducts. Cardona and Sánchez [15] used Aspen Plus® to simulate several process configurations for bioethanol production from lignocellulosic biomass focusing on the energy consumption analysis of integrated flowsheets production processes.

Furthermore, a large number of articles have been published on biomass pretreatment methods with analyses of their advantages, limitations, disadvantages and economic assessment [16–18] so as to illustrate the status and perspectives on production of bioethanol from sugarcane bagasse as well as the trends in bioconversion of lignocellulose. Kumar et al. [16] reviewed various pretreatment methods of lignocellulosic biomasses for efficient hydrolysis and biofuel production while Hamelinck et al. [17] performed a techno-economic analysis of ethanol production from lignocellulosic biomass for short, middle and long-term. Moreover, these authors reported a comparison of various pretreatment methods in terms of lignin removal and hemicellulose hydrolysis. Besides, Zheng et al. [18] emphasize the biomass pretreatment in preparation for enzymatic hydrolysis and microbial fermentation for cellulosic ethanol production.

In addition, different studies analyzed the increase in second-generation ethanol production from sugarcane bagasse and trash taking into consideration standalone and integrated plants [3–5]. Moreover, different hydrolysis technologies, including improvements in hydrolysis yields, pentose biodigestion and fermentation for bioethanol production were studied. One of the most important evidences of implementing pretreatment methods successfully for bioethanol production process is the removal of lignin and hemicellulose through a cost-effective process.

1.1.1. Biological pretreatment

Biological delignification is an attractive approach for pretreatment of lignocellulosic biomass. This route is very cost-effective, requires low energy consumption, and produces low formation of toxic materials including furfural, hydroxymethylfurfural, and the like. Using direct microorganisms as well as enzymes extracted