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Review of design works for the conversion of sugarcane to first and second-generation ethanol and electricity

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ABSTRACT

The conversion of sugarcane, the world's largest crop, to energy vectors, namely first and second-generation ethanol and electricity, is an ongoing scientific endeavor. This conversion makes use of complex processes with numerous unit operations and process blocks addressed in literature. Such processes have also been the subject of detailed thermo-economic and techno-economic evaluations as well as the application of systematic methodologies involving simulation, heat integration, optimization and selection. Key works related to this field are discussed in this review along with their hypotheses and results. The main future technologies are also presented. This review is realized to provide the scientific community with accessible references, information and ideas that will ultimately help researchers build consolidated and optimal designs for this process.

1. Introduction

Sugarcane is one of the world's largest crops and a major contributor in energy diversification and sustainable development. This has spurred increased research activity for its utilization. Even though the conversion of sugarcane juice to bioethanol is a long-established technology, its optimization has seen increased interest. Furthermore, the utilization of its biomass components, bagasse and leaves, have been the subject of research interest, namely in the context of energy optimization and the food versus energy dialogue. Finally, the effect of varying economic conditions on process competitiveness was another subject of research.

This activity was summarized in a number of review articles which highlighted various aspects of the problem at hand.

In this context, the various economic hurdles, namely for sugarcane pricing, hampering the progress of sugarcane utilization in Nepal were showcased in Neupane et al. [1]. The authors however did not fail to stress its many advantages and discussed various win-win scenarios. Neamhom et al. [2] discussed sugarcane's potential in reducing greenhouse gas emissions in Thailand.

Arshad et al. [3] listed the multiple benefits of employing bagasse cogeneration in Pakistani sugar mills and presented this technique as a road for sustainable development in the country. Hofsetzb et al. [4] highlighted the various potential uses of sugarcane bagasse and their evolution, Alvira et al. [5] provided a review of various bagasse pretreatment technologies, Sosa-Arnao et al. [6] dealt with various bagasse drying techniques, Modenbach et al. [7] dealt with the challenges facing efficient enzymatic hydrolysis, Leal et al. [8] on the other hand discussed the availability, quality, recovery and use of sugarcane leaves. Zabed et al. [9] provided a thorough review of potential biomass sources, process technologies and configurations, and promising microorganisms that enable efficient production of second generation ethanol. The authors later expanded their analysis in [10] to cover multiple renewable sources along with lignocellulosic namely sugary and starchy biomass. Bizzo et al. [11] presented the various steps involved in the valorization of sugarcane residual biomass with an emphasis on harvesting techniques. Aditiya et al. [12] presented a guide for future second generation ethanol plant design whilst stressing the multiple technologies for each production step and highlighting their multiple advantages and disadvantages and presenting numerical values when possible. Farzad et al. [13] and Santos et al. [14] discussed the importance of the sugar refinery concept leading to multiple products. The authors also compared the different routes from an economical perspective.

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These reviews, despite their depth and breadth, do not deal with the multitude of engineering design efforts which sought to model, simulate, evaluate, optimize and return optimal designs for the different processes of converting sugarcane to useful products namely electricity and ethanol.

Considering this, this present review seeks to bridge this gap and provide a detailed review of key references dealing with this subject. It will thus provide future engineers and researchers with an accessible baseline to compare their results with respect to design assumptions, values for design variables and ultimately results for performance criteria.

More specifically, attention is turned towards two conversion schemes: (1) production of first generation ethanol and electricity in a combined distillery and cogeneration plant (1 G + COGEN). (2) Production of first and second-generation ethanol and electricity in a combined distillery, hydrolysis and cogeneration plant (1 G + 2 G + COGEN). This review will first focus on works optimizing conventional technologies for each production step before showcasing ongoing research efforts in each step. Tables and graphs are also used to more accurately and concisely summarized the most important points.

2. Review of references optimizing conventional configurations

The block Flow Diagrams for the two studied processes are shown in Fig. 1. The 1G + 2G + COGEN alternative has a similar diagram to the 1G + COGEN scheme, save the additional hydrolysis section and its associated materials: sugars for second generation (2G) ethanol production and combustibles sent to the cogeneration section. The common system breaks down as follows: input sugarcane is first treated namely to extract the solid fraction: bagasse from the sugarcane juice. This juice is then sent to a physical and chemical treatment section to remove remaining impurities and enable its subsequent conversion to ethanol. This is followed by a concentration section where the juice sugar content is increased prior to sterilization and fermentation. This step produces thus diluted ethanol wine which is later sent to distillation and rectification and dehydration for anhydrous ethanol production. In the 1G + COGEN case, bagasse is sent to the cogeneration plant along with input leaves to produce steam and electricity to run the distillery along with potential excess power production and sales. In the 1G + 2G + COGEN case, part of the bagasse is diverted for hydrolysis where it is converted to sugars later sent to the distillery and combustibles sent to the cogeneration section. Finally, the cold utility section cools process streams which do not exchange with other process heat streams.

Even though optimization work has dealt with the various aspects of this process scheme, attention is centered herein on the energy consuming sections, namely juice concentration and distillation and rectification, the energy producing sections namely cogeneration, and the hydrolysis section.

2.1. Juice concentration

Juice concentration brings sugarcane juice from an initial concentration of around 11 wt% to a final concentration of 22.5 wt%. As a result, fermentation reactor volume and distillation the heat requirement are reduced. This is enabled by the employed fermentation technology. Feed Forward Multiple-effect evaporation is the traditional technology employed for this sake. It consists in a sequence of evaporators operating in a heat cascade configuration, with the vapor of a given effect higher pressure effect providing heat for the following lower pressure effect. The corresponding Process Flow Diagram is presented in Fig. 2, along with most relevant references and key mass and heat streams. The most noteworthy is the heat exchange between higher level condensation and lower level evaporation, highlighted in green. The first heating and subsequent cooling requirements are also shown herein.

A pure multiple-effect integration however limits the integration of this section with the rest of the process. Literature works have thus sought to circumvent this problem by the application of two key concepts: vapor bleeding and heat targeting.

Vapor bleeding dealt with controlling the vapor flow rates in the various evaporators to meet lower level heat demands. Heat targeting

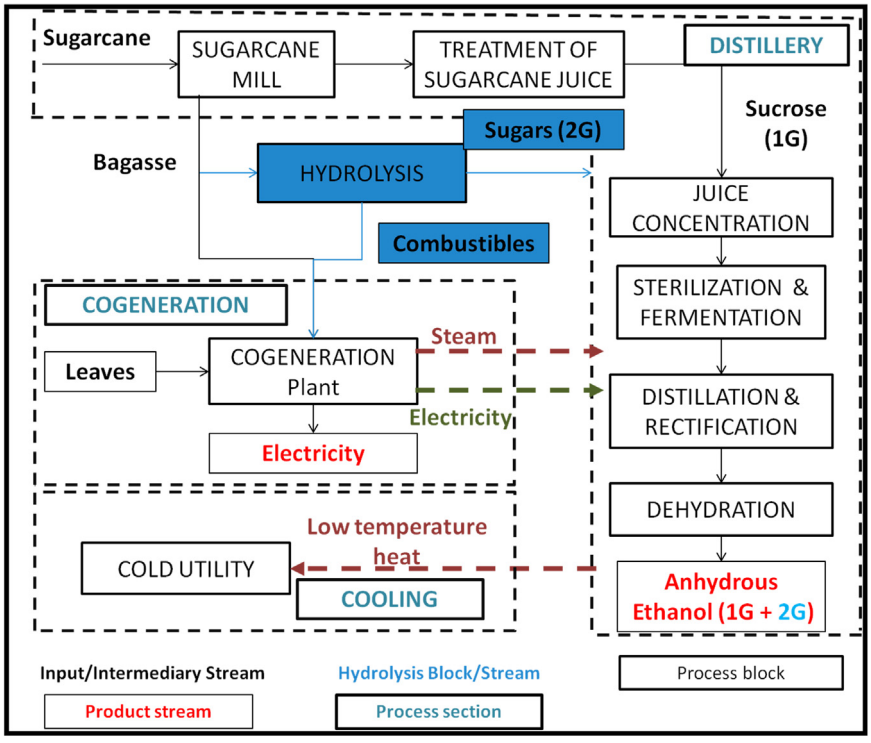

Fig. 1. Breakdown of process scheme.