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Insight into a steam explosion pretreatment of sugarcane bagasse for bioethanol production†

P. Barciela [1], A. Perez-Vazquez [1], M. Carpena [1], S. Seyyedi-Mansour [1], P. Donn [1], M. Fraga-Corral [1,2], Paz Otero [1,2], J. Xiao [1,3], J. Simal-Gandara [1], M.A. Prieto [1,2]*, and L. Cassani [1,2,4]*

[1] Universidade de Vigo, Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Faculty of Science, E32004 Ourense, Spain.
[2] Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolonia, 5300-253 Bragança, Portugal.
[3] International Joint Research Laboratory of Intelligent Agriculture and Agri-products Processing, Jiangsu University, Zhenjiang, China.
[4] Instituto de Investigaciones en Ciencia y Tecnología de Materiales, Consejo Nacional de Investigaciones Científicas y Técnicas (INTEMA-CONICET), Colón 10850, Mar del Plata (7600), Argentina.

* Correspondence: * M.A. Prieto (mprieto@uvigo.es); L. Cassani (luciavictoria.cassani@uvigo.es)

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Abstract: Lignocellulosic biomass is a powerful material for producing sustainable biofuels because it converts into second-generation clean energy capable of coping with the depletion of fossil reserves and rising energy demands. However, pretreatment is required in the conversion process to overcome the recalcitrance of the lignocellulosic biomass, accelerate its disintegration into cellulose, hemicellulose, and lignin and obtain an optimal yield of fermentable sugars in the enzymatic hydrolysis. Steam explosion technology has stood out due to its results and advantages, such as broad applicability, high efficiency in the short term, and lack of contamination. This gentle and quick pretreatment combines high temperature autohydrolysis and structural alteration via explosive decompression. So, steam at high pressure (1-3.5 MPa) and temperature (180-240ºC) is pressed into the cell walls and plant tissues for a duration of seconds (30 s) to several minutes (20 min). In this aspect, sugarcane bagasse is a promising feedstock for bioethanol production due to its high cellulosic content and availability. Finally, the pretreatment of sugarcane bagasse by applying steam explosion seem to be a feasible economic option for the bioethanol production.

Keywords: steam explosion pretreatment, sugarcane bagasse, lignocellulosic biomass, bioethanol.

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1. Introduction: Steam explosion (SE) as lignocellulosic biomass pretreatment

The production of renewable fuels using lignocellulosic waste from agricultural activities has been considered in the past years as an alternative to traditional fuels [1]. Agricultural waste is defined as anything useless and is characterized by its biodegradability solid and lignocellulosic composition [1]. In this way, the non-edible lignocellulosic biomass discarded by agriculture feedstock can be used as a matrix to obtain biofuel, being considered second-generation (2G) biofuel [2,3]. Lignocellulosic biomass is mainly composed of cellulose, hemicellulose, and lignin, which are low-energy-density compounds. So, a pretreatment step is necessary so plant-specific enzymes can release sugars for biofuel production [2,4].

Pretreatment is an essential technological step to convert lignocellulose into fuels and biochemicals [5]. The purpose of this preliminary step is to reduce the lignin and/or hemicellulose content by modifying the cell wall structure of the biomass, thus increasing the surface area and accessibility to carbohydrates such as cellulose and thereby increasing the yield of fermentable sugars [6,7]. Selecting a suitable pretreatment will significantly increase the efficiency of the hydrolysis process by helping to remove the lignin or hemicellulose and expose the cellulosic component [8].

Steam explosion (SE) is one of the most attractive and uncomplicated pretreatment methods due to its low capital investment, high scalability, and lower hazard of the chemicals involved in the process, among other advantages [9]. SE pretreatment, as a physicochemical modification technology in food raw materials, is a method that presses steam at high pressure (1–3.5 MPa) and temperature (180–240ºC) into cell walls and plant tissues for a few seconds (30 s) to several minutes (20 min), combining the thermochemical action of high-temperature boiling coupled with the physical tearing action of instantaneous blasting [10–12]. This leads to the decomposition of the lignocellulosic matrix, partial removal, and/or redistribution of lignin, increasing cellulose accessibility [7]. The hydrolysis of hemicellulose components results in the release of mono- and oligosaccharides, the alteration of the chemical structure of lignin, and an improvement in the cellulose crystallinity index and extractability of lignin polymer [13,14].

SE couples autohydrolysis and biomass alteration through high temperature and explosive decompression [11]. The process is usually divided into two independent stages. The first phase operates as a thermochemical reaction, where the vapor boiling, and explosion phase takes place. The second phase is a process of adiabatic expansion and conversion of thermal energy into mechanical energy [15,16]. **Figure 1** shows the sequence of the basic steps of the SE method and its impact on the matrix.

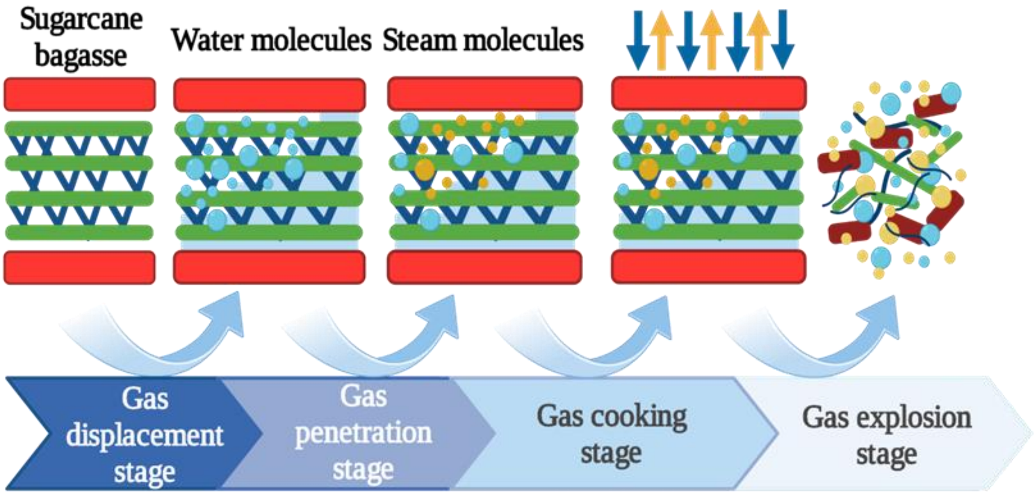

Figure 1. Illustration on the process of lignocellulosic material disruption and released molecules.

SE processes can be operated in continuous or batch mode. Batch reactors are usually used for laboratory-scale pretreatment, while continuous systems are typically used for large-scale industrial processes [11,17]. The equipment is essentially made up of the following three parts: a steam generator, a steam explosion chamber, and a material receiving container [12]. Outstanding benefits of SE pretreatment are the extensive hydrolysis of hemicellulose polymers and the biomass reduction of particle size [18,19]. The smaller particles have, the more available surface area, and the lignin droplets act as a binder, which improves particle-to-particle contact and binding capacity [11]. Also, SE has a high potential for energy efficiency, low capital investment, and lower environmental impact compared to other pretreatment technologies [20].

The effectiveness of SE pretreatment differs depending on factors such as the toughness of the pretreatment conditions (*e.g.*, the temperature and residence time are known as the combined pretreatment severity factor (SF)) and/or the recalcitrance of the biomass (*e.g.*, lignin content) to hydrolysis [21–23]. SF ($R_0 = e^{T_{exp}-100/14.75}$) is an influential parameter that defines the relationship between hydrothermal severity (operating conditions and physicochemical changes) and lignocellulosic biomass fractionation [24].

It should also be noted that the by-products likely to be generated during the SE process are divided into three groups, weak acids, furanic derivatives, and phenolic compounds [25]. In view of the above, the purpose of this review has been to compile the most recent information about SE pretreatment using sugarcane bagasse as raw material.

2. Sugarcane bagasse (SCB) as a potential matrix for bioethanol production

Sugarcane (*Saccharum oficinarum* L.) is a tropical grass of the *Gramineae* family and the *Saccharum* genus, characterized for being large and perennial [26]. The sugarcane cultivation requirements are 6-12 months to grow and 60-100 cm^3 of water [27], being mainly cropped in countries such as Brazil, India, or China for sugar production, contributing to their economic development [26,28]. Sucrose is the main product of sugarcane, which is accumulated in the internodes of the stalk [29]. However, sugarcane production generates a percentage of waste that varies between 25-30% [30], so the by-product reutilization is key from the circular economy point of view. These residues produced by the sugarcane industry can be classified as straw, the harvest residue, and bagasse, the fibrous fraction that follows the juice extraction [26]. These two by-products are characterized by their lignocellulosic composition, being cellulose, lignin, and hemicellulose the major components, having also extractants and ashes in their composition [31]. For bioethanol production, the cellulose, hemicellulose, and lignin matrix composition must be considered [29], so SCB has been considered a suitable matrix for its production. SCB is defined as the waste obtained after the collection of sugarcane stem juice [1]. Bioethanol produced using SCB is less carbon-intensive compared to fossil fuels, so air pollution can be reduced [29]. Therefore, its use is also remarkable from a carbon print perspective. The SCB is approximately composed of 45-50% of cellulose, 25-30% of hemicellulose, 25% of lignin, and 2.4-9% of ash [29].

From an economic point of view, it is necessary to consider the scaling-up feasibility of bioethanol production using SCB and SE pretreatment. In this way, the industrial production of bioethanol has been examined in some studies. The techno-economic feasibility of bioethanol production also includes the enzymatic hydrolysis of sugars, where the bioethanol is obtained, although this work has not highlighted this step. Mary Joseph *et al.* studied the economic feasibility of SCB bioethanol using Aspen Plus V11. Total capital investment per gallon was estimated, being 17 United States dollars as the final cost [32]. Internal rate of returns (IRR) and ethanol production cost were also studied by Junqueira *et al.* Results showed an expense of SCB bioethanol between 0.59, 0.68, and 0.69 R$/L when SE was applied with pentoses fermentation, pentoses biodigestion, or alkaline delignification after pretreatment, respectively [33]. Moreover, this study compared SE and hydrothermal pretreatment costs, showing that ethanol production was higher when SE was applied. The best economic results (considering a high IRR value and a low production cost) were obtained with SE with pentoses fermentation [33].

Considering the data shown, SE seems to be a suitable pretreatment for bioethanol production using SCB biomass since high temperatures and pressure allows the reduction of both lignin and hemicellulose compounds, improving the sugar releasement and hence, bioethanol production. Moreover, this process has been studied from a techno-economic point of view, showing suitable results.

3. Conclusion

A new era of biofuel production has been promoted in recent years due to the current carbon emissions generated by conventional fuels. In this way, alternative pathways have been developed, and bioethanol production using lignocellulosic biomass is one of the suitable options. However, a pretreatment step of the biomass is needed to achieve bioethanol production. Thus, SE has been widely studied as a potential thermo-mechanic pretreatment to be incorporated into this process. SE is a pretreatment method that uses high temperatures and pressure conditions to achieve sugar releasement in a low-time process. SE is also characterized by its broad applicability, high efficiency in the short term, and lack of contamination despite its conventionality. Although different matrices can be used for bioethanol production, SCB has a particular interest since sugar production generates high amounts of this by-product, and elimination is currently an issue. Several studies showed positive results for both sugar conversion and cellulose, hemicellulose, and lignin content reduction when SE was applied in SCB, being the main advantages:

- SE is a low time process that can be performed in batch or continuous mode.
- SE requires low equipment investment; it has a high energy efficiency and low environmental impact.
- By applying SE, hemicellulose is extensively hydrolyzed, and biomass' particle size is significantly reduced.
- SCB is a suitable biomass to be pretreated by SE for the bioethanol production, showing a feasible economic scaling-up.

Considering the data provided, the bioethanol production using SCB as biomass and SE as the pretreatment methodology seems to be a suitable new pathway to be considered.

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