Energy Efficiency of Biorefinery Schemes Using Sugarcane Bagasse as Raw Material

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Abstract

The implementation of the use of biomass to obtain value-added products has been a good alternative for reducing the environmental impact. For this purpose, different studies have been carried out focused on the use of agro-industrial waste. One of raw materials most used has been bagasse obtained from the processing of sugarcane which present a high production in countries like Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, Philippines and United States. Between 2014 and 2015, the world production of sugarcane accounted 175.1 million metric tons. From 1 ton of sugarcane it can be obtained 280 kg of bagasse. Sugarcane bagasse (SCB) is a waste rich in polysaccharides, which makes it a promising raw material for obtaining products such as ethanol, xylitol, electricity, PHB, antioxidants and lactic acid, among others. The concept of biorefinery can be used to get the most benefit from SCB. However, given the composition of the SCB it is possible to obtain different biorefinery schemes, which depend on the products to be obtained.

The objective of this work was to analyze from the energy point of view different biorefinery schemes in which SCB was employed as raw material. The design and simulation of the different biorefinery schemes was performed in Aspen Plus software. From this software, it was possible to obtain the different balances of mass and energy, which were used in the technical and energetic analysis. Exergy was used as a comparison tool for energy analysis. These analyses allowed the selection of the best process structure for a biorefinery from SCB. Finally, it was defined the section or equipment to be optimized in the future to have a more efficient processing and consequently an improved biorefinery based on this residue.

Keywords: *Biorefinery, Sugarcane bagasse, Exergy analysis, Energy analysis*

INTRODUCTION

In the processing of agricultural products, different types of waste are generated, which present an environmental problem in terms of their final disposal. In order to reduce the environmental impact caused by these wastes, different studies have been carried out to evaluate their potential to be used in different transformation processes to obtain additional value-added products [1]. From these different renewable raw materials several studies has been focused on the use of agro-industrial waste [1]. One of the most used raw materials has been bagasse, a residue obtained from sugar production [2] [3]. From 1 ton of sugarcane processed there are generated 280 kg of bagasse [4], which has a high production in countries like Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, Philippines and United States [5]. Between 2014 and 2015, the world production of sugarcane accounted 175.1 million metric tons [6]. The sugarcane bagasse is a residue rich in polysaccharides, that has been widely studied in the production of biofuels [7] and chemicals such as ethanol, xylitol, electricity, PHB, antioxidants and lactic acid, among others [8], [9]. Also it has a high potential for the generation of energy, through the application of the gasification process [8]. Therefore, the development of biorefineries from sugarcane bagasse has been determined in many studies, with a great variety of configurations [10]–[12].

One of the variables to be considered in the processes design is the energy, that usually can be more important for large scale processing such as biorefineries. The biomass conversion into different products involves high energy consumption due to the number of processing stages that are carried out. A tool that allows evaluating beyond the energetic changes that are made in a process is the exergy analysis [13]–[15]. The exergy relates the input and output data of the system in order to compare the different processing zones [16], allowing analyzing in this way the energetic and physical-chemical changes that occur at each stage of the process. Exergy analysis can also be used as a comparative tool for different technologies or, where appropriate, for processes that differ in the type of raw material used.

According with the technology and the processing route used, it is possible to obtain a wide variety of products from sugarcane bagasse. It is possible to obtain sugar monomers such as glucose and xylose, which can be used as platforms for obtaining different products. Both xylose and glucose can be used in fermentation processes to obtain compounds such as butanol, ethanol, lactic acid, xylitol, succinic acid, arabitol, poly-3-hydroxybutyrate (PHB), among others [3], [4], [17]–[23] When xylose and glucose are used in dehydration processes, furfural and hydroxymethylfurfural (HMF) are obtained, respectively [24]–[26]. These compounds can be used as platforms to obtain different products. Based on this information, an analysis of the energy efficiency of three biorefineries in which sugarcane bagasse was used as raw material was carried out in this work. For the energy analysis the distribution of the energy flow at the input and output of each biorefinery was determined. In order to determine the quality of this energy, the exergy of the process was determined.

METHODOLOGY

Process simulation

In the present work, three scenarios based on sugarcane bagasse as raw material for obtaining products such as furfural, HMF, nonane, octane, syngas and electricity were analyzed. The composition of sugarcane bagasse used in this work is present in Table 1. In the first scenario, the processes of acid hydrolysis, detoxification and enzymatic hydrolysis for the production of xylose and glucose were considered, which were transformed into furfural and HMF by dehydration processes. In the second scenario, the same processes used in scenario 1 were considered, but furfural and HMF were used to obtain octane and nonane, respectively. The third scenario was based on scenario 2, to which was added a cogeneration stage in which syngas and electricity were obtained. Figure 1 shows the connection between the different processes used to obtain each of the products corresponding to each proposed scenario. The conditions and main equipment of each process are present in Table 2. The simulation of each scenario was performed in the Aspen plus software. The nonrandom two-liquid (NRTL) thermodynamic model was applied to calculate the activity coefficients of the liquid phase, and the Hayden-O'Conell equation of state was used to describe the vapor phase. In the case of the octane production the state equation Soave Redlich Kwong (SRK) was used. The total raw material flow was 2.9 million metric tons, which represent the 6% of the world production of sugarcane bagasse between 2014 and 2015. For the purification of each of the components of interest, the corresponding phase balances were analyzed in order to determine the major separation process [24]. In the case of the distillation columns, the DSTWU module was employed, which uses an approximate method based on Winn-Underwood-Gilliland equations and correlations. With this module, an initial estimate of the number of theoretical stages, the reflux relation, the location of the feed stage, and the distribution of the components can be obtained. The rigorous calculation of the separation units was carried out in the RadFrac module. This module is based on the inside-out equilibrium method that uses the MESH equations, which involves the simultaneous solution of the mass balance, phase equilibrium, summation expressions, and equations of heat balance of all components in all stages of the distillation column [21], [27]–[29].

Table 1. Composition of sugarcane bagasse employed in this work [30]

Component	Moisture	Cellulose	Hemicellulose	Lignin	Protein	Ash
Percent	50.00	23.70	12.05	11.70	2.40	1.15

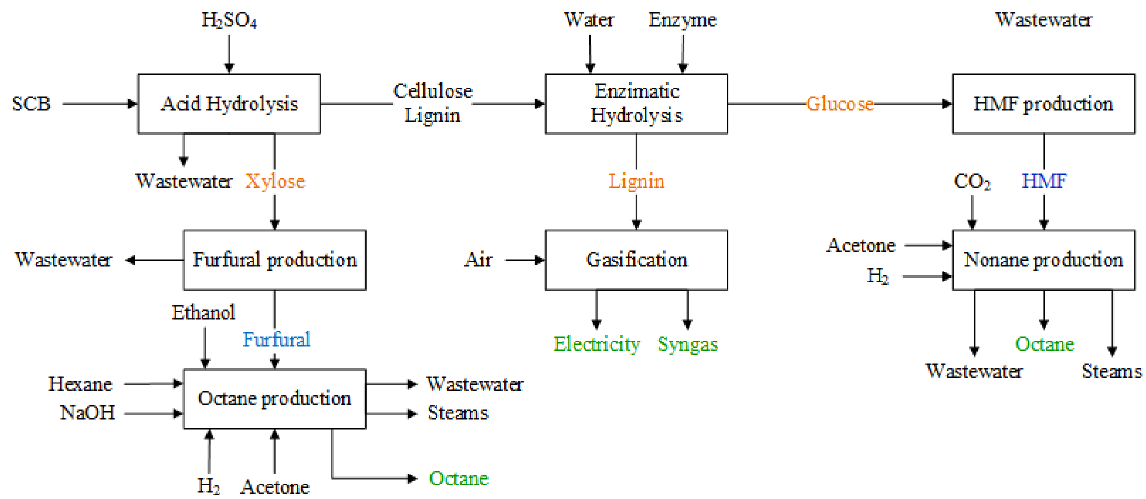


Figure 1. Flowsheet for the sugarcane processing

Table 2. Conditions and main equipment used in each processing stage

Stage	Purpose	Conditions	Reference
Acid hydrolysis			
Crusher	Size reduction to 0.5 mm	1 bar	
Dilute acid reactor	Remove hemicellulose as xylose	1 bar, 122°C, 2% H_2SO_4	[31]
Filter	Separate xylose from cellulose and lignin	1 bar	
Enzymatic hydrolysis			
Enzymatic reactor	Remove cellulose as glucose	1 bar, 50 °C, Cellulose (25 IU/g)	[32]
Filter	Separate glucose of lignin	1 bar	
Detoxification			
Detoxification reactor	Neutralize the acid with $Ca(OH)_2$	1 bar, 60 °C	[33]
Filter	Remove salts presents the xylose solution	1 bar	
Furfural production			
Xylose dehydrator	Furfural production	10 bar, 170 °C	[34]
Decanter	Furfural concentration	1 bar, 25 °C	[35]
Octane production			
Aldol-condensation reactor	Aldol-condensation of furfural with acetone	1 bar, 85 °C, catalyzed by MgO/NaY	[36]
Mild-hydrogenation reactor	Mild hydrogenation of aldol products	2.5 MPa, 140°C, catalyzed by Pt/Co2AlO4	[37]
Dehydration/hydrogenation reactor	Octane production	2.5 MPa, 170 °C	[37]
Distillation columns	Octane separation	1 column: 12 trays, 1.405 reflux ratio, total	

		condenser, 4 bar 2 column: 29 trays, 1.224 reflux ratio, total condenser, 1 bar	
HMF production			
Glucose dehydrator	HMF production	10 MPa, 220°C	
Decanter	HMF separation	1 bar, 25°C	
Nonane production			
Aldol-condensation reactor	Aldol-condensation of HMF with acetone	1 bar, 50°C, MgO/ZrO_2 ad catalyst	[26]
Hydrogenation reactor	Hydrogenation of aldol products in supercritical carbon dioxide	12 MPa, 80 °C, Pd/Si-Al-MCM-41 as a catalyst	[25]
Dehydration/hydrogenation reactor	Nonane production	4 bar, 80 °C	[25]
Distillation column	Nonane separation	13 trays, 1.185 reflux ratio, total condenser, 1 bar	
Gasification			
Gasifier	Syngas production	6 MPa, 850°C	[38], [39]
Turbine	Electricity generation	1 bar	[40]

Energy and exergy analysis

In the Aspen Plus, the software provides information about the energy consumption presented in each of the equipment at each stage of the process. This energy consumption is associated with the energy requirements for heating, cooling and power processes (in cases involving pressure changes). Thus, from the energy requirements of each one of the equipments, the global value of the energy required in the process was determined. Then a distribution of this energy was done for the different stages of the process and the percentage corresponding to energy for heating, cooling, and power processes was obtained. These results are presented through Sankey diagrams.

Afterward, the exergy of the process and its distribution in the different stages were determined. In the exergy calculation, the model presented by Zhang, et al [41] was applied, in which, based on the equation for the exergy calculation considering physical, chemical, kinetic and potential factors. Several simplifications were made, such as not considering kinetic ($Ex^{ki} = mV^2/2$) and potential ($E = mhZ$) exergy, due to the non-significant values and the fact that, in the case of potential exergy, the changes in height that will occur in the process are not known exactly. Through these simplifications, Equation 1 is reduced to Equation 2, in which exergy is associated only with the terms of physical exergy and chemical exergy.

$$Ex = Ex^{ph} + Ex^{ch} + Ex^{ki} + Ex^{po} \qquad Eq. 1$$

$$Ex = Ex^{ph} + Ex^{ch} \qquad Eq. 2$$

Physical exergy considers the deviations in pressure and temperature from the environment and is therefore, defined by Equation 3. The parameter ex_i^{ph} denotes the standard physical exergy specific to component i. To determine this parameter, the calculations of enthalpy and entropy with respect to the reference state (Equations 5 and 6, respectively) are involved. With these two differences, it is possible to know the value of ex_i^{ph}using Equation 4. These values are then replaced in Equation 3 and after, it was multiplied by the respective molar flow of each of the components presented in the stream to be analyzed.

$$Ex^{ph} = \sum_i n_i\ ex_i^{ph} \qquad Eq.3$$

$$ex_i^{ph} = (h_j - h_o) - T_o(s_j - s_o) \qquad Eq.4$$

$$(h_j - h_o) = \int_{T_o}^{T_j} Cp\ dT \qquad Eq.5$$

$$(s_j - s_o) = \int_{T_o}^{T_j} \frac{Cp}{T}\ dT - RLn\left(\frac{P}{P_o}\right) \qquad Eq.6$$

While physical exergy considers temperature and pressure deviations, chemical exergy considers deviations in the chemical composition of the system from the environment. These deviations mainly involve the calculation of chemical reactions (reactive exergy) and expansion, compression, mixing and separation processes (non-reactive exergy). The calculation of the chemical exergy was carried out using Equation 7, in which the term ex_i^{ch} represents the standard chemical exergy specific to each component. This value was obtained from what was reported by Rivero & Garfías [42].

$$Ex^{ch} = \sum_i n_i\left(ex_i^{ch} + RT_oLn\left(\frac{n_i}{\sum n_i}\right)\right) \qquad Eq.7$$

When energy consumption occurs in the different equipment of the process, this energy is associated with exergy. The exergy, associated in each of the equipments with heating or cooling, was determined from Equation 8. In the case of power, the value of the exergy was the same

$$Ex = \int_{T_1}^{T_2}\left(1 - \frac{T_o}{T}\right)\delta Q \qquad Eq.8$$

RESULTS AND DISCUSSION

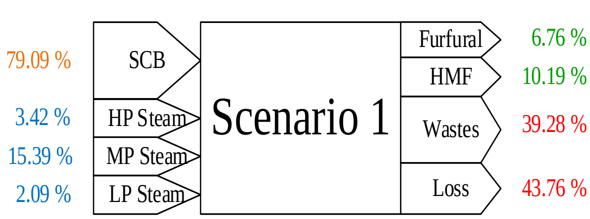
Process simulation

The yields obtained in each scenario were calculated for a high scale biorefinery based on a feed flow of 357,300 kg/h of sugar cane bagasse with the composition presented in the Table 1. In this work, cellulose, hemicellulose and lignin fractions were considered as the main platforms for obtaining value-added products. Compounds such as HMF and nonane were obtained from glucose by means of enzymatic hydrolysis. Furfural and octane were derived from xylose, which was obtained by acid hydrolysis and detoxification processes. The syngas and electricity were obtained from lignin after the separation of the liquor of enzymatic hydrolysis process of the cellulose. Under the conditions presented in the Table, xylose and glucose extraction yields obtained from hemicellulose and cellulose were 0.67 and 0.95, respectively. Based on the sugar cane bagasse flow, the yields of both xylose and glucose were 0.08 and 0.23, respectively. The glucose yield is higher than that of xylose since the cellulose fraction that constitutes the sugar cane bagasse is approximately double than the hemicellulose fraction. When the respective dehydration processes of xylose and glucose were performed to obtain furfural and HMF, yields of 0.57 and 0.68 were presented, respectively. As a function of the sugar cane bagasse flow, the furfural and HMF yields were 0.05 and 0.15, respectively. In the process of obtaining octane from furfural the yield was 0.61, from the xylose flow obtained, it was 0.35 and from sugarcane bagasse was 0.03. While in the nonane production from glucose the yield was 0.70, from HMF and sugarcane bagasse the yields for nonane production were 0.47 and 0.10, respectively. Showing that sugar cane bagasse presents a higher technical viability to obtain nonane than octane. Finally, the yield presented to obtaining syngas was 0.25. Considering that for this process an airflow equivalent to three times the lignin flow obtained from the process was used. When using the syngas to generate electricity by turbines, 0.48 kW per kg of syngas (0.12 kW per kg of sugarcane bagasse processed) were generated.

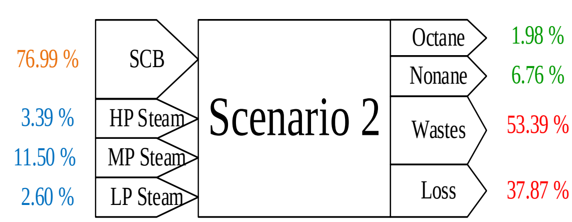
Based on the composition presented by sugar cane bagasse, other raw materials such as empty fruit bunches, oil palm rachis and coffee cut-stems could be have similar yields to the mentioned above. If the sugar cane bagasse (raw material) was changed to rice husks, the yields that could be obtained from both nonane and octane would be nearly the same since this raw material has a similar composition of cellulose and hemicellulose .

Energy and exergy assessment

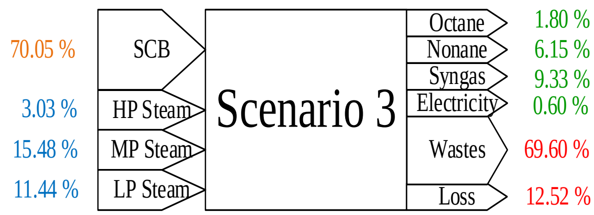
During a process, the energy was feed both in the raw material and in the utilities required to supply the different heating and cooling processes. Thus, energy requirements in scenarios 1, 2 and 3 were 13, 15 and 21 MJ per kg of sugarcane bagasse processed. Through the addition of processing steps to scenario 1, energy requirements increased to supply the energy demand presented by each processing unit. As a result, the percentage of energy represented by sugarcane bagasse decreased in scenarios 2 and 3. Figure 2 shows the distribution of energy both at the input as the output of each scenario. At the beginning of each scenario, the energy was distributed both in the raw material and in the utilities employed. Meanwhile, at the output, the energy of the process was found both in the products and in the waste generated during the different stages of processing. However, in the different processes analyzed, energy losses were presented which are associated with the non-idealities of the process. Comparing the three scenarios analyzed, a higher utilization of raw material (scenario 3) shows that energy losses in the process decrease by more than 30% compared to scenarios 1 and 2 (see Figure 2.a and 2.b), and a 6% in the case of scenario 2 compared to scenario 1 (see Figure 2.a and 2.c). While energy losses decrease, the energy potential of waste increases. This increase is associated with the increase in the waste flow. In order to obtain a more efficient use of the raw material was necessary to add processing stages, which required the addition of new reagent streams to the process. After the corresponding purification stages, the reagents that did not react and some of the products that not react were separated. Nevertheless, these streams have an energy potential to be employed in other transformation processes, which would contribute to obtaining a better energetic use of the both mass and energy streams involved in the process. The implementation of these processes would contribute to a more efficient use of the energy contained in the raw material (sugar cane bagasse for the present work). This will increase the energy efficiency of the biorefinery schemes already proposed and will allow the production of other products from the same raw material.



(a)



(b)



(c)

Figure 2. Sankey diagrams for the energy distribution of scenarios 1, 2 and 3

The only determination of the energy distribution in a process does not provide information about the percentage of energy that is being used. This use is associated with the amount of energy present in each of the products of the process with respect to the energy content of the raw material. Evaluating the energy efficiency for each of the main products for each scenario, values of 12.89, 8.55, 8.78, 2.57, 13.32 and 0.85% were obtained for HMF, furfural, nonane, octane, syngas and electricity, respectively. From these efficiency values can be observed that sugar cane bagasse has a high potential for obtaining HMF and syngas, since these are the products with the highest energy efficiency. Products such as octane and electricity do not have high-energy efficiency under the conditions analyzed. These results are related to the yields presented in the process. Thus, the energy efficiency value for a product is not only related to the product flow, it also considers the energy content of the component.

In order to analyze the energy quality in each of the proposed scenarios, the exergy in each of the processing stages was determined. Figure 3 shows the cumulative exergy by adding processing stages. As can be observed, the addition of stages not only allows the obtaining of different products, but also allows the increase of exergy. As a result, from the addition of stages, the energy potential of each process increases when a greater mass flow increases. Thus, the exergy flow in scenario 3, which involves a greater number of processing stages, was 43,831 MJ/h, while the exergy flows in scenarios 1 and 2 were 28,533 and 33,672 MJ/h.

Figure 3 shows that the octane and nonane production stages and the gasification process involve three transformation routes. Following only the lignin gasification route, it is observed that this route presents a greater exergetic flow in comparison with the routes followed to obtain octane and nonane. Comparing the last two routes, similar exergy flow was obtained although the mass flow of nonane was greater than that of octane. In addition, during the process of octane production, streams with a higher energy potential than the streams involved in the process of obtaining nonane are involved.

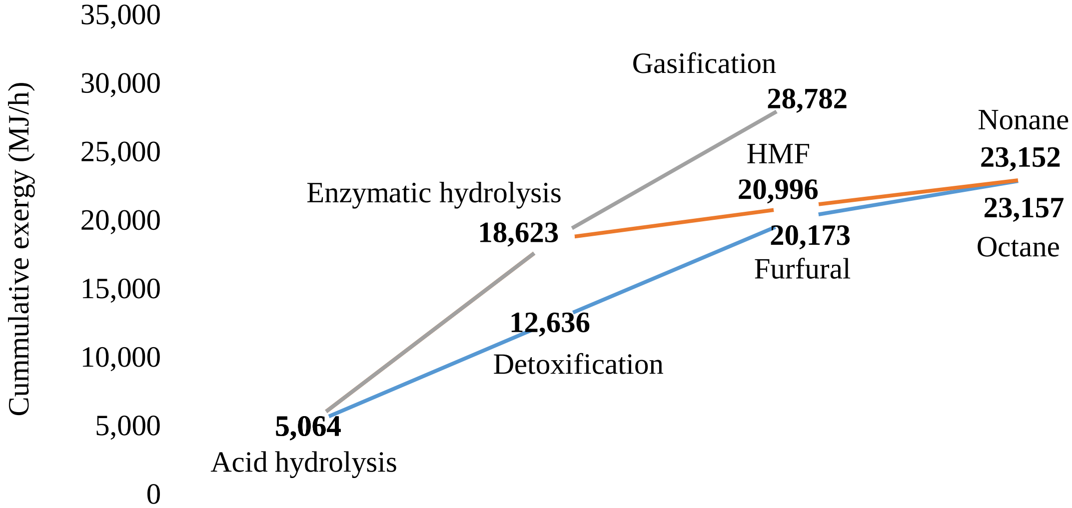


Figure 3. Cummulative exergy based on the transformation route

An energy comparison of the three scenarios shows that from scenario 3 it is possible to obtain a more efficient use of the energy present in the sugar cane bagasse. The scenarios 1, 2 and 3 presented an exergy of 0.08, 0.09 and 0.12 MJ per kg sugarcane bagasse. The scenario 3 presents a higher energy quality than the other two scenarios, i.e., it presents a higher value of exergy per kg of processed sugarcane bagasse. These results are showing that with the transformation of glucose and xylose into other products the exergy of the process does not show considerable variations. Nevertheless, with the addition of the gasification stage the exergetic flow presents a considerable increase, because this process allows the generation of electricity allowing a higher utilization of the energy present in the raw material. This is reflected in the exergetic efficiencies of each stage for each scenario, which are present in the Table 3.

Table 3. Exergy efficiency by stage in each scenario

Stage	Scenario 1	Scenario 2	Scenario 3
Acidy hydrolysis	17.75	15.04	11.55
Detoxification	26.54	22.49	17.28
Enzymatic hydrolysis	20.98	17.78	13.66
Furfural	26.41	22.38	17.20
HMF	8.32	7.05	5.41
Octane	-	8.86	6.81
Nonane	-	6.40	4.92
Gasification	-	-	23.18

CONCLUSION

The addition of processing stages can lead to a reduction in the energy losses of the process. However, this causes an increase in the energy potential of the process waste by increasing the mass flow. In order to identify the best transformation route in both technical and energy terms, it is necessary to evaluate different transformation alternatives. These would allow the identification of the best alternative for the transformation of a raw material.

The implementation of processing stages, which allow a better use of a raw material, leads to a better use both in technical and energy terms. However, since the same raw material may have different processing routes, different alternatives must be evaluated in order to select the best possible combination. In the present case the scenario 3 with the higher processing confirms that the exergy as well as the use of the energy are the best.

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