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Comparison between Single and Multi-Effect Evaporators for Sugar Concentration in Ethanol Production

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Among lignocellulosic materials, the waste generated in banana cultivation, such as the discarded fruit, peels, leaves and pseudostem demonstrates great potential for ethanol production. After hydrolysis, a concentration step of the hydrolyzate material is carried out to increase the amount of sugar available for the subsequent fermentation process, which is directly related to ethanol production. Despite being widely employed, the concentration continues to demonstrate certain limitations with respect to its use for cellulosic materials in second generation ethanol production due to the high energy consumption. Besides, the use of banana waste is not completely established, so studies concerning this process are important to evaluate all productive routes. Based on this, simulations of concentration of sugar from hydrolyzed lignocellulosic banana waste were carried out using the software Aspen HYSYS ®, aiming to obtain a concentrated broth containing 65 g/L of sugars with a simple evaporation system operating an atmospheric pressure. Same conditions were used to compare these results with a multi-effect evaporation system. Glucose concentration, the total amount of available sugars and inhibitors concentration were evaluated. Results have demonstrated that the energy consumption with multi-effect evaporator system is low with all residues: discarded fruit (636 kJ/h), banana peels (720 kJ/h) and pseudostem (734 kJ/h). Similar behavior was found for steam requirement: respectively 0, 2397 kg/h 0.3317 kg/h 0.3385 kg/h. As it is known, this is due to the fact that the steam generated in the first effect is used as heating fluid of the next effect. Even the multi-effect system proposed did not reach the 65 g/L of glucose with all residues, it is considered better than a single evaporator because the hydrolyzate streams contain additional sugars that can also be metabolized to ethanol during fermentation.

1. Introduction

As cited by Lora et al. (2002), renewable energy sources, such as biomass, minimize the environmental impact and are an attractive alternative for energy production. One example is ethanol, which is produced from sugar cane in Brazil, from corn or starch in the USA, and from beetroot in Europe.

As an alternative to the conventional substrates, the production of biomass from agricultural or agroindustrial waste is extremely environmentally friendly. Indeed, the overall environmental impact is minimized because the emission of CO_2 into the atmosphere is balanced by its absorption during the growth of new biomass (Balat et al., 2008). Waste, resulting either from agriculture or from any other source, is generated across the world. Thus, it appears reasonable to use it as a source for energy production. Among lignocellulosic materials, the waste generated in banana cultivation, such as the fruit peels, the pseudostem, the leaves, and the banana plant stalk, demonstrates great potential for ethanol production. Soffner (2001) relates that a conventional banana plantation generates a large amount of waste with an excellent fibrous potential, which is suitable for biomass production.

The model for ethanol production from lignocellulosic materials includes the hydrolysis of biomass polysaccharides into fermentable sugars, the subsequent fermentation of these sugars for ethanol production, and a final purification step. After the delignification step (i.e., pre-treatment), various methods of polymer hydrolysis can be used, including enzymatic and acid hydrolysis. Cellulose hydrolysis generates glucose and cellobiose (which is a glucose dimer). In contrast, hemicellulose hydrolysis generates sugars (i.e., pentoses) and byproducts (primarily, diphenols, phenylpropane derivatives, ketones, furfural, and acetic acid) that often inhibit microbial fermentation (Porto, 2005).

After hydrolysis, a concentration step of the hydrolyzate material is performed to increase the amount of sugar available for the subsequent fermentation process, which is directly related to ethanol production (Yadav et al., 2011). Despite being a widely employed step in ethanol production, the concentration step continues to demonstrate certain limitations with respect to its use for cellulosic materials in second generation ethanol production due to the high energy consumption (Nene et al., 2002). Many systems can be used to concentrate the hydrolyzate broth. For example, Yun et al. (2013) studied the simulation of the film evaporation process to achieve higher purity of the components in the hydrolyzate stream and to optimize the energy consumption for biodiesel production. Fonseca (2009) also described the process of concentration under vacuum for sugarcane bagasse hydrolyzate to increase the sugar content. Additionally, Sasaki et al. (2013) studied the concentration process via the nanofiltration of sugars present in rice straw hydrolyzate broth.

As an alternative to save energy, some industries utilize multiple-effect evaporators for broth concentration. Dias et al. (2014) described the basic principle of this process, which consists of dividing the evaporation into various vessels, which are termed effects or stages, and using the evaporated flow of one effect as the heating medium of the following effect. The use of multiple effects enables a large number of possible arrays depending on the vapor and liquid flows. Any multiple-effect evaporation operates in decreasing pressure levels along the direction of the vapor flow.

Because few studies have reported the use of waste from banana crops, it is important to evaluate all steps of ethanol production, even if they have already been well established for other raw materials. The present work aims to evaluate the concentration step of sugars in the hydrolyzate broth obtained from lignocellulosic residues of banana crop in the production process of ethanol. This study was conducted using the Aspen HYSYS® simulator and the objective is to simulate the sugar concentration step after the hydrolysis of banana waste (i.e., discarded fruit, peel, and pseudostem) comparing a single and multi-effect evaporators systems.

2. Material and Methods

The hydrolysis step of the ethanol production process using banana residues has already been addressed through simulations by Souza et al. (2013). Thus, this study focus on the subsequent process, i.e., the concentration of the hydrolyzate broth, which utilized the data from the cited study, i.e., the composition of the three streams of the hydrolyzate broth that were obtained from the discarded banana fruit, peel, and pseudostem residues. The analyzed components, both those available in the database of the simulator or hypothetical components (i.e., user defined), were introduced as presented by Souza et al. (2013).

The hydrolyzate stream obtained from the banana residues is directed to the evaporation system (i.e., the sugar concentration step) at a temperature of 99 °C and at atmospheric pressure. Table 1 shows the hydrolyzate stream composition, in weight fraction, for each residue. Xylose is introduced only in the stream corresponding to the pseudostem because this was the only residue that contained a quantified amount of hemicellulose, the hydrolysis of which produces this sugar. Similarly, furfural and acetic acid, which result from the degradation of xylose, were only evaluated when the pseudostem was used as the residue. The present study corresponds to the simulation of a continuous process, resulting from a hydrolysis process at a flow rate of 0.4 kg/h, which is equivalent to a residence time of 15 min, as was experimentally used.

The hydrolyzate broth stream was concentrated up to 65 wt.% in reducing sugars (approximately 65 g/L), which was defined based on the results of Dias et al. (2014), who described the operation of the industrial production of ethanol from bagasse and sugarcane in sugar-alcohol plants.

Table 1: Feed composition, in mass fractions, for each residue used

Variable	Discarded fruit	Peels	Pseudostem
Fructose	0.0188	0.0028	-
Water	0.9497	0.9919	0.9962
Glucose	0.0207	0.0050	0.0020
Sucrose *	0.0106	0.0003	-
Xylose	-	-	0.0017
Furfural	-	-	0.000057
Acetic Acid	-	-	0.000034

* Represented by sum of glucose and fructose

The simulation was performed using the HYSYS software from Aspen Tech, version 7.3. An NTRL thermodynamic model was defined, as indicated by Dias et al. (2014). The simulation of the sugar concentration step was performed for the discarded fruit, peel, and pseudostem using a single evaporator under atmospheric pressure, which employed a flash-type separator with the energy supplied by the saturated vapor operating at a temperature of 130 °C and a pressure of 2.74 bar. To determine the energy demand in this process, the operation temperature of the evaporator was gradually varied (from 120 °C to 200 °C with an interval of 20 °C) until the maximum weight fraction of glucose was obtained, and all of the glucose mass remained in the concentrated broth stream. Additionally, the vapor streams, the weight fractions of water, fructose, glucose, sucrose, xylose, acetic acid, furfural, and hydroxymethylfurfural (HMF), and the energy supplied to the process were analyzed.
The multi-evaporator system was simulated with initial atmospheric pressure, with a pre-evaporator and four effects. In this case, the decrease in pressure between each effect was fixed at approximately 20 kPa such that the pressure in the last evaporator was identical to that in the study reported by Dias et al. (2014). The conditions used in the simulations are presented in Table 2.

Table 2: Operational conditions employed in the simulations using multiple-effect evaporation

Variable	Pre-evaporator	1st effect	2nd effect	3rd effect	4th effect
Pressure (bar)	1.013	0.800	0.600	0.400	0.200
Temperature (^oC)	100.0	93.5	86.2	76.7	73.4

3. Results and Discussion

3.1 Single evaporator

Table 3 shows the results obtained for tests carried out with a single evaporator. The temperature was determined by increments until reach the maximum of glucose in concentrated stream with loss of this component for the vapour phase.

Table 3: Compiled results from the system using a single evaporator at atmospheric pressure for the residues of discarded banana fruit, peel, and pseudostem considering only glucose as available sugar for fermentation

Variable	Discarded fruit	Peels	Pseudostem
Temperature (^oC)	160.0	129.0	155.0
Glucose weight fraction	0.47	0.65	0.53
Concentrated flow (Kg/h)	0.01711	0.002964	0.001490
Energy (KJ/h)	881.2	898.5	934.6
Steam flow required (Kg/h)	0.4095	0.4139	0.4305

Using a single evaporator and considering glucose, only the hydrolyzate from banana peels reach the desired 65 g/L of this sugar in concentrated broth. Considering the studies of Ozmihci and Kargi (2007), the best ethanol yield was obtained with feed sugar concentration between 100 and 125 g/L. Based on this, results obtained with only one evaporator indicate that the residue of banana peels is recommended for use aiming ethanol production.
When the water present in the hydrolyzate broth is evaporated, the sugar in the desired stream is concentrated. However, the concentration of components that inhibit the fermentation process can also occur. When all of the components present in the streams coming from the separator outlet at the temperature indicated in Table 3 were analysed, HMF, furfural and acetic acid weight fractions were not sufficiently high to inhibit the fermentation process. Indeed, because the boiling temperature of this components are lower than the concentration temperature, they are partially evaporated (which is in agreement with the composition of the vapor stream).
Note that the hydrolyzate stream from the residues fruit is composed of other sugars. These sugars can be metabolized to ethanol during fermentation. In this regard, the sum of all of the available fermentable sugars in the outlet stream of the separator resulted in a concentration of reducing sugars of 65 wt.% for all residues studied, as illustrated in Table 4. That is, a lower temperature is required when only glucose is considered to obtain the final desired concentration.

The flow rate of the hydrolyzate stream is higher for the total sugars due to the less evaporation of water, which is the major component (evaporation occurs at minor temperature) and the concentration of all fermentable sugars (i.e., glucose, fructose, sucrose, and xylose) present in the concentrated broth stream.

Table 4: Compiled results from the system using a single evaporator at atmospheric pressure for the residues of discarded banana fruit, peel, and pseudostem considering all fermentable sugars

Variable	Discarded fruit	Peels	Pseudostem
Temperature (°C)	101.8	102	102.6
Glucose weight fraction	0.6514	0.6545	0.6507
Concentrated flow (Kg/h)	0.0415	0.0047	0.0022
Energy (KJ/h)	786.0	873.4	890.8
Steam flow required (Kg/h)	0.3620	0.4023	0.4103

It is important to consider the degradation temperature of the reducing sugars. Dehkhoda (2008) states that at temperatures higher than 120 °C, the degradation of sugars present in the hydrolyzate broth can occur. This aspect is not observed in the simulation due to the limitation of the software. Additionally, the simulator does not identify the temperature of the hydrolysis of sucrose into glucose and fructose without the catalytic action of invertase, which can thermally occur in acidic medium. According to Kelly et al. (1978), this phenomenon may occur at temperatures above 100 °C. So, in case of consider only glucose as available sugar for fermentation, a higher concentration of glucose and fructose in the stream could have been attained for discarded fruit once this residue exhibits a high amount of sucrose (1.06 %). But, more than this, the use of lower temperatures could be interesting to prevent degradations like this reported.

3.2 Multi-effect evaporators

For tests with multi-effect evaporator system, the hexose broth is concentrated using a pre-evaporator and four effects. As illustrated in Figure 1, the glucose weight fractions obtained at the outlet of the last evaporator were 35 %, 54.99 %, and 47.94 %, for the discarded fruit, peel, and pseudostem, respectively. In all cases, a concentration below the desired value of 65 wt.% of glucose was achieved. Based on this, a greater number of stages would be necessary to obtain higher yields (approximately 65 wt.% of the desired hexose). Same indication was done by Gnansounou and Dauriat (2010) who studied a techno-economic analysis of lignocellulosic ethanol. The authors evaluated a system with 5 evaporators and recommended the use of more units.

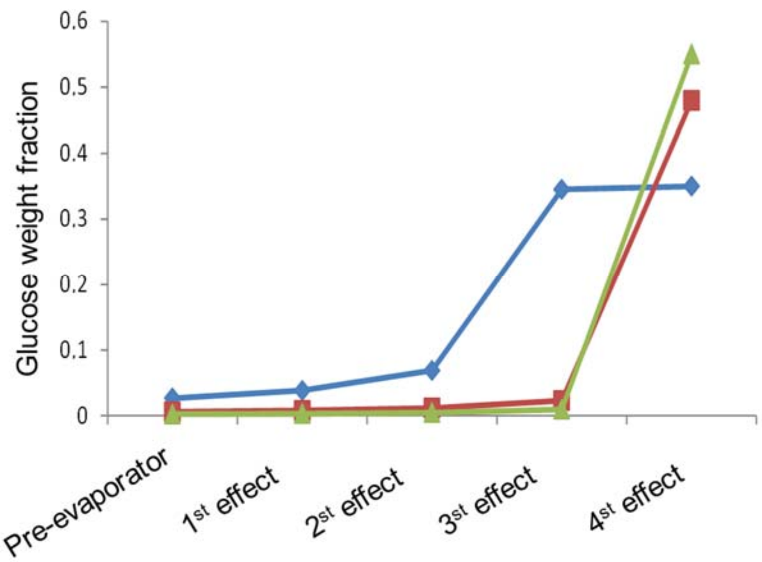

Figure 1: Glucose weight fraction profiles in concentrated streams for a multi-effect evaporator operating at atmospheric pressure (-♦- discarded fruit, -■- peels, -▲- pseudostem)

However, the hydrolyzate broth contains other sugars in addition to glucose. A comparison of the results of the concentration of glucose alone with the sum of all of the available hexoses in the broth (which results from the discarded fruit and the peel) and xylose (which results from hemicellulose hydrolysis of the pseudostem) (Figure 2), revealed that the desired sugar weight fraction is obtained in the latter case. Indeed, in the last stage, the sugar weight fractions attained the values of 84%, 86%, and 88% for the discarded fruit, peel, and pseudostem, respectively. Thus, streams much richer in fermentable sugars were produced when the desired hexoses were summed than in a stream in which glucose alone was considered.

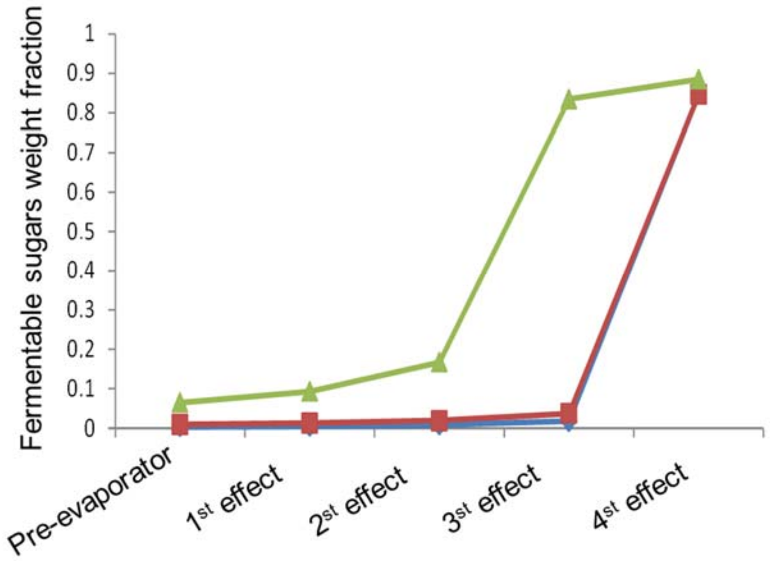

Figure 2: Available sugars weight fraction profiles in concentrated streams for a multi-effect evaporator operating at atmospheric pressure (-◆- discarded fruit, -■- peels, -▲- pseudostem)

No differences in the analysis of the furfural and acetic acid inhibitors were observed in the single evaporation system in comparison to the process with multi-effect evaporators. However, the HMF concentration was above the limit of 0.00025, specifically, 0.0038 for the discarded fruit, 0.0021 for the peel, and 0.0012 for the pseudostem. This finding indicates that the inhibition caused by HMF must be considered in the process using these types of banana crop waste.

When the multiple-effect evaporation process at atmospheric pressure was used instead of a single evaporator operating at atmospheric pressure, the energy consumption was lower for the three types of waste (636 kJ/h, 720 kJ/h, and 734 kJ/h, for the discarded fruit, peel, and pseudostem, respectively) as was the vapor demand (0.2397 kg/h, 0.3317 kg/h, and 0.3385 kg/h for the discarded fruit, peel, and pseudostem, respectively) because the vapor generated in the first effect was used as the heating fluid of the following effect. In addition, these results are in agreement to those reported by Dias (2008) that observed an increase in vapor demand as far as the sugar concentration is higher.

4. Conclusions

In the simulations of the hydrolyzate broth utilizing a single evaporator at atmospheric pressure, the desired value of 65 wt.% of glucose was observed only using banana peel as the substrate. However, if considered all fermentable sugars, all residues could be used to obtain the desired sugar concentration. However, it is important to notice that for case of pseudostem co-cultures should be employed once different microorganism metabolises glucose and xylose. For the three types of banana crop waste, the amount of inhibitor produced was negligible.

The proposal of multi-effect evaporators presents a good alternative to concentrate the hydrolyzate once enables reduces the energy requirement, as expected. When considered only glucose as available sugar, the multi-effect system exhibited lower sugar concentrations, except for pseudostem. But it is important to consider that this residue has major potential of use, so the result obtained encourages the use of this concentration system.

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