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Economic and environmental assessment of syrup production. Colombian case

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HIGHLIGHTS

- Six Colombian agroindustrial wastes were used for glucose syrup production.
- A techno-economic analysis for glucose syrup production was made.
- An environmental analysis of glucose syrup production was made.
- Energy cost is an important factor for the total production cost of syrups.
- Heat integration strategy is suggested for syrup production.

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ABSTRACT

This work presents a techno-economic and environmental assessment of the glucose syrups production from sugarcane bagasse, plantain husk, cassava husk, mango peel, rice husk and corncobs. According to the economic analysis, the corncob had both, the lowest production cost (2.48 USD/kg syrup) and the highest yield (0.61 kg of sugars/kg of wet agroindustrial waste) due to its high content in cellulose and hemicellulose. This analysis also revealed that a heat integration strategy is necessary since the utilities consumption represent an important factor in the production cost. According to the results, the pretreatment section requires more energy in the syrup production in comparison with the requirements of other sections such as production and sugar concentration. The environmental assessment revealed that the solid wastes such as furfural and hydroxymethylfurfural affected the environmental development of the process for all the agroindustrial wastes, being the rice husk the residue with the lowest environmental impact.

1. Introduction

One of the main issues in the management of agroindustrial chains in Colombia is related to the final disposal of the generated residues. Residues from fruits, vegetables, corn, wood and other industries based on biomass are obtained in large quantities. This fact is due to the low efficiencies in different processing steps such as cultivation, transportation, cooling chain and distribution, among others. The potential chemical composition of the agroindustrial wastes allows using them as source to obtain value added products under modern biomass utilization technologies (Quintero et al., 2011).

Different agroindustrial residues have been used to produce compounds with high value in the market. Ethanol has been produced from empty fruit bunches reaching yields of 59.6% after hydrolysis (Piarpuzán et al., 2011) also; fuel ethanol has been produced from lignocellulosic biomass with an energy consumption of 41.96 MJ/l of ethanol (Cardona and Sánchez, 2006). Rice husk has been used as substrate for microalgae growth to produce oil reaching a yield of 0.37 kg of oil/kg of dry microalgae with a production cost of 0.56 USD/kg of oil (Jaramillo et al., 2012). In the case of fruits, compounds as essential oils, pectin, flavonoids, phenolic compounds and anthocyanins, among others can be obtained from their residues (Yepes et al., 2008). On the other hand, residues such as sugarcane bagasse and corncobs are considered important lignocellulosic residues, because of its large quantities and its potential application in ethanol production.

Some important agroindustrial wastes in Colombia are related to the residues generated from Plantain (*Musa sapientum*), Cassava (*Manihot esculenta*), Mango (*Manguifera Indica* L.), Rice (*Oryza sativa*) and Corn (*Zea mays*) processing. For 2011, Colombia had a

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production of 2.82, 1.87, 2.24, 23.18, 1.07 and 0.22 millions of tonnes of plantains, cassava, rice, sugarcane, corn and mango, respectively (MADS, 2012).

The agroindustrial chains of the crops above mentioned have not only high losses due to the low efficiencies in several production steps but also large quantities of generated residues. For instance, in the case of plantain approximately 20% to 30% of the total biomass is utilized while the remaining is used as fertilizer and as animal supplement food (Botero and Mazzeo, 2009). In the cassava processing approximately 96.2% of the total wastes correspond to solids which have an inadequate management causing negative impact over the environment (Marmolejo et al., 2008). In the pulping process of mango, approximately 55% of the residues are obtained as solids wastes (Mejía et al., 2007). In the case of rice, 400,000 tonnes of husk are produced per year (Piñeros et al., 2011). In the corn processing, the corncobs production is approximately 532,000 tonnes per year. Finally, taking into account that the sugarcane production in 2011 was 23.18 millions of tonnes (MADS, 2012) and that this crop generates approximately 280 kg of bagasse per tonne of sugarcane then, 6.49 millions of tonnes of sugarcane bagasse were produced.

The agroindustrial wastes above mentioned have low or no cost throughout the year, besides its availability and its important composition in cellulose and hemicellulose are characteristics that allow considering these wastes as adequate substrates for sugar production (Mejía et al., 2007; Piñeros et al., 2011). Moreover, some of these agroindustrial wastes can also be considered as potential feedstocks for ethanol production in Colombia (Quintero et al., 2008).

Considering the above mentioned, this work presents a techno-economic and environmental assessment for the glucose syrup production in the Colombian context using sugarcane bagasse, plantain husk, cassava husk, mango peel, rice husk and corncobs as feedstocks. Computer-aided process engineering tools are used as a promising alternative to evaluate this kind of processes. In order to carry out the techno-economic and environmental assessment, operational conditions, yields and relevant data from experimental works reported in the literature are used.

2. Methods

The methodology employed in this work consists on three steps using different computational tools. The first step corresponds to the process simulation to obtain the mass and energy balances of the process using *Aspen Plus V8.0* (AspenTech: Cambridge, MA). The physicochemical properties of all the involved compounds in the simulation were obtained from the National Institute of Standards of Technology (NIST, 2012). To calculate the properties in the liquid and vapor phases, the Non Random Two Liquids (NRTL) model and the Hayden O'Conell (HOC) equation were used, respectively. NRTL model was used to estimate the activity coefficients of all the compounds from its mole fractions in the liquid phase. The HOC equation provides a method for predicting a second virial coefficient for multi-compounds vapor mixtures. These methods are used to calculate successfully phase equilibria in the type of mixtures with non-conventional compounds (Cardona and Sánchez, 2006; Jaramillo et al., 2012; Quintero et al., 2008). The second step corresponds to the economic analysis using *Aspen Process Economic Analyzer* (AspenTech: Cambridge, MA). This evaluation was developed for the six proposed agroindustrial wastes used as raw materials. The final step corresponds to the environmental analysis where the *Waste Algorithm Reduction* Software (WAR GUI) developed by the U.S. Environmental Protection Agency (EPA) was employed. This software uses a method of direct data sum based on the mass and energy streams of the process and the environmental impact that these streams can have over four principal categories (Human toxicity, ecological toxicity, global atmospheric impacts and regional atmospheric impacts). These impacts are calculated according to parameter values such as Lethal Dose (LD50) which eliminates the 50% of the population (e.g. rats), Limit Concentration (LC50) which eliminates the 50% of the population and Permissible Exposure Limit (PEL) for a substance or compound.

The steps one and two using Aspen Plus software were performed following a sequence of calculations from the information given by the user. Once the flow diagram and compounds are defined, the thermodynamic models are selected according to the characteristics of each compound and units as well as operational conditions. After, the simulation is run to obtain the mass and energy balances of the process.

Thus, the economic analysis is made extracting the information about mass and energy balances, flows, temperatures, pressures and number of units from Aspen Plus. This information is combined with the economic parameters given by the user such as economic life of the project, tax rate, desired rate of return, utilities, costs (raw materials, reagents, products, electricity, potable water and fuel), operating cost (operator, supervisor) and depreciation method to carry out the economic evaluation. Once all of this information is provided, it is used to calculate the raw materials and utilities costs and the depreciation expensive as well as the operating, general and administrative, plant overhead and charge costs. Thus, it is possible to calculate the total production cost and energy requirements of the process.

2.1. Raw material

Table 1 shows the chemical composition of sugarcane bagasse, plantain husk, cassava husk, mango peel, rice husk and corncobs, which were the selected agroindustrial wastes (Baah et al., 1999; Dagnino et al., 2013; Guo and Rockstraw, 2007; Happi et al., 2007; Hoareau et al., 2004; López et al., 2013; Mansilla et al., 1998; Marmolejo et al., 2008; Mejía et al., 2007; Miura et al., 2004; Pandey et al., 2000).

2.2. Process simulation description

Fig. 1 shows the glucose syrup production scheme, which is the same for all the selected raw materials. The process begins drying the feedstock with air to remove the moisture. Then, the dried material was milled to obtain particles with sizes smaller than 0.45 mm. In order to improve the cellulose accessibility, a diluted acid hydrolysis using sulfuric acid (2% v/v) at 121 °C was carried out. Diluted acid hydrolysis was selected not only because it is the most commonly employed chemical pretreatment but also because it permits to enhance biomass digestibility obtaining good cellulose accessibility. Besides, this pretreatment allows achieving high reaction rates and producing lower quantities of fermentation inhibitors that could reduce the syrup quality (Agbor et al., 2011; Dagnino et al., 2013; Haghighi et al., 2013). Other pretreatment methods such as ionic liquids and organosolv present higher costs because of the solvent recovery. In the case of Ammonia Fiber Explosion (AFEX), costs increase because of the ammonia (Haghighi et al., 2013). Other methods such as concentrated acid hydrolysis and steam explosion produce appreciable amounts of toxic compounds, affecting the quality of the syrup. On the other hand, alkaline methods require long pretreatment resident time (Agbor et al., 2011; Haghighi et al., 2013). From this pretreatment, traces of furfural and hydroxymethylfurfural (HMF) were obtained. After, the liquid phase was sent to a xylose recovery process while the solid phase was used to produce glucose through an enzymatic hydrolysis at 50 °C (Sindhu et al., 2011).

Once the stream containing xylose is separated, the remaining water is evaporated. Additionally, a detoxification process with