Analysis of the improvement of a biorefineries based on sugarcane through the sugarcane bagasse inclusion as platform

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Abstract

According to the International Energy Agency (IEA) Bioenergy Task 42, a biorefinery is defined as "A sustainable processing of biomass into a spectrum of marketable products and energy" [1]. An integrated biorefinery employs the combination of raw materials and its basic concept is to produce bioenergy and chemical platforms from biomass through transformation routes, integrating processes and equipment. Its goal is to reduce the environmental impact, to consume less fossil energy and create economic advantages [2]. In this case it is important to note the purpose of the biorefinery is that the integration reaches better features that the stand-alone processes. In this sense, this work has as main goal to show the results of a comparison between biorefineries from sugarcane (SC) making emphasis in inclusion of the sugarcane bagasse as feedstock and the number of products to be obtained. The first biorefinery considers the obtaining of three products (i.e. sugar, ethanol and electricity), the second and third biorefinery have the products mentioned before plus, xylitol and polyhydroxybutyrate (PHB), respectively. The comparison is made taking into account technical and economic aspects determined based on characterization indices such as, Biorefinery complexity index (BCI), Biorefinery mass index (MI_B), Biorefinery water-mass index (MI_B^w), Biorefinery reagents-mass index (MI_B^r), Biorefinery co-products and by-products-mass index $\left(MI_B^{cop-byp}\right)$, Biorefinery energy index by equipment ($EnI_{B-equip}$) and Biorefinery economic index (EcI_B).

Keywords. Sugarcane, biomass processing, biorefineries, characterization indices.

1. Introduction

The search for alternatives that generate environmentally friendly and economically sustainable processes, has for many years been one of the main topic in the industry. Likewise, the use of renewable feedstocks to obtain added-value products has become a necessity of the current market [3]. For example, in the last years SC has been used in the production of sugar, ethanol and electricity. Sugar is produced from sugarcane juice, ethanol from sugarcane molasses through fermentation and electricity from sugarcane bagasse (SCB) by combustion reaction. SCB is a fibrous material obtained as residue in the sugar mills. Where, 50% of this residue is used for the energy production [4].

SCB as main residue in the processing of sugarcane is presented. For each ton of SC processed to obtain juice, 280 kg of SCB is produced [4]. SCB is composed of cellulose 40-45%, hemicellulose 30-35%, lignin 20-30% and ash 1.9%, which gives it advantages in comparison with other lignocellulosic residues [4]. The high production of this waste encourages its use to obtain added-value products [4]. The SCB as lignocellulosic residue can be used as raw material to obtain chemicals (organic acids) and biofuels (ethanol and butanol) [5], generating a range of additional alternatives to the energy production. When a set of products is obtained at the same time and with the same importance appears the biorefinery concept. This concept gives an integral harnessing of feedstock and generates economic and environmental advantages to the use of sugarcane bagasse.

In recent years, biorefinery has been a research objective, given that this configuration of processes for the use of biomass, presents better economic and environmental characteristics compared with stand-alone processes [6]. According to this concept, the selection of feedstock, technologies and products are a fundamental issue for the design of biorefineries with the best characteristics. However, this selection is not easy and is necessary applying tools to guide and simplify the process. The characterization indexes allow reducing the working time and simplifies the calculations in the design of the biorefineries [7].

In this sense, this work assesses the feasibility of sugar mill as base scenario and biorefinery schemes (addition of products to base scenario) for the transformation of SC. SC was considered as raw material to produce sugar, electricity, ethanol, xylitol and PHB. Three cases were proposed in order to evaluate the effect of the addition of products to base scenario and to analyze its improvement through proposed characterization indices. The characterization indices were determined in order to generate a preliminary screen during the conceptual design of SC biorefineries.

2. Methodology

Currently in Colombia the SC is used to produce sugar, ethanol fuel and electricity in plants called sugar mills. In this work, this base case was evaluated and two scenarios were proposed in order to assess the effect of the addition of products under biorefinery concept to the base case. The sugarcane bagasse was used to obtain the added-value products (xylitol and PHB). The scenarios were assessed from technical and economic point of view based on proposed characterization indices in order to generate a preliminary screen during conceptual design of studied biorefineries.

2.1 Raw material

Sugarcane (SC) is mainly composed of cellulose 6.55%, fructose 0.61%, glucose 0.91%, hemicellulose 5.45%, lignin 1.43%, protein 0.4%, sucrose 13.64%, moisture 70.40%, ash 0.51% and anthocyanins 0,1% [8]. This chemical composition is used as starting point in the simulation procedure to obtain sugar, ethanol, electricity, xylitol and PHB as main products.

2.2 Scenarios

Three scenarios of SC transformation were proposed in order to perform a technical an economic assessment of the sugar, ethanol, electricity, xylitol and PHB production. **Table 1** presents a detailed description of the processes involved in the three scenarios. The typical SC transformation in Colombia (the production of sugar, ethanol and electricity) was selected as base case (scenario 1) for the comparison with two biorefineries that include the obtaining of additional one and two products, where the conceptual design methodology of a biorefinery was applied [9].

Table 1. Description of scenarios considered in SC processing.

Scenarios	Products	Description
1	Sugar, ethanol and electricity	Current Colombian base case. Sugar production from cane juice, ethanol production from molassess (sugar milling) and electricity generation from sugarcane bagasse (sugar milling).
2	Sugar, ethanol, xylitol and electricity	Xylitol production from xylose obtained in the acid hydrolysis of sugarcane bagasse and electricity generation from remaining solids of acid hydrolysis.

3	Sugar, ethanol, xylitol, PHB and electricity	PHB production from glucose obtained in the enzymatic hydrolysis (after acid hydrolysis) of sugarcane bagasse and electricity generation from remaining solids of enzymatic hydrolysis.

2.3 Process description

For the simulation procedure, a maximum plant processing capacity of 10 ton SC h^{-1} was considered. **Figure 1** presents the schematic description of the processes involved in the SC processing. SC biorefinery can be described as a six processes system. A detailed description of each stage and the technologies used in the biorefinery are presented below.

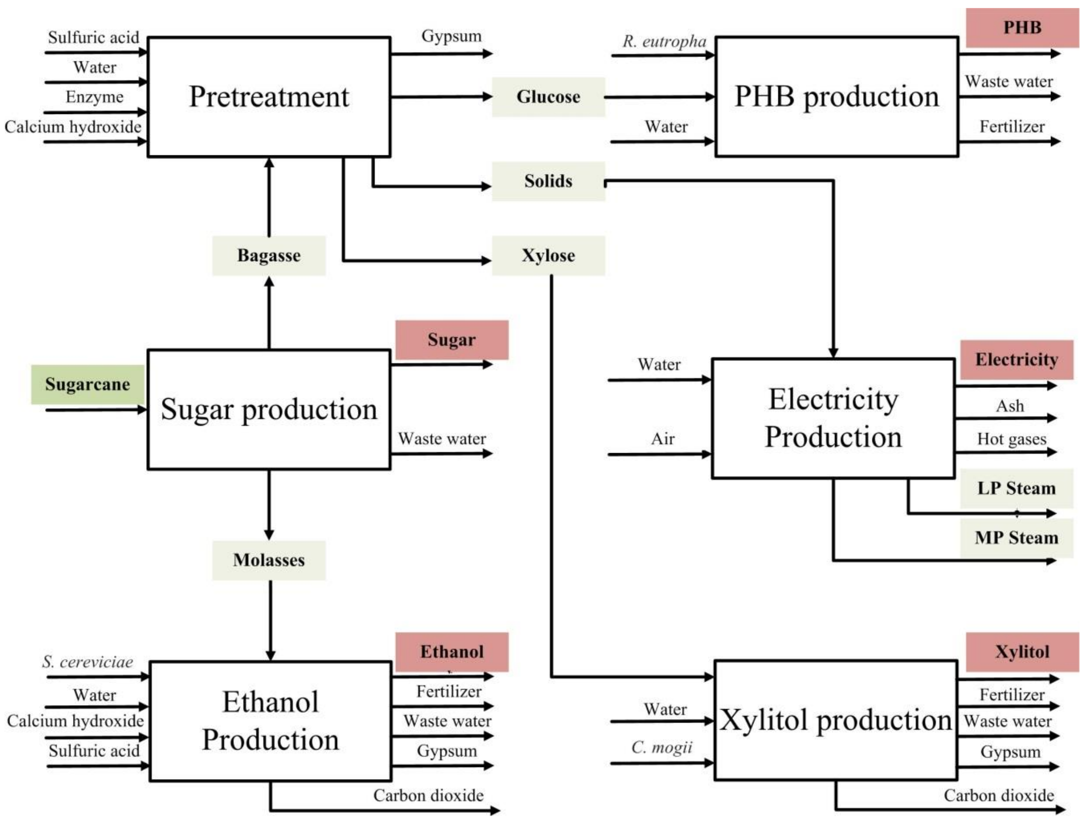

Figure 1. Global schematic description of the processes involved in the sugar, ethanol, xylitol, PHB and electricity production (Scenario 3).

2.3.1 Sugar milling

Sugar production process was developed using a conventional technology from sugar milling. The SC was submitted to milling where the juice from bagasse was extracted [8]. The sucrose extraction yield reached 95%. In the scenario 1, the bagasse was sent to electricity generation, in the scenarios 2 and 3, the bagasse was sent to a particle size reduction, acid hydrolysis and/or enzymatic hydrolysis in order to extract the sugars contained in the lignocellulosic material. Then, the juice was submitted to clarification at 110°C and filtration processes [8]. The clarified cane juice was sterilized and was sent to sugar production. After this pretreatment stage, sugar concentration was carried out in an evaporation train as the well-known technology for concentrating the juice approximately to 80% by weight to obtain the syrup [10]. Finally, sugar rich syrup was passed through a section of crystallizers at vacuum pressure where sugar crystals were formed and molasses were obtained. The molasses were used as raw material to produce ethanol.

2.3.2 Ethanol production

The molasses were submitted to acid hydrolysis in order to reduce it to simple sugars as fructose and glucose. The acid hydrolysis was carried out at 70°C and pH 2.5 with H_2SO_4 [11]. Rich-glucose liquor obtained in acid hydrolysis was submitted to detoxification in order to neutralizer the inhibitors produced (i.e. HMF, furfural) [12]. The glucose was submitted to a fermentation process to obtain ethanol based on the kinetic expressions using *Saccharomyces cerevisiae* as microorganism at 37ºC [13]. Afterwards, cell biomass was separated from the culture broth by a simple gravitational sedimentation technology. After the fermentation stage, the culture broth containing approximately 5-10% (wt/wt) of ethanol was taken to the separation step, which consists of two distillation columns. In the first column, ethanol was concentrated nearly to 45-50% by weight. In the second column, the liquor was concentrated until the azeotropic point (96% wt/wt) followed by a dehydration step with molecular sieves to obtain an ethanol concentration of 99.6% (wt/wt) [14].

2.3.3 Electricity generation

The technology used for the cogeneration procedure was the biomass integrated gasification combined cycle (BIGCC) [15], [16]. Basic elements of BIGCC system include biomass dryer, gasification chamber, gas turbine and heat steam recovery generator (HRSG). Gasification is a thermo-chemical conversion technology of carbonaceous materials (coal, petroleum coke and biomass), to produce a mixture of gaseous products (CO, CO_2, H_2O, H_2, CH_4) known as syngas added to small amounts of char and ash. Gasification temperatures range between 875-1275 K [17]. A gas turbine is a rotator engine that extracts energy from a combustion gas. It is able to produce power with an acceptable energy efficiency, low emission and high reliability. The gas turbine is composed in this case by three main sections: compression (the pressure of the air is increased aiming to improve the combustion efficiency), combustion (adiabatic reaction of air with fuel to transform chemical energy to heat) and expansion (production of pressurized hot gas at high speed that generates mechanical work through a turbine) [18].

2.3.4 Sugar extraction

Sugarcane bagasse from the sugar milling were submitted to three stages process: i) particle size reduction, ii) acid hydrolysis and iii) enzymatic hydrolysis. The particle size reduction and acid hydrolysis increases the availability of the raw material for enzymatic hydrolysis. The expected final particle size is 1 mm. The acid hydrolysis was carried out at 100°C with H_2SO_4 solution of 2% (v/v) [19]. Rich-pentose liquor obtained in acid hydrolysis was submitted to detoxification [12]. Then, this liquor was used in the xylitol production (scenario 2). The cellulose fraction was hydrolyzed based on kinetics expressions at 50ºC to obtain hexoses and remaining hemicellulose together with lignin as a solid system [20]. Rich-hexose liquor was used in the PHB production and the solid residues to generate electricity (Scenario 3).

2.3.5 Xylitol production

The rich-pentose liquor was sterilized at 121°C in which the biologic activity was neutralized. The fermentation process to obtain xylitol with *C. mogii* was performed at 30°C under aerobic conditions (dissolved oxygen concentration of 20%) [21] and the purification process consists on an evaporation to eliminate the excess of water for facilitating the concentration by crystallization, adding ethanol in order to decrease drastically the xylitol solubility and supersaturate the solution to carry out the crystallization at 5°C [22].

2.3.6 PHB production

The rich-hexose liquor was sterilized at 121°C in which the biologic activity was neutralized. The fermentation process to obtain PHB is carried out using *R. eutropha* at 30ºC [23] and the purification process consists on evaporation and spray drying to obtain PHB approximately at 98% wt/wt.

2.4 Techno-economic assessment

For all proposed scenarios, mass and energy balances were obtained using simulation procedures. Thus, an integral analysis of the flowsheet allows understanding the technical feasibility of the proposed biorefinery. The commercial package Aspen Plus (Aspen Technology, Inc., USA) was used as the main simulation tool. Specialized package for programming mathematical calculations especially for kinetic analysis such as Matlab (MathWorks, USA) was also used. Non-Random Two-Liquid (NRTL) thermodynamic model was the

selected thermodynamic model to calculate the activity coefficients of the liquid phase and the Hayden-O'Connell equation of state was used for describing the behavior of the vapor phase.
The capital and operating costs are calculated using the software Aspen Process Economic Analyzer (Aspen Technologies, Inc., USA). This analysis was estimated in US dollars for a 10-year period at an annual interest rate of 17% (typical for the Colombian economy), considering the straight-line depreciation method and an income tax of 25%. Prices and economic data used in this analysis correspond to Colombian conditions such as the costs of the raw materials, income tax, labor salaries, among others. **Table 2** summarizes the economic data for raw material, reagents and products.

Table 2. Price/cost of feedstock and products used in the economic assessment.

Item	Unit	Price	Reference
SC	USD ton^{-1}	35	*
Sulfuric acid	USD kg^{-1}	0.094	[24]
Calcium hydroxide	USD kg^{-1}	0.11	[25]
Sugar	USD ton^{-1}	414.26	[26]
Ethanol	USD kg^{-1}	0,995	[27]
Xylitol	USD kg^{-1}	3.5	[25]
PHB	USD kg^{-1}	3.6	[25]
Low pressure steam	USD ton^{-1}	1.57	[10]
Medium pressure steam	USD ton^{-1}	8.18	[10]
High pressure steam	USD ton^{-1}	9.56	[10]
Cooling Water	USD m^{-3}	0.74	*
Electricity	USD kWh^{-1}	0.0371	*
Operator labor	USD h^{-1}	2.72	*

* Prices adapted to the Colombian context.

2.5 Characterization indices to evaluate the efficiency of a biorefinery

This work proposes the use of three levels to characterize the performance of a biorefinery. The characterization indices were determined in order to generate a preliminary screen during the conceptual design of SC biorefineries. A description of proposed indices to characterize a biorefinery is presented below.

2.5.1 Biorefinery complexity index (BCI)

In the case of oil refineries, there is an index that allows measuring its conversion capacity with respect to the capacity of primary distillation. This index is called "Nelson's complexity index" and it allocates a complexity factor to each process that composes the refinery. The index indicates the required investment or the refinery cost and the potential of value-added products. Analogous to this, for biorefineries there is an index called "biorefinery complexity index - BCI".

A biorefinery has features as feedstocks, platforms, products and processes [7]. The BCI is estimated for each feature through a Feature Complexity Index (FCI) using the equation (1).

$$\mathrm{BCI} = \sum_{j=1}^{m} \mathrm{FCI_i} \qquad (1)$$

The FCI is determined as the product of Number of Features (NF) and Feature Complexity (FC) as indicates the equation (2).

$$\mathrm{FCI_i} = \sum_{j=1}^{m} \mathrm{NF_i} * \mathrm{FC_i} \qquad (2)$$

The FC is determined based on the equation (3), which considers the Technology Readiness Level (TRL) for each feature. The TRL is assessed taking into account a level description in a range of 1 (basic research) to 9 (system proven and ready for full commercial deployment) [7]. In the case of feedstocks and products, that can be or will be commodities in the market, are evaluated according to "Market Readiness Level (MRL)" that is analogous to TRL.

$$\mathrm{FC_i} = 10 - \mathrm{TRL_i} \tag{3}$$

When the BCI and FCI for each feature are obtained, the numerical meaning of technical and economic state of a biorefinery is calculated as Biorefinery Complexity Profile (BCP) as indicates the equation (4).

$$\mathrm{BCP} = \mathrm{BCI}(\mathrm{FCI_{platforms}}/\mathrm{FCI_{feedstocks}}/\mathrm{FCI_{products}}/\mathrm{FCI_{processes}}) \tag{4}$$

Where:
FCI: Feature Complexity Index
NF: Number of Features
FC: Feature Complexity
TRL: Technology Readiness Level
BCP: Biorefinery Complexity Profile

2.5.2 Biorefinery mass index

This index relates the ratio of the mass of valuable products to fresh biomass fed into the biorefinery. This index can be called Biorefinery mass index ($\mathrm{MI_B}$) and it is defined by equation (5). A $\mathrm{MI_B}$ is good when the value tends to 1, namely the yields are high.
Other alternative indices for $\mathrm{MI_B}$ are Biorefinery water-mass index ($\mathrm{MI_B^w}$), Biorefinery reagents-mass index ($\mathrm{MI_B^r}$) and, Biorefinery co-products and by-products-mass index ($\mathrm{MI_B^{cop-byp}}$). $\mathrm{MI_B^w}$considers the ratio of the mass of valuable products to water inputs streams and biomass fed. $\mathrm{MI_B^r}$ determines the ratio of the mass of valuable products to biomass fed and chemical reagent inputs (i.e. sulphuric acid, sodium hydroxide, etc.). $\mathrm{MI_B^{cop-byp}}$ relates the mass of valuable co-products and by-products to fresh biomass fed. The goal of these indices is to assess with major deep the technical efficiency of a biorefinery and show the effect with the addition of others streams to the calculation. Then, $\mathrm{MI_B^w}$, $\mathrm{MI_B^r}$ and $\mathrm{MI_B^{cop-byp}}$ are defined by Equations (6), (7) and (8) respectively.

$$\mathrm{MI_B} = \frac{\sum_{i=1}^{n} m_i^p}{\sum_{j=1}^{n} m_j^f} \tag{5}$$

$$\mathrm{MI_B^w} = \frac{\sum_{i=1}^{n} m_i^p}{\sum_{j=1}^{n} m_j^w + \sum_{j=1}^{n} m_j^f} \tag{6}$$

$$\mathrm{MI_B^r} = \frac{\sum_{i=1}^{n} m_i^p}{\sum_{j=1}^{n} m_j^r + \sum_{j=1}^{n} m_j^f} \tag{7}$$

$$\mathrm{MI_B^{cop-byp}} = \frac{\sum_{i=1}^{n} m_i^{cop} + \sum_{i=1}^{n} m_i^{byp}}{\sum_{j=1}^{n} m_j^f} \tag{8}$$

Where:
i: Denotes the species i, referring to products, co-products and by-products.
j: Denotes the species j, referring to feedstock, water and reagents.
m: Denotes the mass flow rate of feedstock, water, reagents, products, co-products and by-products, and superscripts f, w, r, p, cop and byp denote feedstock, water, reagents, products, co-products and by-products, respectively.

2.5.3 Biorefinery energy index

This index relates the energy required per equipment to fresh biomass fed. This index can be called Biorefinery energy index by equipment ($EnI_{B-equip}$) and is defined by equation (9).

$$EnI_{B-equip} = \frac{\sum_{j=1}^{n} En_j^{equip}}{\sum_{j=1}^{n} m_j^f} \tag{9}$$

Where:
En: Denotes the heat duty required by equipment.

2.5.4 Biorefinery economic index

This index relates the production cost with the sale price of valuable products in the biorefinery. This index can be called Biorefinery economic index (EcI_B) and it is defined by equation (10). An EcI_B is good when the value tends to zero, namely the gains are positive.

$$EcI_B = \frac{\sum_{i=1}^{n} pc_i^p}{\sum_{j=1}^{n} sp_j^p} \tag{10}$$

Where:
pc: Denotes the production cost of products and superscript p denotes products.
sp: Denotes the sale price of products and superscripts p denotes products.

3. Results and discussion

The BCI is useful to determine the most promising configuration and to judge the technological and economic risks. **Figure 2** indicates the BCI and BCP of SC biorefineries taking into account the number of platforms, feedstocks, products and processes that considers each system. The BCP for biorefineries considered in scenarios 1, 2 and 3 are, $17(2/1/3/11), 30(5/1/4/20)$ and $38(6/1/6/25)$, respectively. As can be seen, the addition of processes (xylitol and PHB) to the base scenario influences positively the BCP increasing their values, mainly the number of platforms and processes. It means that the scenarios 2 and 3 have higher conversion capacity and are more complex than scenario 1.

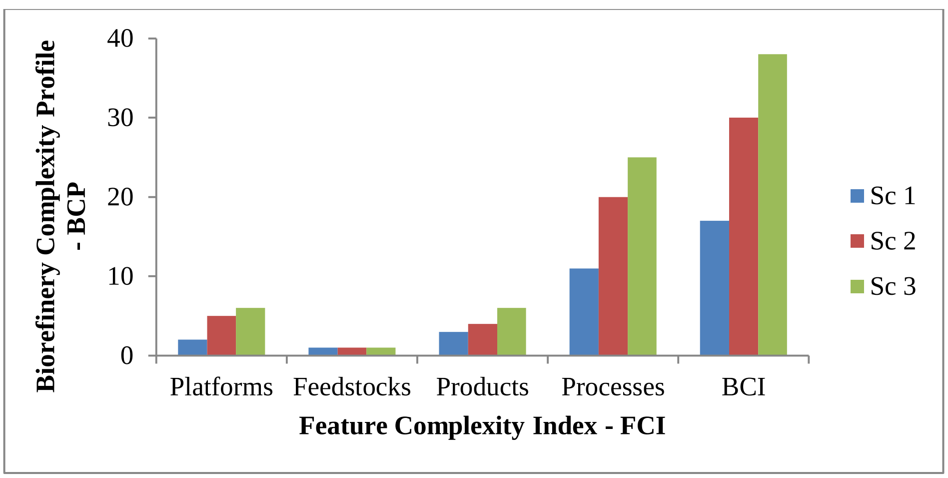

Figure 2. Biorefinery complexity profile of SC biorefineries.

Figure 3 shows the mass indices for three scenarios of SC biorefinery. The MI_B presents an upward trend, as the products are added in each scenario this index increases in logic way, improving the global yield of biorefinery. In the base scenario, the individual yields for sugar and ethanol are 0.11 kilograms of sugar per kilogram of SC and 62.4 liters of ethanol per ton of SC respectively. The yields obtained in simulation are

close to values reported in literature, 0.12 kilograms of sugar per kilogram of SC [28] and 70 liters of ethanol per ton of SC [29].
In biotechnological processes, the water consumption is presented as critical point due to high requirements. In this work, the $\mathrm{MI_B^w}$ shows low values for all scenarios indicating that the water consumption is considerable. The addition of products in the scenarios 2 and 3 affects the water index, reporting lower values than base scenario. The scenarios 2 and 3 consider the pretreatment stage of sugarcane bagasse, which demands large volumes of liquid in order to extract sugars from lignocellulosic material that are the substrate to obtain xylitol and PHB. For the case of $\mathrm{MI_B^r}$, the ratio between the products and, reagent demand and raw material is very similar for all scenarios. The obtained values indicate that the demand of reagents is higher than the flow of product.
In all scenarios the electricity generation is taken as co-product and as can be seen when the sugarcane bagasse is only dedicated to its generation (Scenario 1) the $\mathrm{MI_B^{cop-byp}}$ is highest. This index is calculated with the electricity remaining after to supply the requirements of the processes considered in each biorefinery, namely, is the electricity that can be sold. For scenario 3, the remaining electricity is minimum, for this reason the index is near to zero.

For scenarios 1, 2 and 3, the $\mathrm{EnI_{B-equip}}$ is 8.16, 13.24 and 15.76 respectively. The amount of required energy in each scenario is directly proportional to the addition of products. Namely, the energy requirements by equipment increase with the number of products. As can be seen, the values obtained for scenarios 2 and 3, the addition of pretreatment stage of SCB, xylitol and PHB production contributes significantly to energy demand of biorefineries affecting negatively the energy index. However, the cogeneration system is considered in the biorefineries mitigates these requirements with the production of low and medium pressure steam.

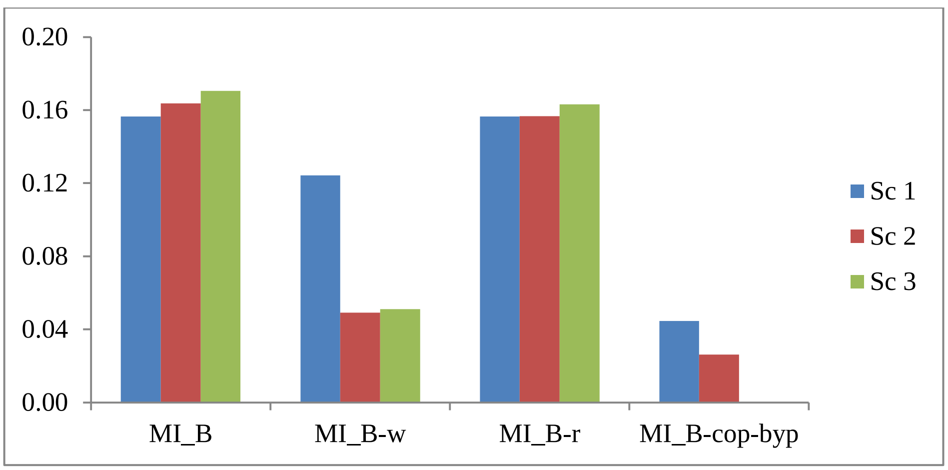

Figure 3. Mass indices for SC biorefineries.

After to obtain the mass indices, an analysis of the $\mathrm{EcI_B}$ in function of processing capacity for all scenarios was made in order to see the trend and define the economic performance of the same biorefineries to small-scale. **Figure 4** indicates the results obtained in this analysis, $\mathrm{EcI_B}$ vs processing capacity for all SC scenarios. The decreasing of processing capacity affects in negative way the economic index of all scenarios. The addition of xylitol and PHB to scenarios 2 and 3 increase the economic index making the systems unfeasible economically. However, if the biorefineries consider processing capacities higher than 10 ton h^{-1} exists the probability to obtain better economic results. These results allow to conclude that the biorefinery is not feasible from economic point of view if is carried out to low scale.

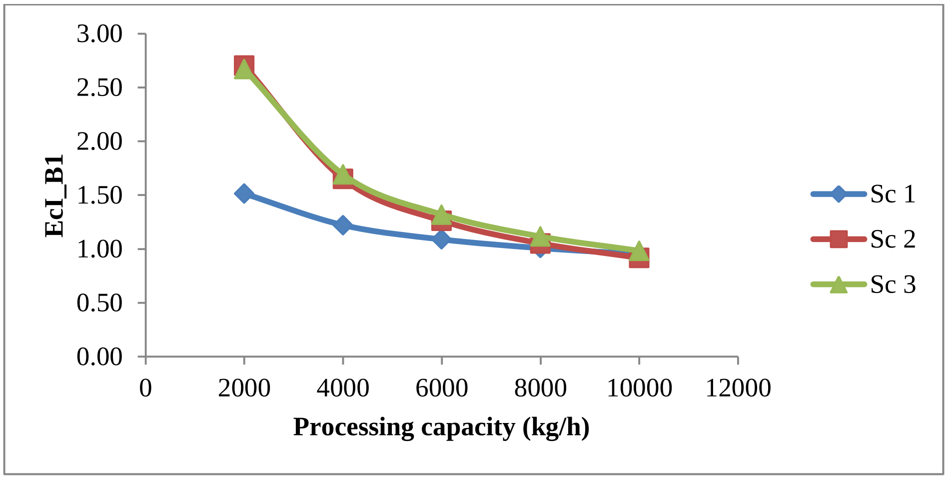

Figure 4. Economic index vs processing capacity for SC biorefineries.

4. Conclusions

The characterization indices allowed doing an elemental analysis of technical and economic feasibility in the generation of a preliminary screen during the conceptual design of SC biorefineries. The characterization indices are presented as a practical tool that involves easy and understandable calculations.
According to the obtained results, the use of SCB as additional platform in the sugar mills for the obtaining of added-value products present better economic opportunities in comparison when only it is dedicated to the electricity generation, considering high processing scales.

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