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Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case

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Abstract

The Colombian government has defined the use of bioethanol as a gasoline enhancer to reduce greenhouse gases, gasoline imports, and to boost the rural economy. To meet the projected fuel ethanol demand needed to oxygenate the gasoline in the whole country, the construction of about five additional ethanol production plants is required. For this, a comparative analysis of the technological options using different feedstocks should be performed. In this work, a comparison of the economical and environmental performance of the ethanol production process from sugarcane and corn under Colombian conditions has been carried out. Net present value and total output rate of potential environmental impact were used as the economical and environmental indicators, respectively. Through the integration of these indicators into one index by using the analytical hierarchy process (AHP) approach, sugarcane ethanol process was determined as the best choice for Colombian ethanol production facilities. AHP scores obtained in this study for sugarcane and corn ethanol were 0.571 and 0.429, respectively. However, starchy crops like corn, cassava or potatoes used as feedstock for ethanol production could potentially cause a higher impact on the rural communities and boost their economies if social matters are considered.
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Keywords: Economic evaluation; Environmental assessment; Fuel ethanol; Sugarcane; Corn

1. Introduction

In addition to the progressive depletion of energy resources, mostly based on non-renewable fuels, the world faces climate changes and atmospheric pollution as consequences of the combustion of oil-derived fuels. These problems are more serious in large cities where vehicular exhaust emissions rank among the main sources of polluting gases [1]. Ethanol produced from bioenergy crops and lignocellulosic biomass has the potential to become a renewable transportation fuel in place of gasoline. Its use as a gasoline oxygenate increases the oxygen content, allowing better oxidation of hydrocarbons and reducing the amounts of aromatic compounds and carbon monoxide released onto the atmosphere. Moreover, CO_2 emissions generated by the combustion of this biofuel are compensated by the CO_2 absorption during the growth of the crops from which ethanol is produced, avoiding a net emission of this gas [2]. The offset of CO_2 emissions is valid when unexploited or cattle farming lands are used for cultivating bioenergy crops. However, in the case of some agricultural expansion into virgin forest, this is not necessarily true.

Abbreviations: AHP, analytic hierarchy process; ATP, aquatic toxicity potential; AP, acidification potential; BOD, biological oxygen demand; CFBC/TG, circulating fluidized bed combustor/turbogenerator; DDGS, distiller's dried grains with solubles; GWP, global warming potential; HTPE, human toxicity potential by inhalation or dermal exposure; HTPI, human toxicity potential by ingestion; IRR, internal rate of return; LCA, life cycle assessment; MESH, mass, equilibrium, summation, and heat; NPV, net present value; NREL, National Renewable Energy Laboratory; NRTL, non-random two-liquid; ODP, ozone depletion potential; PCOP, photochemical oxidation potential; PEI, potential environmental impact; PSA, pressure swing adsorption; SSF, simultaneous saccharification and fermentation; Ton, metric tonne; TTP, terrestrial toxicity potential; USEPA, Environmental Protection Agency of the United States

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Among the bioenergy crops used for fuel ethanol production, sugarcane is the main feedstock utilized in tropical countries like Brazil and India. In North America and Europe, fuel ethanol is mainly obtained from starchy materials, especially corn [3]. On the other hand, intensive research on the utilization of lignocellulosic biomass as feedstock has been carried out during the last years. Different countries like the USA and Sweden have defined strategic policies for the development of this technology in order to produce large amounts of renewable biofuels and diminish their dependence on imported fossil fuels.

This work appoints to the integral comparison of two processes for fuel ethanol production, each of which has its own technological configuration and utilizes a different feedstock. The two selected feedstocks (sugarcane and corn) represent the most important raw materials for ethanol production in Colombia, a tropical country with vast biomass resources. In order to provide evaluation data for making decisions on the commercial-scale implementation of the process under Colombian conditions, the aim of this paper is to determine which of the two analyzed processes has the best performance from the economic and environmental point of view.

2. Features of the Colombian ethanol program

Colombia is a country with important oil reserves. However, the country imports gasoline due to its refining limitations. In addition, the pace of new oil discoveries in the country has decreased. Colombia faces the depletion of its reserves and possible oil imports in 2010. For this reason, besides environmental considerations, the country decided on replacing part of the fossil fuels with alternative energy sources. The production and use of liquid biofuels (bioethanol and biodiesel) is the strategy adopted by the Colombian government to diminish the oil dependence and reduce the polluting gases released by the transportation sector in the Colombian cities. Moreover, it is expected that the implementation of biofuels programs allow the development of the rural sector that, in certain regions, is attacked by the violence associated with the use of land for illegal crops.

The Congress of Colombia issued the Act 693 of 2001 mandating the addition of 10% (v/v) ethanol to gasoline (hereinafter referred to as the E10 program) in cities with more than 500,000 inhabitants. Thus, since November 2005, ethanol is being progressively added to gasoline consumed in several cities in the country, including its capital, Bogotá. In the mid-term, the use of ethanol–gasoline blends will be extended to the whole nation. The perspectives for the ethanol market in Colombia are bright. The amount of fuel ethanol needed in the zones where the E10 program is being implemented reach 1,200,000 L/d. The expansion of the program to the rest of the country requires a total ethanol production of about 2,500,000 L/d. In addition, Colombia has all the conditions to become an ethanol-exporting country considering its agro-ecological conditions, its geographical location, as well as the growth of potential markets in North America, Europe and Asia. To make the most of these conditions, the country should produce an estimated 3,800,000 L/d of fuel ethanol by 2020 to meet the national demand and export the surplus to new growing markets [4]. Furthermore, the future implementation of a biodiesel program in Colombia based on palm oil implies the utilization of either methanol or ethanol for its production. Colombia has significant palm plantations and the government is encouraging its increase. Methanol is not being produced in Colombia and it would have to be imported for biodiesel production. In contrast, national ethanol production is increasing. This makes ethanol the logical alternative as a feedstock for biodiesel along with palm oil. This offers an interesting opportunity to increase the size of existing ethanol-production facilities or construct new ones. The latter is necessary to meet the alcohol needs of the gasoline oxygenation program, potential exports of fuel ethanol, and the biodiesel industry.

The implementation of the E10 program depends on raw materials and technological limitations. For this reason and driven by the availability of the feedstock and the capacity of the well-structured sugar industry, main cities of the West Southern and West Central departments (administrative regions in which Colombia is divided) started this program. The Cauca River valley is the major sugarcane production region and it is located in these departments. This region concentrates the best cultivable lands for sugarcane cropping (about 200,000 Ha) since it has the most appropriate conditions: Extensive and fertile alluvial valleys located at an average of 1000 m above sea level in tropical latitude. Currently, five ethanol production plants co-located in large sugar mills are operating. However, the synergies of the sugar sector, controlled by a few economic groups, have not allowed achieving a great impact upon the creation of new rural jobs. According to estimations by the Colombian Ministry of Agriculture [5], the surface cropped with sugarcane in 2006 did not increase compared to data obtained in 2005 (see Table 1). Despite the enhancement in the production of fuel ethanol during these 2 years, Colombia has not projected any increase in cane plantations. This means that the generation of new rural jobs related to ethanol production is practically null. In fact, part of the cane produced is diverted to ethanol

Table 1
Sugar and ethanol production in Colombia for the 2005–2006 period

Item	2005	2006	Variation
Cropped land with cane, Ha	200,218	200,218	0.00
For sugar production	196,218	170,218	−13.25
For ethanol production	4000	30,000	650.00
Sugar production, ton	2,683,203	2,356,617	−12.17
Sugar consumption, ton	1,503,561	1,515,380	0.79
Sugar exports, ton	1,179,642	841,237	−28.69
Fuel ethanol production, L	27,387,000	268,456,000	880.25

Source: Colombian Ministry of Agriculture and Rural Development [5].

distilleries, decreasing the volumes of sugar for export. Regulations issued by the government have included the sugar value in the international market as a variable considered in calculating the price of fuel ethanol produced in the country. Thus, future increases in the international price of sugar will not discourage the national production of fuel ethanol. This situation allows the development of new commercial projects for ethanol production in order to guarantee a permanent offer of ethyl alcohol for the E10 program.

The Colombian government expects that the construction of new ethanol-producing facilities in other regions of the country will lead to real improvement in the economic situation of the rural communities through new demands for agricultural raw materials. Therefore, other feedstocks for ethanol production are being analyzed considering the future growth of fuel ethanol market. Corn, cassava, and beet have been considered as potential feedstocks. Sugarcane is also considered for ethanol production in zones other than in the Cauca River valley. This implies the cropping of cane by specific rural communities not related to the big sugar companies. Many rural communities cultivate sugarcane to producing non-centrifugal sugar called *panela* (solid brown sugar), a sweetener and low-cost beverage base widely used by popular segments in Colombia. However, the quality of life of *panela* producers is traditionally low within the Colombian context. For this reason, the government is actively encouraging the organization of the communities linked to the *panela* economy for them to supply the feedstock for new projects of fuel ethanol production.

The relatively mature technology for ethanol production from corn is one of the options to be considered under Colombian conditions since corn is an important crop mainly cultivated in Northern and Eastern regions. The construction of ethanol plants using corn could offer the production of valuable co-products (e.g., distiller's dried grains with solubles (DDGS) for cattle food). Furthermore, this technology may be the base for the development of ethanol production processes from other starchy materials as cassava or potato, crops with a significant economic importance in Colombia. Additionally, the projected signing of a free trade agreement with the USA, the first world producer of corn, implies the search for new markets for local corn production.

3. Process description

Fuel ethanol production can be described as a five-stage process: raw material pretreatment, hydrolysis, fermentation, separation and dehydration, and wastewater treatment. The production of bioethanol from starch includes the breakdown of this polysaccharide to obtain an appropriate concentration of fermentable sugars, which are transformed into ethanol by yeasts. The simplified flowsheet for ethanol production from corn is shown in Fig. 1. After washing, crushing and milling the corn grains (dry milling process), the starchy material is gelatinized in order to dissolve the amylose and amylopectin. In dissolved form, starch is accessible for enzymatic attack in the following liquefaction step. This step is considered as a pretreatment process because of the partial hydrolysis

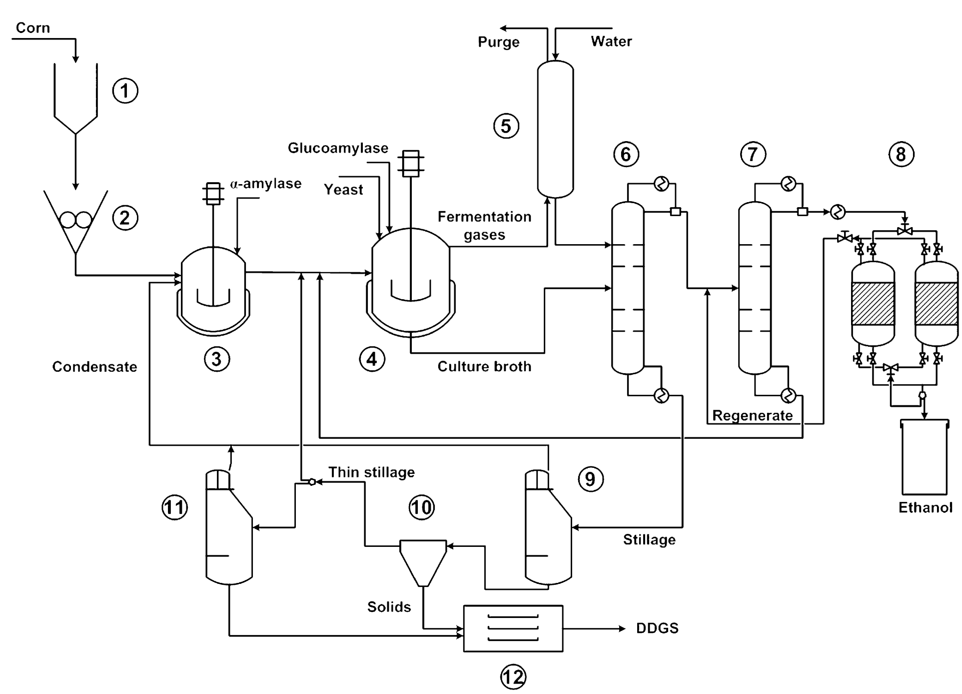

Fig. 1. Simplified flowsheet of fuel ethanol production from corn. 1. Washing tank, 2. Crusher, 3. Liquefaction reactor, 4. SSF reactor, 5. Ethanol absorber, 6. Concentration column, 7. Rectification column, 8. Molecular sieves, 9. First evaporator train, 10. Centrifuge, 11. Second evaporator train, 12. Dryer.

(about 10%) of the starch chains using thermostable bacterial α-amylase. The hydrolyzate obtained has reduced viscosity and contains starch oligomers called dextrins. Then, the liquified starch enters the simultaneous saccharification and fermentation (SSF) process where it is hydrolyzed by microbial glucoamylase to produce glucose. This sugar is immediately assimilated by the yeast *Saccharomyces cerevisiae* in the same reactor and converted into ethanol. Fermentation gases, mostly CO_2, are washed in an absorption column to recover more than 98% of the volatilized ethanol from the SSF reactor, and sent to the first distillation column. The culture broth containing 8–11% (w/w) ethanol is recovered in a separation step consisting of two distillation columns. In the first (concentration) column, aqueous solutions of ethanol are concentrated up to 63%. In the second (rectification) column, the concentration of the ethanolic stream reaches a composition near the azeotrope (95.6%). The dehydration of this ethanol is achieved through adsorption in vapor phase with molecular sieves. The stream obtained during the regeneration of molecular sieves containing 70% ethanol is recycled to the rectification column.

The stillage from the concentration column is evaporated and the solids obtained are separated by centrifugation. These solids are dried for producing DDGS, a co-product used for animal feed, given its high protein and vitamin content. The remaining liquid or thin stillage is evaporated in a double effect evaporator. The syrup obtained is combined with the DDGS and dried. The condensed water from the evaporators is recycled into the liquefaction stage, while the bottoms of the rectification column and one fraction of the thin stillage are recycled to the SSF.

During ethanol production from sugarcane in an autonomous distillery (i.e., not annexed to a sugar mill), the feedstock is washed, crushed and milled to extract the sugarcane juice and produce bagasse (see Fig. 2). The cane juice is sent to a clarification process, where pH is adjusted, some impurities are removed, and the *cachaza* is generated. This material is the filter cake obtained during the removal of suspended solids in the rotary drum filter utilized for juice clarification. The *cachaza* is commercialized as a component of animal feed or for composting. The cane juice is sterilized and directed to the fermentation stage. Fermentation is performed by using the yeast *S. cerevisiae*, which is continuously separated by centrifugation and recycled to the fermenter. The separation scheme of this process is the same as that of the corn-based process.

For sugarcane, the stillage treatment consists of an evaporation step allowing the generation of a commercializable by-product employed as a fertilizer of cane plantations. If the stillage is not concentrated or evaporated at a low degree, it can be utilized for both irrigation and fertilization of cane plantations surrounding the ethanol production facility. Hence, the environmental impact of the whole process is reduced since the most important liquid effluent is converted into a value-added product. Condensed water from evaporators and bottoms from the rectification column are collected and sent to the wastewater treatment step. Part of this water can be used as feed water for the cogeneration system.

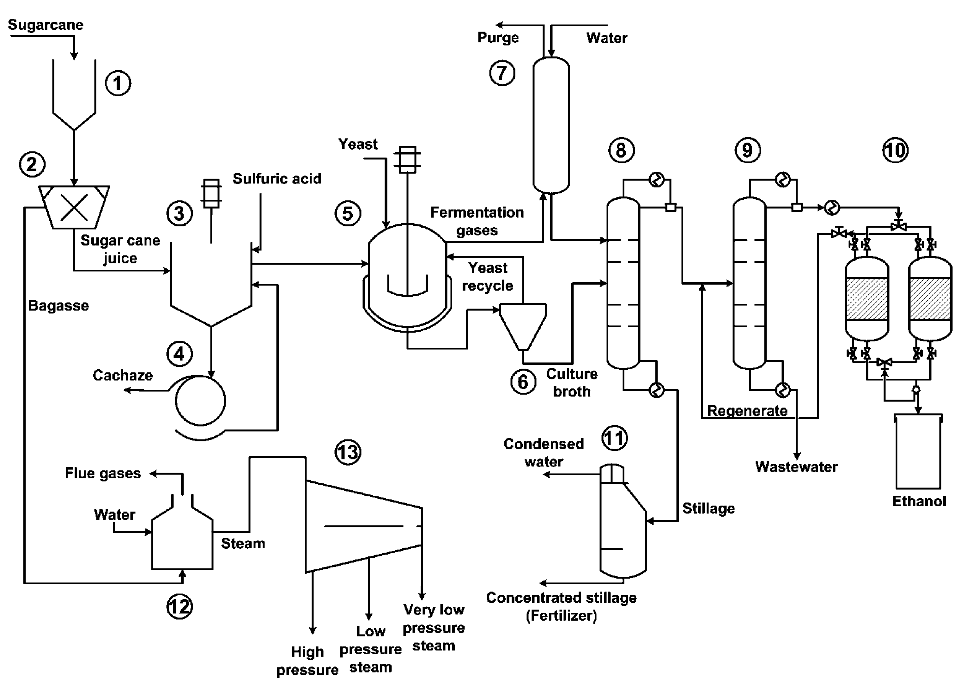

Fig. 2. Simplified flowsheet of fuel ethanol production from sugarcane. 1. Washing tank, 2. Mill, 3. Clarifier, 4. Rotary drum, 5. Fermenter, 6. Centrifuge, 7. Ethanol absorber, 8. Concentration column, 9. Rectification column, 10. Molecular sieves, 11. Evaporator train, 12. Combustor, 13. Turbogenerator.

Currently, the bagasse obtained is employed in sugar mills and cane-based distilleries for combined generation of the steam and power required by the process. For this, cogeneration units have to be installed. These units basically comprise a burner (combustor) for combustion of solid bagasse, a boiler where the feed water is converted into steam, and a turbogenerator (steam turbine), where exhausted steam for the process is obtained along with power. The electricity surplus not consumed by the plant can be sold to the energy network.

4. Methodological approach

The evaluation of the two described process configurations took into account both economic and environmental aspects. In the present work, the calculation of the net present value (NPV) was performed to assess the profitability of fuel ethanol production utilizing each of the two analyzed feedstocks. For this, mass and energy balances calculated via simulation are the starting point to determine capital and operating costs of both processes and consequently, their economic performance.

Another issue to be assessed during this analysis is the impact of aforementioned processes upon the environment. Several indicators and methodologies, like the Sustainable Process Index [6] and life cycle assessment (LCA) [7,8], have been proposed to evaluate and minimize the environmental impacts of chemical and biochemical processes at the design stage. A proper consideration of these indicators and evaluation methods during the early stages of design can lead to the generation of environmentally friendly processes, avoiding the implementation of expensive modifications in the already-constructed production plants.

One of the tools used for the generation of environmental indicators in chemical and biochemical processes is the Waste Reduction Algorithm (WAR algorithm) designed by the Environmental Protection Agency of the United States (USEPA). This algorithm is based on the determination of the Potential Environmental Impact (PEI), which is a conceptual quantity representing the average unrealized effect or impact that mass and energy emissions would have on the environment. In general, the PEI of a chemical process are caused by the energy and materials that the process takes from or emits to the environment [9]. Here, process simulation provides most of the information required for the calculation of specific environmental indexes, specifically, data related to the composition of streams generated during the process or leaving it. In the particular case of the WAR algorithm, there exists an interface link to one of the most popular process simulators, the Aspen Plus.

After accomplishing the environmental performance, an evaluation considering economic and environmental indexes was carried out in order to obtain a combined index useful for the selection of the most appropriate technology. This combination was done by following the procedure exposed by Chen et al. [7] where the economic and environmental objectives were aggregated into a single objective function using the analytic hierarchy process (AHP) approach. The AHP is one variant of multi-criteria analysis that uses a number of pairwise comparisons between quantitative or qualitative criteria to assess the relative importance of each criterion. These comparisons can be arranged in a hierarchical manner to form sets of attributes, and qualities (levels) within these attributes [10].

The hierarchical structure for this study is shown in Fig. 3. Once mass and energy balances have been calculated by simulation, the economic and environmental evaluations are performed by using the corresponding tools (process evaluation software and WAR algorithm, respectively). The indexes (NPV and PEI) for each process are determined from these evaluations. Alternatively, other economic indexes like internal rate of return (IRR) could be used. The indexes are normalized, so that they do not exceed a normalization value, and converted to quantitative scores. The normalization value for each index was calculated as the sum of the index values in both processes. The economic score of a given process was determined as the ratio between the NPV of the process and the corresponding normalization value, i.e. the sum of the two calculated NPV. The environmental score was calculated taking the difference between the corresponding normalization value and the PEI of the process and dividing the result obtained by the normalization value.

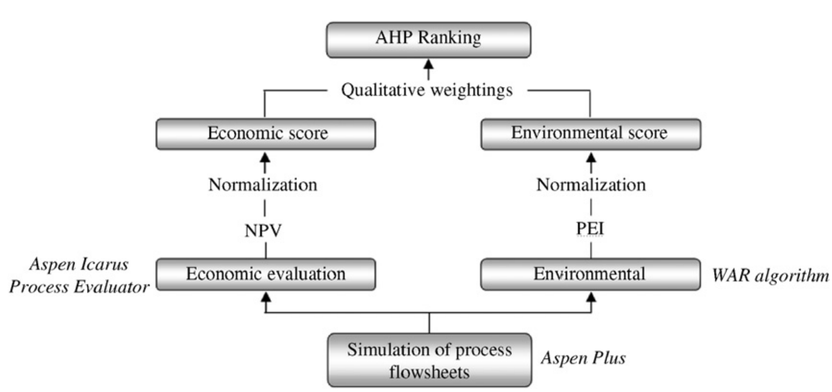

Fig. 3. Analytical hierarchy structure (AHP) utilized for the analysis of two processes for fuel ethanol production. Adapted from [7].

The AHP score of a process design represents the sum of the products of the average process score for a given attribute and the weighting for that attribute, that is

$$AHP = P_{Ecn} \times weight + P_{Env} \times weight, \quad (1)$$

where P_{Ecn} is the normalized economic score calculated from the NPV of the two analyzed processes, and P_{Env} is the normalized environmental score resulting from the PEI values of the two processes. The qualitative weightings of economic and environmental attributes were taken as 0.82 and 0.18, respectively. These values are suggested by Chen et al. [7] who applied them to several chemical processes based on the survey carried out by Dechanpanya [11] on the comparison of economic and environmental attributes for a chemical process from several faculty members and graduate students at Michigan Technological University using the AHP approach [10].

5. Simulation procedure

Process simulation was the base for both economic and environmental evaluation as mentioned above. The simulation of both technological configurations (ethanol production from either sugar cane or corn) was carried out using Aspen plus (Aspen Technology Inc., USA). Main input data utilized for process simulation are shown in Tables 2 and 3. For the two processes, the simulation considered a production capacity of about 17,830 kg/h of anhydrous ethanol. Part of the physical-property data of the components required for simulations were obtained from Wooley and Putsche [14]. The non-random two-liquid (NRTL) thermodynamic model was utilized to calculate the activity coefficients in the liquid phase and the Hayden–O'Conell equation of state was used to model the vapor phase.

For the simulation of distillation columns, residue curves maps were analyzed by applying the principles of

Table 2
Main process data for simulation of fuel ethanol production from corn

Feature	Value	Feature	Value
Feedstock	Corn	Product	Fuel ethanol
Composition	Starch 60.6%, cellulose 3.46%, hemicellulose 4.6%, lignin 0.4%, glucose 8.7%, protein 2.2%, fatty acids 3.64%, ash 1.17, moisture 15.5%[a]	Composition	Ethanol 99.5%, water 0.5%
Feed flow rate	50,630 kg/h	Flow rate	17,837 kg/h
Co-product	DDGS		
Pretreatment		Ethanol dehydration	
Milling		Technology	PSA with molecular sieves
Number of mills	2	Number of units	2
Hydrolysis (liquefaction)		Temperature	116 °C
Bioagent	α-amylase	Pressure	1.7 atm (adsorption) 0.14 atm (desorption)
Temperature	88 °C	Cycle time	10 min
Residence time	5 min	DDGS processing	
Number of units	6	Number of evaporator trains	2
Starch conversion	99%	Number of evaporators (1st train)	2
Simultaneous saccharif. and fermentation		Number of evaporators (2nd train)	2
Bioagents	Glucoamylase and *S. cerevisiae*	Average area of each evaporation unit (1st train)	1186 m^2
Temperature	33 °C	Average area of each evaporation unit (2nd train)	42 m^2
Residence time	48 h	Type of dryer	Indirect contact rotary dryer
Number of units	10		
Ethanol percentage	11%		
Conventional distillation			
Number of columns	2		
Pressure of columns	1 atm	Involved components	19
Ethanol content at distillate (1st column)	63%	Blocks	23
Ethanol content at distillate (2nd column)	90%	Streams	83
		Substreams in streams	3

[a]All the percentages are expressed by weight.

Table 3
Main process data for simulation of fuel ethanol production from sugarcane

Feature	Value	Feature	Value
Feedstock	Sugarcane	Product	Fuel ethanol
Composition	Sugars 14%, fiber 13.5%, protein 0.4%, ash 1,5%, acids and fats 0.6%, moisture 70%[a]	Composition	Ethanol 99.5%, water 0.5%
Feed flow rate	292,619 kg/h	Flow rate	17,822 kg/h
Co-product 1	*Cachaza*	Co-product 2	Concentrated stillage
Pretreatment		Ethanol dehydration	
Milling		Technology	PSA with molecular sieves
Number of mills	2	Number of units	2
Water flow rate	75,640 kg/h	Temperature	116 °C
pH conditioning and sucrose hydrolysis		Pressure	1.7 atm (adsorption) 0.14 atm (desorption)
Agent	Dilute H_2SO_4	Cycle time	10 min
Temperature	65 °C	Co-generation system	
Residence time	5 min	Solid fuel	Cane bagasse
Number of units	1	Solid fuel flow rate	77,623 kg/h
Sucrose conversion	90%	Flue gases temperature	176 °C
Fermentation		Temperature of steam from boiler	510 °C
Bioagent	*S. cerevisiae*	Pressure of the exhausted steam from turbines	
Temperature	31 °C	High	13 atm
Residence time	48 h	Low	4.42 atm
Number of units	16	Very low	1.68 atm
Ethanol content	6%	Stillage concentration	
Conventional distillation		Number of evaporators	5
Number of columns	2	Average area of each evaporation unit	2458 m^2
Pressure of columns	1 atm	Involved components	21
Ethanol content at distillate (1st column)	58%	Blocks	34
Ethanol content at distillate (2nd column)	90%	Streams	137
		Substreams in streams	3

[a]All the percentages are expressed by weight.

thermodynamic topology (analysis of the statics) [15]. To define the preliminary specifications of distillation columns, the DSTWU short-cut method included in Aspen Plus was employed. This procedure employs the Winn–Underwood–Gilliland method that provides an initial estimate of the minimum number of theoretical stages, the minimum reflux ratio, the localization of the feed stage, and the products split of the column. With this information and the results of the analysis of the statics, the rigorous calculation of the distillation columns was performed using the RadFrac module of Aspen Plus, which is based on mass, equilibrium, summation, and heat (MESH) equations and uses the inside-out calculation algorithm. Sensitivity analyses were carried out in order to study the effect of the main operation variables (e.g., reflux ratio, feed temperature, number of stages, etc.) on the composition of products and energy costs. The estimation of energy consumption was conducted based on the simulation data of thermal energy required by the heat exchangers, reboilers and related units. Enzymatic hydrolysis and fermentation processes were simulated based on a stoichiometric approach that considered the conversion of starch or sucrose into glucose as well as the transformation of glucose into cell biomass, ethyl alcohol and other fermentation by-products such as aldehydes, succinic acid and glycerol among others.

A circulating fluidized bed combustor/turbogenerator (CFBC/TG) system was analyzed as the cogeneration technology. This system has been contemplated in the model process designed by the National Renewable Energy Laboratory (NREL) for cogeneration using the lignin released during the conversion of lignocellulosic biomass into ethanol [16]. CFBC/TG technology offers an increased efficiency in the generation of steam and power related to conventional cogeneration units working with low-pressure boilers, which usually generate steam at 280–300 °C and 20–21.7 atm [17,18]. Mass balance data of CFBC/TG systems reported in [16] were utilized for conceptual design and simulation of the cogeneration unit using cane bagasse. This unit was simulated through several process modules of Aspen Plus. The burner was described through a stoichiometric reactor considering the incomplete combustion of bagasse organic components (e.g., lignin, cellulose, hemicellulose, etc.), taking into account the formation not only of CO_2, but also of CO. In the same way, reactions for NO_x formation were included. The boiler was studied as a heat exchanger where the feed water enters at 121 °C and 97.5 atm and the generated steam exits at 510 °C and 84.9 atm. A pump elevating the pressure of the feed water up to 97.5 atm was included in this analysis. The simulation of the cogeneration unit also took into account that the combustion gases leaving the boiler can be utilized not only for preheating the air required to burn the bagasse, but also for drying the wet bagasse generated in the mills. As exposed in [19], a previous drying enables the reduction of bagasse moisture down to 40%, improving the combustion and increasing the amount of generated steam. The analysis of the cogeneration system also included a cyclone for separating most particulate matter from the flue gases leaving the bagasse dryer. On the other hand, the electricity production using a turbogenerator was simulated through the compressor module of Aspen Plus considering a negative change of pressure and selecting the isentropic type of compressor. Thus, it is possible to simulate the power generation and calculate the properties of the exhausted steam. In this paper, a multistage turbine was taken into consideration for producing three types of steam: high-pressure steam (used for preheating the water feeding the boiler), low-pressure steam (used for the energy supply of most of the process units like heaters, sterilizers and column reboilers), and very low-pressure steam (employed for stillage evaporation).

The economic analysis was performed by using the Aspen Icarus Process Evaluator (Aspen Technology, Inc., USA) package. This analysis was estimated in US dollars for a 10-year period at an annual interest rate of 16.02% (typical for the Colombian economy), considering the straight line depreciation method and a 33% income tax. Prices and economic data used in this analysis correspond to Colombian conditions and were calculated at an exchange rate of 1984 Colombian pesos per US dollar (see Table 4). The above-mentioned software estimates the capital costs of process units as well as the operating costs, among other valuable data, utilizing the design information provided by Aspen Plus and data introduced by the user for specific conditions as for example project location. In this way, the NPV of each process was determined.

The PEI of both processes were calculated through the WAR GUI software (provided by the USEPA) [20] using the mass and energy balances obtained by the simulation with Aspen Plus. The greater the PEI is, the more negative is the impact of the process studied. The overall PEI of a given process considers the aggregation of the PEI in different categories. The WAR algorithm manages eight different impact categories. These can be grouped into four environmental (atmospheric) physical potential effects: acidification potential (AP), global warming potential (GWP), ozone depletion potential (ODP), and photochemical oxidation potential (PCOP); two human toxicity effects: human toxicity potential by ingestion (HTPI) and human toxicity potential by inhalation or dermal exposure (HTPE); and two ecotoxicity effects: aquatic toxicity potential (ATP) and terrestrial toxicity potential (TTP). Weighting factors (between 0.0 and 10.0) could be used within the WAR GUI software to give special importance to any of the categories according to the relative or site-specific concerns of the user. Highest weightings (10.0) were assigned to the four local toxicological categories in comparison to the weightings of the four global environmental physical categories (2.5). These assignments were done to give higher importance to the local conditions taking into account that Colombia is an agricultural country with vast hydric resources and rich biodiversity that should be protected. Some of the values assigned were taken from weightings suggested in [7] for equivalent impact categories. Results using equally weighted categories can be found in a previous work [21].

Table 4
Prices used in the economic analysis

Item	Unit	Ethanol from corn	Ethanol from sugarcane
Anhydrous ethanol[a]	US$/kg	0.7478	0.7478
Sugarcane[b]	US$/kg	–	0.0124
Corn[c]	US$/kg	0.1300	–
DDGS	US$/kg	0.1320	–
Concentrated stillage[d]	US$/kg	–	0.0204
Cachaza[d]	US$/kg	–	0.0055
Electricity	US$/kWh	0.1000	0.0000[e]
Cooling water	US$/m^3	0.0100	0.0100
Steam	US$/ton	8.1800	0.0000[e]
Operator labor	US$/h	3.3000	3.3000
Supervisor labor	US$/h	4.9500	4.9500

[a]Current purchase price according to the official quotation.
[b]Average purchase price provided by local distilleries annexed to sugar mills.
[c]Average value considering both Colombian production cost and import price.
[d]Personal communication from a local distillery annexed to a sugar mill.
[e]This value considers the operation of the co-generation unit utilizing cane bagasse.

6. Results and discussion

6.1. Process simulation

Some simulation results of main streams for corn-to-ethanol and cane-to-ethanol processes are shown in Table 5 and 6, respectively. The compositions of the streams calculated by simulation, agree very well with those reported for commercial processes. For the corn-based process, the DDGS generally contains 9% moisture and 27–32% protein [24]. Results of many analyses done during a 5-year period (1997–2001) to determine the composition of DDGS obtained in corn dry-milling ethanol production facilities in the USA [25] revealed good agreement with the simulation data obtained (see Table 5). For the cane-based process, the moisture and fiber contents of bagasse and *cachaza* are close to the contents of moisture (bagasse: 50%, *cachaza*: 75%) and fiber (bagasse: 46%, *cachaza*: 13%) reported for these co-products in [22,23]. The value of generated cane stillage per liter of ethanol obtained from simulation (11.01 L/L EtOH) is within the range reported in [26] from experimental data (10–20 L/L EtOH). The stillage composition calculated by simulation is close to the stillage composition of Brazilian distilleries, as cited in [27]. For instance, the content of organic matter in non-concentrated stillage is calculated at 26 g/L, while the corresponding average values in Brazilian distilleries using cane juice and cane molasses are 19.5 and 63.4 g/L, respectively. In general, streams data determined through simulation for both processes were compared to available data of existing production facilities taken from literature and personal communications. Thus, the simulation results were satisfactorily validated.

The simulation of the co-generation system in the case of the cane-based process also showed a good agreement with the reported industrial data. The CO_2, CO and NO_x emissions obtained in this work are close to the average emission factors reported by the USEPA and other authors for combustion of bagasse in sugar mills [28–30] (see Table 7). Also, the presence of moisture in the bagasse bears important influence on the amount of thermal energy released during its combustion. This fact is confirmed by simulation. Thus, the use of non-preheated wet bagasse (about 50% moisture) implies a 7.3% reduction in the amount of produced steam with a pressure of 84.9 atm in comparison to the case when the bagasse is dried down to 40% moisture. This very high-pressure steam from boiler is used for power generation in the turbines. In contrast, the reduction of available steam reaches 13.18% when low-pressure boilers (29 atm) are used as indicated in [19]. The total amount of exhausted steam from the turbogenerator covers all the needs of thermal energy required by the ethanol production facility. This fact dramatically improves the economic performance of the overall process. A fraction of the energy released in the turbogenerator is also employed to cover the needs of mechanical energy required during cane milling. Moreover, the power produced (33 MW) meets plant requirements (13.90 kWh/ton cane, according to simulation results), remaining a significant surplus that can be sold to the electric network. Herein, the electricity surplus was not considered during the economic evaluation. Nevertheless, the cogeneration

Table 5
Flow rates and composition of some streams for corn-based ethanol process

Compounds	Streams			
	Corn (wt%)	Purge (wt%)	Ethanol (wt%)	DDGS (wt%)
Ethanol	–	0.05	99.50	–
Sugars	2.19	–	–	1.96
Starch	60.59	–	–	0.17
Fiber	8.21	–	–	33.21
CO_2	–	98.13	–	–
Fats	3.64	–	–	14.70
Protein	8.69	–	–	35.15
Water	15.50	1.81	0.50	9.82
Ash	1.18	–	–	4.76
Others	–	0.01	–	0.23
Total flow rate (kg/h)	50,629.99	17,247.83	17,836.83	12,483.97

Table 7
Main atmospheric emissions from the co-generation system using sugarcane bagasse

Pollutant	Emission			Source
	kg/ton bagasse	kg/ton steam	mg/m^3	
CO_2	840.6511	335.5544	159,388	This work
	706.6800	390.0000	–	[28,29]
CO	8.1478	3.2523	1544	This work
	–	–	1526	[30]
NO_x	0.7592	0.3031	144	This work
	0.5436	0.3000	–	[28,29]
	–	–	92	[30]

Table 6
Flow rates and composition of some streams for cane-based ethanol process

Compounds	Streams					
	Sugar cane (wt%)	Bagasse (wt%)	*Cachaza* (wt%)	Purge (wt%)	Ethanol (wt%)	Concentrated stillage (wt%)
Ethanol	–	–	–	0.02	99.62	–
Sugars	14.00	1.02	–	–	–	28.84
Fiber	13.50	47.33	16.28	–	–	–
CO_2	–	–	–	98.25	–	–
Protein	0.40	0.12	1.94	–	–	–
Water	70.00	49.90	67.80	1.67	0.38	44.93
Ash	1.50	1.53	7.30	–	–	10.38
Others	0.60	0.10	6.68	0.06	–	15.85
Total flow rate (kg/h)	292,618.77	77,623.30	20,369.78	17,143.62	17,821.67	24,702.60

system examined generates 99.06 kWh/ton cane of electric energy available for sale. The indicated amount of power is within the range of modern co-generation technologies based on extraction-condensation turbogenerators, which can reach 90–150 kWh/ton cane of electricity surplus [17]. This type of co-generation units has been proposed for new Brazilian sugar mills and distilleries, being an excellent option for new ethanol production facilities in Colombia.

6.2. Economic evaluation

The results obtained for ethanol yield in both processes, along with total operating and capital costs are shown in Table 8. The average yield of technified corn crop in Colombia is about 5 ton/Ha for a harvesting time of 4 months [31]. For sugarcane in the case of the most productive zone (the Cauca River valley), this value is of 123 ton/Ha for a harvesting time of 13 months [32]. The average yield for all the country including non-technified cane crops, reaches 92.7 ton/Ha that can be compared to the average yield of sugarcane in Brazil (73.91 ton/Ha) and India (59.05 ton/Ha) [33], the major sugar producers in the world. Note from Table 8 that the calculated ethanol yield from corn (in terms of produced ethanol per tonne of feedstock entering the plant) is greater than that from sugarcane because of the higher amount of fermentable sugars (glucose) that may be released from the original starchy material. However, the annual ethanol yield from each hectare of cultivated corn is 23.6% lower than that for sugar cane. This fact preliminary shows the comparative advantage of using sugarcane as feedstock for ethanol production under high-productivity conditions for cane cropping in Colombia.

Total operating costs are significantly higher for ethanol production from corn than from sugarcane (Table 8). This is mostly explained by the feedstock cost as shown in Fig. 4 and Table 9, where operating costs were disaggregated. In comparison to corn case, the greater cane demand for producing the same amount of ethanol (about six times the grain requirements) is compensated by the lower cost of this raw material. In fact, the main part of fuel ethanol costs corresponds to the feedstock: 66.45% and 70.84% using sugarcane and corn, respectively. Usually the feedstock cost for Brazilian cane ethanol is about 60% of the production costs [34], whereas for corn (mostly transgenic) is about 63% in USA [24]. These results confirm the validity of the data obtained by simulation, as well as the assumptions considered during the economic analysis. Steam and power generation through the combustion of cane bagasse reduces the utilities cost considerably. This makes a big difference in cane-to-ethanol processes (see Fig. 4) and justifies the installation and operation of bagasse combustion systems. On the contrary, corn-based process requires the consumption of fossil fuels that

Table 8
Ethanol yields and total capital and operating costs for fuel ethanol production from two feedstocks

Item	Corn	Sugarcane
Ethanol yield (L/ton of feedstock)	446.51	77.19
Ethanol yield (L/[Ha × year])	6698	8764
Total capital costs (thous. US$)	36,447.50	75,613.00[a]
Total operating costs (thous. US$/year)	70,670.30	36,255.20

[a]Includes the cost of the co-generation unit.

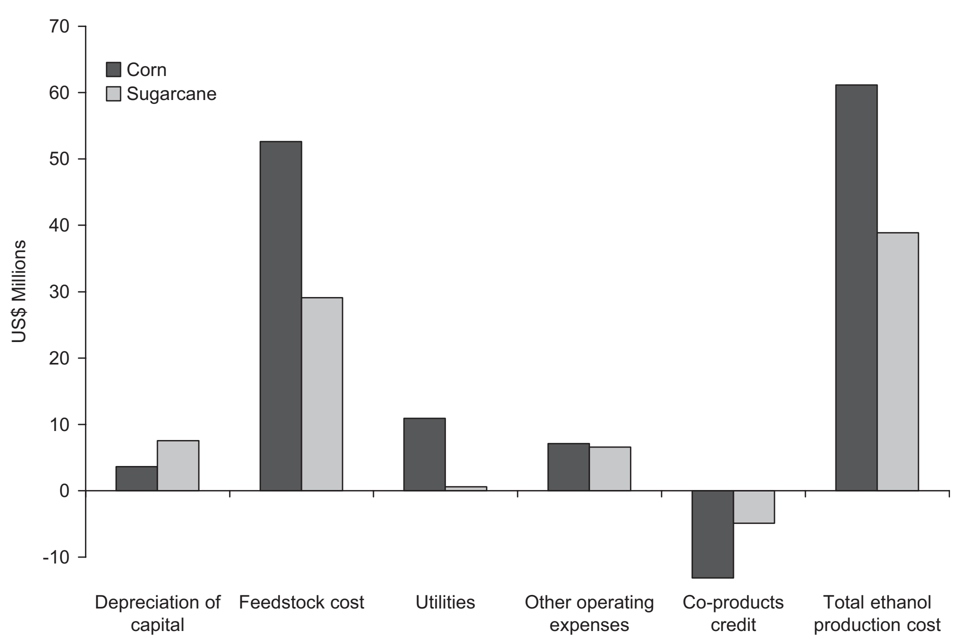

Fig. 4. Total production costs of fuel ethanol using corn and sugarcane as raw materials. Operating costs are represented by the feedstock cost, utilities cost and other operating expenses (operating labor, maintenance and operating charges, plant overhead, and general and administrative costs).

Table 9
Unit costs of fuel ethanol (US$/L of anhydrous ethanol)

Item	Corn-based process	Share (%)	Cane-based process	Share (%)
Raw materials	0.2911	70.84	0.1611	66.45
Utilities	0.0604	14.70	0.0033	1.35
Operating labor	0.0017	0.41	0.0028	1.14
Maintenance and operating charges	0.0053	1.30	0.0117	4.83
Plant overhead and general and administrative costs	0.0322	7.84	0.0218	8.97
Depreciation of capital[a]	0.0202	4.91	0.0418	17.26
Co-products credit	−0.0728	–	−0.0272	–
Total	0.3381	100.00	0.2153	100.00

[a]Calculated by straight line method.

negatively affects its operating costs and environmental performance (see below).

Total capital costs are lower for corn process (Table 8), even though it has a more complex configuration involving an additional enzymatic hydrolysis step. For the cane-based process and due to the higher amount of feedstock to be handled, a greater capacity of equipments is required. In addition, the co-generation system increases the required investment for such type of configurations. Nevertheless, the possibility of selling electricity contributes to compensate these additional expenses.

The production costs structure of 1 L of ethanol produced from corn (as shown in Table 9) is comparable to the costs structure estimated by the NREL for the mature process of ethanol production from corn via dry-milling technology in the USA. In the latter case, ethanol production costs reach US$0.232/L of anhydrous ethanol [24]. The main difference in the production costs are mostly explained by the higher corn prices in Colombia related to cheaper US corn (0.076 US$/kg). In fact, the utilization of imported corn from the USA as feedstock for new ethanol production facilities located in the Colombian Caribbean coast has been proposed by different organizations including the Colombian government. In any case, the volatility of corn price is a crucial factor to be accounted for. Production costs obtained in this paper are very close to those reported by Macedo and Horta [17] for ethanol production from milo (grain sorghum) in the USA. It should be noted that co-product (DDGS) sales in corn ethanol production play a significant role for process sustainability.

The calculated ethanol production cost for cane-based process (see Table 9) is higher than the average production cost of Brazilian ethanol (0.198 US$/L in 2007) [34]. The price of Brazilian hydrous ethanol could be even lower as stated in [17]: about 0.150 US$/L. This could be explained by the lower cost of the sugarcane in Brazil (about 0.010 US$/kg in some producing states). However, the cost obtained for cane-based ethanol under Colombian conditions is still very low compared to corn ethanol. Similar to Brazil, the high productivity of sugarcane, the advantageous output/input energy ratio of the cane-to-ethanol process compared to corn or lignocellulosic biomass, and the low cost of labor force, among other factors, makes this feedstock the more viable option for new ethanol production facilities. The commercialization of the co-products (e.g., *cachaza* and concentrated stillage) allows a substantial economic balance improvement (see Fig. 4).

Table 10
Some economic indicators of two processes for fuel ethanol production using different feedstocks

Economic indicator	Ethanol from corn	Ethanol from sugarcane
Payout period (years)	3.85	4.13
Net present value (thous. US$)	130,251.00	174,453.00
Internal rate of return (%)	66.75	59.48

Table 10 shows a confirmation of the economic viability of the two analyzed processes. In relation to their profitability indicators, both processes are comparable although the production costs for sugarcane are clearly smaller. Moreover, ethanol from cane offers a higher NPV with a lower IRR. Different evaluations simulating changes in the price of the main feedstock show that the process utilizing sugarcane is much more stable to this kind of variations. Thus, a 71% increase in the price of corn (likely to occur under Colombian conditions) leads to negative NPV during the lifetime of the project. In contrast, this same increase in the price of sugarcane (whose price is much more stable in Colombia) only leads to a 38.7% reduction in NPV and 28.4% decrease in IRR. These results enable us to conclude that ethanol production process from sugarcane represents the best investment possibility under Colombian conditions.

6.3. Environmental evaluation

The composition and flow rate data of all the streams involved in the two simulated processes allowed accomplishing the environmental evaluation. The total output rate of environmental impact for processes examined is shown in Fig. 5 and the PEI generated within the system is shown in Fig. 6. It is evident that ethanol production from cane has lower impact on the environment compared to the corn process: the latter process exhibits a higher PEI per mass of products. This environmental indicator is the index to be considered for the overall evaluation of both processes using the AHP approach. On the other hand, the corn-based process has a more negative generated PEI meaning that the PEI of the substances entering the system is reduced by their transformation into other less dangerous compounds. For the sugarcane process, the higher value of generated PEI (although negative) indicates that the conversion of entering substances also occurs, but to a lesser degree. This feature can be related to the fact that this process requires the input of a greater amount of feedstock.

The improved environmental performance (in the terms of PEI leaving the system per mass of products) of the sugarcane-based process can be explained by the operation of the co-generation unit. In this unit, one of the process by-products, the bagasse, is utilized as renewable fuel in order to generate all thermal and mechanical energy required by the process, as well as the power needed. In contrast, the energy demand for the corn process should be supplied by fossil fuels whose combustion generates atmospheric emissions having a direct influence on most of the impact categories studied (especially on ATP and AP). When bagasse is burned, the negative effect of CO_2 released onto the atmosphere during its combustion is compensated positively by the CO_2 fixed from the atmosphere during the sugarcane growth. Therefore, the utilization of bagasse as fuel does not necessarily imply a net increase of CO_2 in the atmosphere. However, the environmental impact of the involved mass and energy flows in the whole life cycle is not assessed by the WAR GUI software. It only performs the evaluation of the PEI of the streams leaving or generated during the conversion process. To overcome this problem for the case of CO_2 emissions, the flue gases stream leaving the co-generation unit was analyzed as if it were free of carbon dioxide. Thus, zero CO_2 net emissions were considered on life cycle basis. If this assumption were not taken into account,

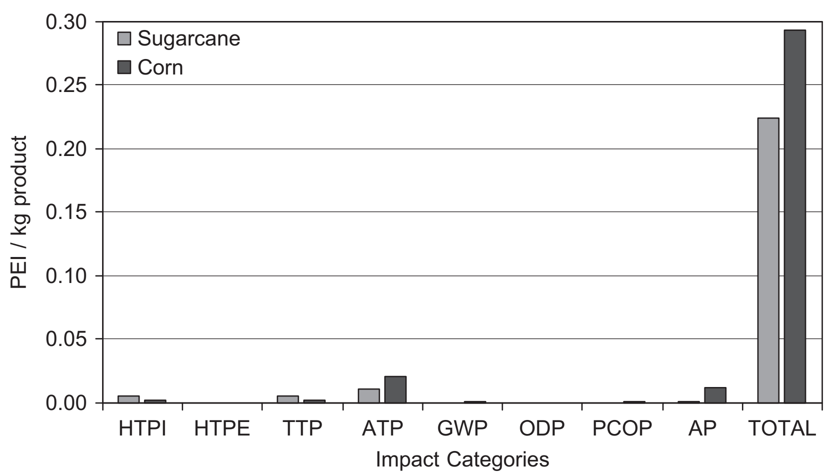

Fig. 5. Total output rate of environmental impact for the studied processes. The impact is expressed as the PEI leaving the system per mass of product streams.

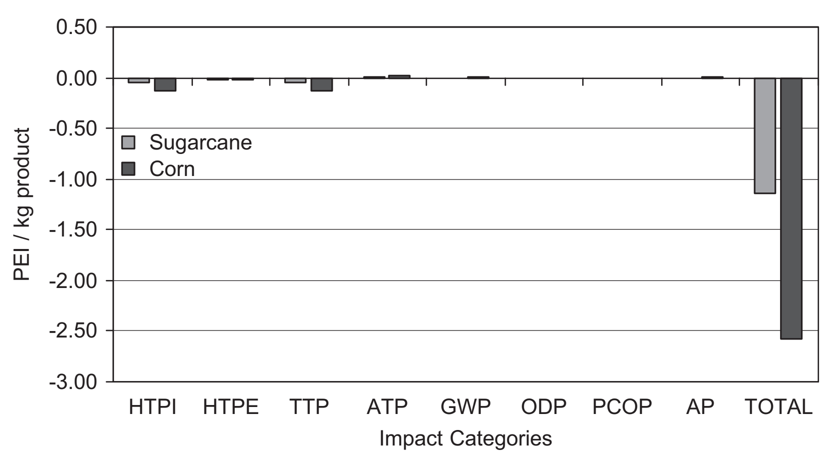

Fig. 6. Potential environmental impact generated within the studied processes. The impact is expressed as the PEI generated within the process per mass of product streams.

the corn-based process would exhibit better environmental indicators despite consuming significant amounts of fossil fuels.

The commercial utilization of *cachaza* and concentrated stillage imply the drastic reduction of two polluting streams generated during the cane-to-ethanol process. This is also valid for DDGS in the corn-based process. Stillage is a highly contaminating liquid stream due to its high biological oxygen demand (BOD) (30,000–60,000 mg/L). Several methods have been proposed for its treatment, but few have been employed. The evaporation of stillage to obtain a co-product used as a fertilizer for cane plantations is one of the most popular applications along with its use for irrigation. However, the properties of the soil may be affected by the utilization of huge volumes of concentrated stillage. These effects have not been properly studied within the framework of life cycle assessment methodology and further studies are required.

6.4. Combined evaluation by AHP

Table 11 shows the results obtained from the integration of the economic and environmental assessments following the proposed methodological approach shown in Fig. 1. From these results, the sugarcane-based process exhibit a higher AHP score, indicating that it has better performance than the corn-based process when both economic and environmental criteria are analyzed in a combined manner.

Changes in the evaluation of the AHP, when different weightings are selected for both processes are shown in Fig. 7. According to this figure, the cane-based process will always have a better performance with any value of the economic weighting. When this weighting is increased (i.e., equivalent to the reduction of the environmental weighting), the AHP score will also increase. In contrast, the corn-based process shows slightly worse performance when the economic attribute has a higher weight. This means that the economic advantages for the sugarcane process are actually better than those displayed for the corn scenario. Therefore, assigning weightings for this case study does not affect the final qualitative result of the combined evaluation within the AHP framework. Thus, the process that employs sugarcane for producing fuel ethanol shows better performance.

Table 11
Results of environmental and economic integration for fuel ethanol production process using two feedstocks

Feedstock	NPV (thous. US$)	P_{Ecn}	PEI	P_{Env}	AHP
Sugarcane	174,453.00	0.573	0.224	0.567	0.571
Corn	130,251.00	0.427	0.293	0.433	0.429

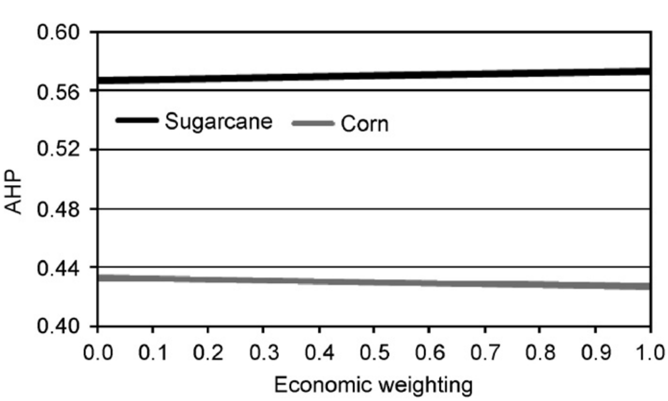

Fig. 7. Variations in the evaluation of AHP score in dependence on the selected economic weighting.

7. Conclusions

For selected production volume of ethanol and according to the feedstock requirements (292,618 ton/h of sugarcane or 50,629 ton/h of corn), it would be necessary to plant 20,618 Ha of sugarcane or 27,002 Ha of corn to produce the same amount of anhydrous ethanol under Colombian conditions. Although the ethanol yield from corn is higher than that from sugarcane, the lower annual yield of corn per cultivated hectare makes it necessary to use larger cropping areas. The main share of production costs for a fuel ethanol process corresponds to the raw material. For the Colombian case, results obtained show that the fuel ethanol process from corn has worse economic indexes related to sugarcane. In addition, the corn process has a greater environmental impact mostly due to the utilization of fossil fuels to produce the thermal and electric energy required during grain conversion. This situation suggests the exploration of other starchy materials with better indicators. Currently, preliminary studies on the use of cassava for ethanol production are being conducted to demonstrate the feasibility of such a process.

The integration of economical and environmental aspects into one index as a design guidance for process selection leads to a significant improvement of the evaluation process. This is particularly important when many process configurations must be assessed in order to select the best alternative. In particular, it is clear that a fuel ethanol process from sugarcane is the best choice to implement new ethanol production facilities under Colombian conditions regarding both economic and environmental considerations. This awareness has pushed government to promote the development of new projects for fuel ethanol production from sugarcane instead of corn, although economic arguments seem to have had greater weight. Cassava and beet are other potential feedstocks for bioethanol production. In the case of cassava, a small experimental production facility is starting its operation. More integral evaluations of the type presented in this work should be undertaken in order to assess the suitability of employing these feedstocks for ethanol production.

The procedure proposed to analyze different flowsheet configurations proved to be a useful methodology for process synthesis and can support the decision making for further experimental studies at pilot scale and industrial levels. This is a key issue considering the limited resources for an extensive and long-term research in such countries like Colombia.

Nevertheless, other issues have to be taken into consideration when selecting the appropriate feedstock for new ethanol production plants. In Colombia, the inappropriate organization level of farmers is a common feature as well as their limited investing capabilities. Only big farmers linked to the main economic groups own the technological and financial resources to implement successful agro-industrial projects. For instance, the government has led efforts to organize small and medium-sized cane producers linked to *panela* economy by involving them in the development of new ethanol-production projects. However, the financial "muscle" of the big Colombian sugar industry could force these commercial projects to fall into the orbit of its interests, which does not necessarily coincide with the interests of the country's rural sector. Within this context, the selection of starchy materials as a feedstock for ethanol production could represent an appropriate option for those communities, given the absence of a strong economic group monopolizing the production and processing activities of crops like corn, cassava, or potatoes. Moreover, in the scenario of the new free trade agreements signed by the country and the corresponding aperture of the primary sector, it is paramount the searching for new markets for the national agricultural production. Small ethanol-producing facilities based on starchy crops harvested in the neighboring areas could be an attractive alternative. In this case, small and specialized rural communities and farmers' organizations can participate in the fuel ethanol business without major restrictions. Therefore, social aspects (including environmental concerns) should play a more significant role in the selection of the most suitable feedstocks for the alcohol industry. In this way, financial indicators would not be necessarily the decisive factors when new large-impact projects for biofuels production are studied and implemented in developing countries like Colombia.

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