Environmental and economic assessment of current and expansion ethanol production scenarios in Colombia

Diego Andrés Rueda-Ordoñez[a*], Cindy Johanna Sarmiento-Ardila[b*], Otávio Cavalett³, Antônio Bonomi[c,d], Manoel Regis Lima Verde Leal[c], Luís Augusto Barbosa Cortez[a,b]

a: University of Campinas, Bioenergy PhD Program, 80 Monteiro Lobato Street, Cidade Universitária "Zeferino Vaz", Campinas, SP, Brazil
b: University of Campinas, School of Agricultural Engineering, 501 Cândido Rondon Avenue, Cidade Universitária "Zeferino Vaz", Campinas, SP, Brazil
c: Brazilian Bioethanol Science and Technology Laboratory (CTBE), 10000 Giuseppe Máximo Scolfaro Street, Guará, Campinas, SP, Brazil
d: University of Campinas, School of Chemical Engineering, 500 Albert Einstein Avenue, Cidade Universitária "Zeferino Vaz", Campinas, SP, Brazil
*Corresponding author's email: diegoandresruedaordonez@gmail.com; cna.sar7@gmail.com

Abstract

This study presents an environmental and economic assessment of two scenarios for sugarcane ethanol production by using an innovative framework, the so-called Virtual Sugarcane Biorefinery. The scenarios are (a) current ethanol production in the Cauca Valley (current scenario), and (b) a promising ethanol production alternative in the *Llanos Orientales* region (expansion scenario). In the current scenario, we considered an annexed mill to represent the technological configuration currently used in the region, producing sugar, ethanol and electricity. Favorable climate conditions and the large amount of arable land available for agriculture make *Llanos Orientales* region the most suitable option for ethanol production expansion in Colombia. For this scenario, we evaluated an autonomous distillery producing ethanol and electricity. The economic and environmental assessments included all the operations from agricultural to industrial stage to determine potential economic and environmental impacts of ethanol production alternatives. The results indicate that current ethanol production presents favorable environmental and economic impacts compared with gasoline. Most of the greenhouse gas emissions are due to sugarcane production stage and coal combustion in the boiler. Results indicate that increment on ethanol production in *Llanos Orientales* region should lead to improved sustainability to the Colombian transport sector.

Keywords: Sugarcane ethanol, first generation ethanol, life cycle assessment, climate change

1. Introduction

Worldwide, energy policies encourage the increment of bioenergy in the energy matrix and biofuels production arises as one of the sustainable options positioned as an alternative to the use of fossil fuels, mainly by its renewable condition. Demand for biofuels has grown considerably over the last years and key questions about biofuels intensification have become important. Several countries are implementing programs to reduce fossil fuel consumption and to improve their biofuel production chains. In view of the current environmental impacts in recent years and the Colombian oil dependence, there has been an interest in producing bioethanol as a renewable vehicle fuel in place of gasoline. Its use as an oxygenated gasoline allows better oxidation of hydrocarbons and reduces the carbon monoxide emissions released onto de atmosphere [1].

Sugarcane is one of the most important energy crops in tropical countries like Brazil, Colombia and India. In a study performed by [2], they compared different feedstocks produced in Latin America and concluded that sugarcane is the most competitive feedstock for first generation ethanol production. Furthermore, crop expansion and/or harvest intensification of sugarcane has also become an interesting topic due to the possible negative impacts. Colombia is a tropical country with a large biodiversity and a wide range of crops and natural resources at high productivity levels, which encourages increasing sugarcane for ethanol production. By so, it is important to study the potential environmental impacts of such complex situations.

Colombia embrace the ethanol program since 2001 and now has become the third sugarcane ethanol producer in Latin America with one of the major sugarcane yields in the world. The Colombian energy policies implicate that biofuels production must gradually increase until 2020 [4]. By so, the private sector and the government expect a significant increase of bioenergy production and an expansion in the available land for energetic agriculture. Consequently, the Colombian government has approved tax exemptions, as well as other economic policies, as a way to promote the biofuels program. Furthermore, through the free trade agreement, the exportations of biofuels to the United States and the European Union represent a great economic opportunity by accessing one of the biggest ethanol markets without customs duty [3].

Sugarcane ethanol production in Colombia is concentrated in the Cauca River Valley region with six plants with the capacity to process 24 million tons of sugarcane per year. In 2014, the average harvested area was near to 230 thousand ha of sugarcane and the ethanol production was higher than 400 million liters, enough to reach a national blending mandate of 8% (v/v). Furthermore, this region presents highest sugarcane and sugar yields in Colombia, the best climate, as well as the administrative organization of the sugarcane supply chain [5]. The current area for sugarcane plantation in Colombia is limited and is expected an increasing demand of biofuels and other products from sugarcane. Therefore, considering a sustainable expansion of sugarcane in other regions, the Llanos Orientales region presents the most suitable option for ethanol production in Colombia. However, this expansion region could hardly replicate notable sugarcane yields from Cauca Valley [6]. Moreover, this region has favorable weather conditions and, with 1/3 of Colombian territory, presents an availability of arable lands of more than 5 million hectares for agriculture [7].

In this paper, we performed an economic and environmental assessment of two scenarios for sugarcane ethanol production. The scenarios are: (a) current ethanol production in the Cauca River Valley (current scenario), and (b) a promising ethanol production alternative in the Llanos Orientales region (expansion scenario). This paper focuses on the economic and environmental impacts of sugarcane ethanol production in Colombia using an innovative framework, the so-called Virtual Sugarcane Biorefinery (VSB), developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) [8]. We used this framework for the assessment and comparative evaluation of two sugarcane ethanol scenarios in Colombia. Results can be useful to support policy makers and the assessment approach is suitable to design future sugarcane biorefineries taking into consideration sustainability aspects.

The Ethanol Production in Colombia

Usually, first generation ethanol production is incorporated into the sugarcane supply chain. In Colombia, its production is based in annexed distilleries to the sugar plant, which produce both sugar and ethanol. Ethanol is produced from non-exhausted molasses (impure solution of sugars that remains after sucrose crystallization) associated to the sugar production process.

In the Colombian annexed plants, different residues obtained from the industrial process, such as filter cake, ashes from the boiler, concentrated vinasse and flegmass, are used for compost production (natural fertilizer). Remaining sugarcane residues stay in the field acting as natural cover. In the wastewater treatment area, residual water is treated by anaerobic digestion and then discharged to the nearest rivers. The residual sludge from this process is also used in the composting process [6]. This facility is self-sufficient in energy terms. All the thermal and electric energy required for the production process is produced in combined heat and power (CHP) systems using sugarcane bagasse and coal. Some portion of electricity is consumed in the industrial process, while the surplus is sold to the grid. Fig, 1 shows the process flowsheet for sugar, ethanol, and electricity production from sugarcane in annexed plants.

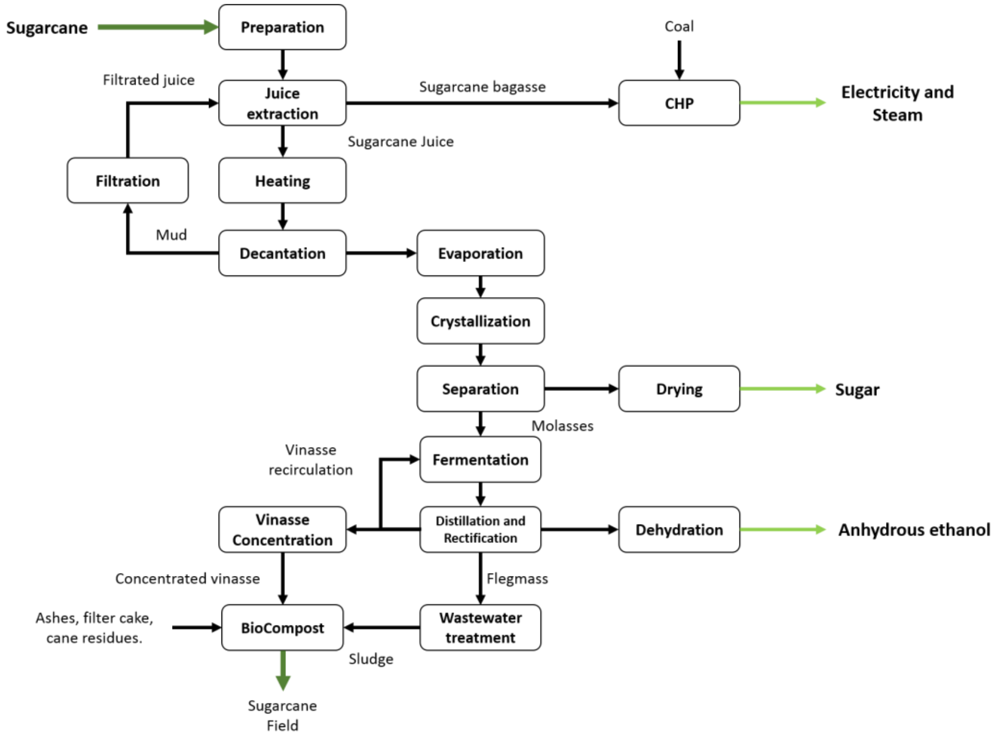

Fig. 1. Process flowsheet of the annexed ethanol, sugar and electricity plant.

The process for ethanol production in an autonomous distillery has the objective to transform the sugar from sugarcane into ethanol, which takes place through several operations illustrated in Fig. 2.

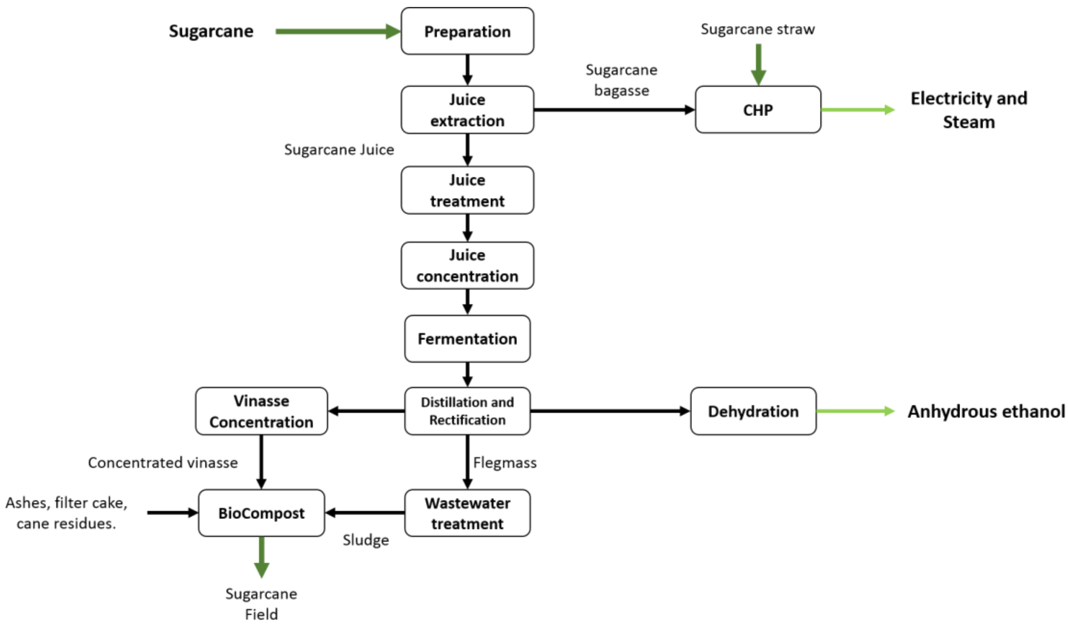

Fig. 2. Process flowsheet of an autonomous distillery.

The main difference of an autonomous plant from the annexed distillery is related to the ethanol production process, which is only from sugarcane juice in the autonomous plant. Additional unit operations presented in an autonomous distillery are preparation and extraction of sugars, physical and chemical treatment of juice and juice concentration. The autonomous distillery is also self-sufficient in energy consumption, but uses only bagasse and 50% of sugarcane straw recovered from the field as a fuel to produce energy to the plant.

Currently, Colombia does not have autonomous distilleries in operation, but there is a project in the Llanos Orientales region in execution that contemplates 14,400 ha of sugarcane completely mechanized and expects an ethanol production of 480,000 liter/day [9].

2. Methodology

This paper focuses on the economic and environmental impacts of the sugarcane ethanol production in Colombia in two different scenarios (current and expansion). Table 1 summarizes main characteristics between these scenarios.

Table 1. Main parameters of current and expansion scenarios.

Parameter	Current	Expansion
Days of operation	330	240
Fraction of area with mechanical harvesting	51%	100%
Type of planting	Semi-mechanized	Mechanized
Irrigation	Yes	No
Fraction of sugarcane straw recovered from the field	0%	50%
Sugarcane processed	3 Mt/y	4 Mt/y
Ethanol production from	Molasses	Sugarcane Juice
Products	Sugar, ethanol, electricity	Ethanol and electricity

The Virtual Sugarcane Biorefinery (VSB) was used in this assessment. It is a comprehensive framework developed and constantly improved by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) to evaluate, from a sustainability standpoint, different biorefinery alternatives [8]. The VSB framework integrates the computer simulation platforms with economic, social and environmental evaluation methodologies to assess technical and sustainability impacts of different sugarcane biorefinery alternatives/routes. It integrates all the stages of the sugarcane chain: agricultural production, transport, industrial, and use and final disposal of the products. Fig. 3 presents the general concept of the VSB. It is important to point out that the social indicators were not considered in this study.

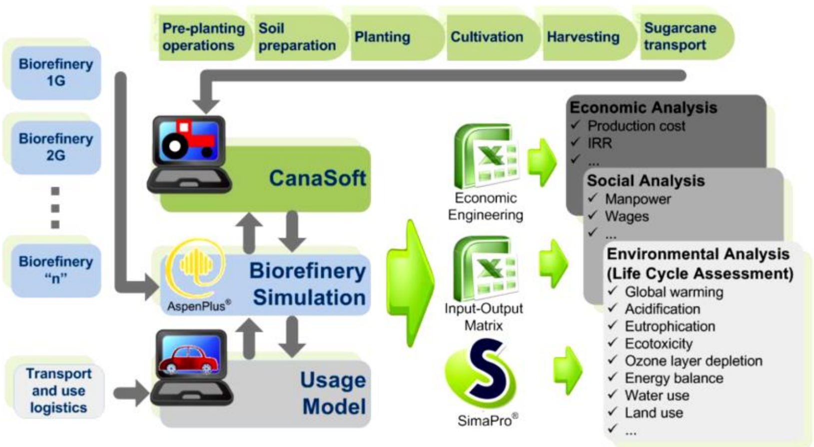

Fig. 3. General concept of the Virtual Sugarcane Biorefinery (VSB) [8].

The construction of this approach is directly focused on key scientific and technological aspects of future biorefineries. Among other results, the VSB framework allows to: (a) evaluate different technologies and product alternatives for the biorefinery, (b) optimize the concepts and processes of the new biorefineries considering the whole production chain, and (c) benchmark the development stage of new technologies for production of ethanol and co-products, considering the integral use of sugarcane biomass [8].

The feedstock production was modeled using the *CanaSoft* model within VSB. Some important agricultural parameters such as yield, operational efficiencies and transport distances were updated to represent the Colombian sugarcane sector. The study concerned two different technologies for sugarcane planting and harvesting for each scenario. In this study, we considered different sugarcane yields for each scenario, due to the distinct conditions in these two regions. Based on the scenario definition, *CanaSoft* provides the agricultural life cycle inventory (LCI) and allows calculation of sugarcane and straw production costs.

Regarding the industrial phase, different process flowsheet and operational efficiencies were considered in the process simulation using Aspen Plus® platform. Operating and process parameters of the annexed and autonomous distilleries were obtained from literature and consulting industries. Sugar, ethanol and electricity production as well as investment estimates and industrial LCI are the main outputs from the mass and energy balances obtained from computer simulation.

Economic Analysis

In the economic evaluation, the most used approaches in Engineering Economics, such as internal rate of return (IRR), net present value (NPV) and production costs were calculated to analyze economic feasibility. In this methodology, a cash flow is projected for each technological scenario to be evaluated taking into account the investment (CAPEX) needed for the project and all operational costs (OPEX) and revenues for an expected project lifetime. The main operational costs and revenues were calculated based on technical parameters obtained in the simulation step and from monetary values observed in the last nine years, such as ethanol and electricity prices. We used the sugar price reported in [10] updated to December of 2014.

Production of anhydrous ethanol, sugar, and surplus electricity was determined for each scenario based on the results of the simulations. These results, along with investment costs and prices of feedstock and sugarcane products, presented in Table 2, were employed to perform economic analysis in the VSB framework. At the same time, sensitive analysis of the most important parameters of technologies under evaluation and their relation in cost and investment.

Table 2. Economic assumptions adopted for both scenarios.

Product	**Value**	**Reference**
Project lifetime	25	Consideration
Minimum attractive rate of return (%)	17.6	Calculated through CAPM method*
Construction and start-up (years)	2	Consideration
Depreciation (linear)	10	Consideration
Tax rate (%)	33	Colombian tax rate
Sugar price (US$/kg)**	0.50	Updated value to Dec 2014 based on [10]
Anhydrous Ethanol (US$/l)**	0.99	Average of the last 9 years (MME Resolutions)
Electricity (US$/MWh)**	58.43	Average of the last 9 years for energy contracts [12]

*Capital Asset Pricing Model based on data from [11]

**price in Brazil, considering the exchange rate US $ 1.00 = R$2.30 (2014)

Results of the economic assessment were defined in terms of internal rate of return (IRR) and production costs defined as the average interest rate paid per year by the evaluated project. The IRR of an investment is discount rate at which the NPV of cost (negative cash flow) of the investment equal the NPV of the benefits (positive cash flow) of the investment. IRR can be found when NPV equal to zero considering a market value allocation strategy for the production costs of different products, for the project to be accepted, the IRR must be greater than or equal to the minimum acceptable rate of return (MARR) [8].

A breakdown of sugarcane production costs is analyzed for each sugarcane production stage.

Life cycle Assessment

The environmental assessment was performed using the Life Cycle Assessment methodology (LCA). LCA is a recognized methodology for determining the environmental impact of a product (or good or service) during its entire life cycle, from extraction of raw materials through manufacturing, logistics, use and final disposal or recycling [13]. The LCA method consists of four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation [14] [15]. We selected six environmental indicators from ReCiPe Midpoint Impact Assessment method [16]. Climate Change (CC) measured in kg of CO_2 eq (equivalent); Ozone Depletion (OD) measured in kg of CFC-11 eq; Human Toxicity (HT) measured in kg of 1.4 DCB eq (dichlorobenzene); (PMF) particle mater formation measured in kg of PM_{10} eq; Terrestrial Acidification (TA) measured in kg of SO_2 eq and Fossil Depletion (FD) measured in kg of oil eq.

According to LCA methodology, allocation is required for multi-output processes [12] [14]. In this study, we applied an economic allocation (see Table 3) based on the market value of the process output (the same used for the production costs in Table 2).

Table 3. Economic allocation used for each scenario.

Product	Current	Expansion
Ethanol	33%	93%
Electricity	63%	7%
Sugar	3%	-

3. Results and discussion

The two Colombian sugarcane production scenarios were modeled using the Canasoft Model. It allowed characterization and quantification of main sugarcane inputs such as fertilizers, machinery, diesel, labor and related emission, among others. The model calculated and organized the information providing complete inventories for economic and environmental assessment.

In Table 4, we present the industrial dataset for the evaluated scenarios. The main difference between scenarios, besides products, are inputs and emissions specifically related to sugar, ethanol or CHP processes, which depend on the processing capacity.

Table 4. Industrial dataset for the main industrial process scenarios evaluated (per 1000 kg of sugarcane processed)

Name	Current	Expansion
Inputs		
Straw (dry mass) (kg)	-	61.30
Water (kg)	1,750	1,500
Lime (kg)	1.21	0.82
Sulfuric Acid (kg)	0.57	1.90
Phosphoric Acid (g)	206	316
Zeolite (g)	8.5	28.4
Lubricating Oil (g)	13	13
Industrial equipment (Steel) (kg)	0.18	0.37
Outputs		
Ethanol (l)	26.5	88.7
Electricity (kWh)	46.7	109.6
Sugar (kg)	97.8	-
Concentrated vinasse (kg)	44.3	42,9
Filter cake (dry mass) (kg)	8.1	10.2
Ashes (dry mass) (kg)	5.2	10.0
Emissions to Air		
Biogenic carbon dioxide from boiler (kg)	219	360
Biogenic carbon dioxide from Fermentation (kg)	21	70
Ethanol from distillation (g)	34.7	120

The economic assessment for current and expansion scenario is summarized in Fig 4. The current scenario showed the highest IRR (29.84% per year). The IRR of the expansion scenario is heavily reliant on ethanol prices while the IRR from current scenario depends, mainly, on sugar prices. The IRR of the Colombian scenarios studied in this paper are higher when compared with the IRR for annexed and autonomous distilleries from Brazil, whose values are around 16% and 14%, respectively [8]. This is mainly due to the significantly higher ethanol prices of in Colombia (US$ 0.99) when compared to the ethanol prices of in Brazil (US$0.45) [8]. Moreover, the NPV of expansion scenario is higher compared to the current scenario due to its largest processing capacity, which provides higher revenue. In conclusion, the NPV and IRR associated with both scenarios showed that they are economically feasible.

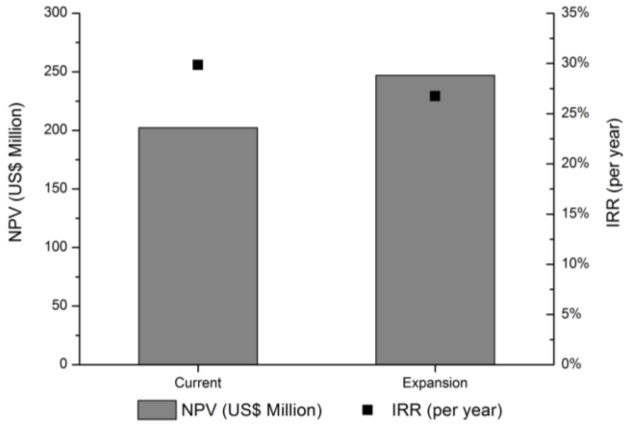

Fig. 4. Summary of economic results for current and expansion scenario.

In order to evaluate the impact of changes in product prices and investment (simultaneously) on the IRR taking into consideration eventual uncertainties on the investment and market fluctuations, a sensitivity analyses was carried out (see Fig. 5). We can infer that expansion scenario is more sensitive to changes on market princes and investment.

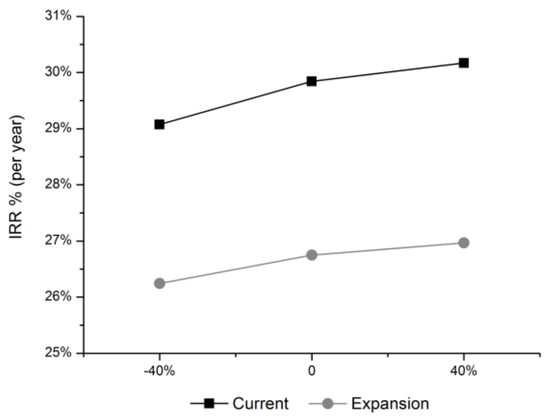

Fig. 5. Sensitivity analyses for the impact of investment and ethanol, electricity and sugar price on the internal rate of return (IRR) for the studied scenarios.

We also verified that individual variations on the investment affected the IRR more significantly than variations on electricity prices. For the current scenario, variations on sugar prices had the greater impacts followed by ethanol and sugarcane prices. For the expansion scenario, the variations are mainly due to ethanol prices.

Concerning production costs of the products (see Table 5), the expansion scenario showed the highest values for ethanol and electricity compared to the current scenario, mainly due to higher sugarcane production cost and higher dependence on ethanol market prices.

Table 5. Production costs for the products and biomass of each scenario.

Products	Current	Expansion
Sugar (US$/kg)	0.344	-
Ethanol (US$/l)	0.672	0.747
Electricity (US$/MWh)	39.81	44.29
Feedstock (US$ per ton of cane)	21.89	31.14

The breakdown of ethanol production cost presented in Fig. 6 showed lowest ethanol production cost in current scenario mainly because of the cost allocation of sugar. Considering that current scenario produces a considerable amount of sugar per ton of cane in comparison to the expansions scenario, a higher share operating cost is allocated to sugar production, thus decreasing ethanol production costs. The expansion scenario is affected mainly by the higher sugarcane cost due to the increased mechanized agricultural operations and transportation of sugarcane and straw. And ,mainly, lower sugarcane yields

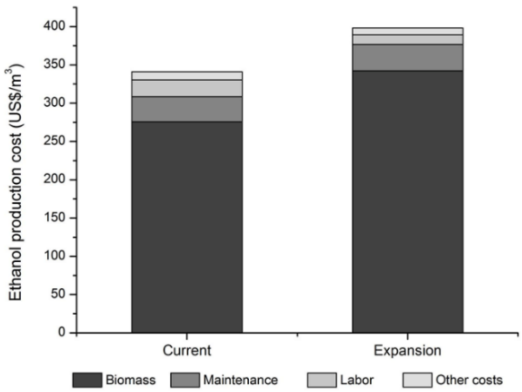

Fig. 6. First generation ethanol cost of annexed plant (current scenery) and autonomous distillery (expansion scenery) considering ethanol, electricity, and sugar moving average prices over the last nine years).

The environmental assessment results for selected impact categories per unit of mass of ethanol are presented in Fig. 7. These scores give the relative environmental impacts of ethanol production including sugarcane production, transportation, inputs and industrial processes along its life cycle.

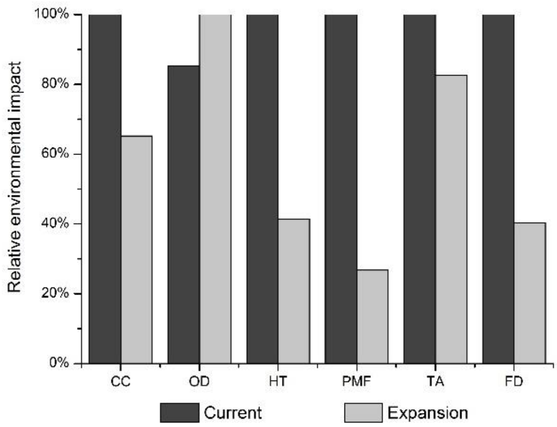

Fig. 7. Comparative environmental scores for ethanol production in the evaluated scenarios (Note: CC climate change, OD ozone depletion, HT human toxicity, PMF particle mater formation, TA terrestrial acidification, FD fossil depletion).

Results showed that for all impacts categories, except ozone depletion (which is proportional to the ethanol production), current scenario presented the higher environmental impacts. It is mainly due to coal use in the boiler and the pre-harvesting burning of sugarcane. The expansion scenario have a high potential for decreasing environmental impacts of ethanol production mainly due to surplus electricity commercialization reducing allocation factor for ethanol. In addition, the elimination of the pre-harvesting burning operation also significantly reduces emissions of greenhouse gases emissions (CO_2, N_2O and CH_4). The impacts in expansion scenario are mainly associated to higher mechanization level in the harvest operations and the sugarcane straw transportation, increasing diesel consumption. Sugar production in the current scenario has a similar effect to the one observed for electricity in the expansion scenario reducing allocation factor for ethanol.

Breakdown of the environmental impacts of ethanol production in the evaluated scenarios is presented in Fig. 8 and Fig. 9. For the current scenario, results showed that coal combustion generates most of the environmental emissions in the CC category and has a high contribution in PMF and TA categories. The process emissions are higher in HT and FD due to the coal production stage. Sugarcane production emissions are mainly related to fertilizer use, diesel consumption and pre-harvesting burning,

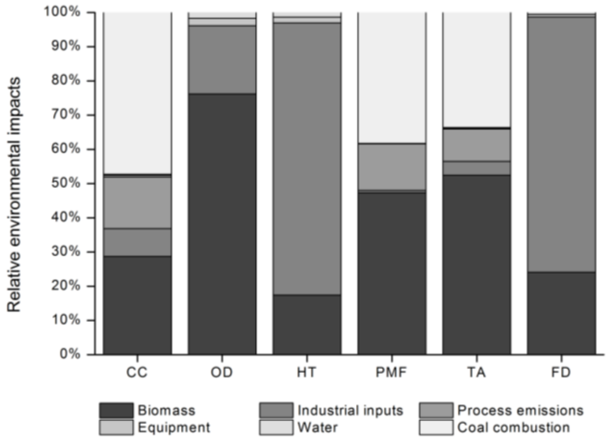

Fig. 8. Breakdown of the environmental impacts of ethanol production in the current scenario (Note: *CC* climate change, *OD* ozone depletion, *HT* human toxicity, *PMF* particle mater formation, *TA* terrestrial acidification, *FD* fossil depletion).

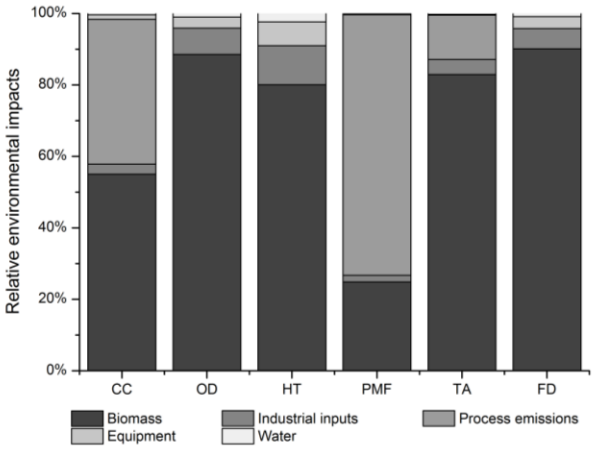

Fig. 9. Breakdown of the environmental impacts of ethanol production in expansion scenario. (Note: *CC* climate change, *OD* ozone depletion, *HT* human toxicity, *PMF* particle mater formation, *TA* terrestrial acidification, *FD* fossil depletion).

For the expansion scenario, results indicate that sugarcane agricultural phase has a very high impact in the ethanol production chain. Direct process emission are observed only in CC, PMF, and TA categories, due to emissions from bagasse and straw burning in industrial boiler. In CC category, the impact is mainly related to N_2O, CH_4 and CO emission, since CO_2 from biomass is biogenic and has no contribution to global warming. CC is also affected by the emissions in the compost process. In TA, impacts are related to nitrates and sulfates emissions. Industrial inputs have an important contribution in FD, HT and OD, the main contributor is phosphoric acid (used in juice treatment).

4. Conclusions

The VSB allowed performing an economic and environmental assessment for the current and expansion ethanol production scenarios in Colombia. Important aspects for the improvement of sustainability of the ethanol production in Colombia were identified. The environmental assessment using the LCA methodology indicated that technologies analyzed for the expansion scenario considered in this study have a great potential for a significant decrease in environmental impacts compared to the current ethanol production scenario in the *Cauca Valley*. Ethanol production in the current scenario presented higher environmental impacts, mainly due to the coal use in the boiler, and pre-harvesting burning of sugarcane. The economic assessment showed that both scenarios are economically feasible. The current scenario presented a slightly higher IRR and lower ethanol production cost, mainly because the sugar production compared to the expansion scenario. In conclusion, results indicate that both current and expansion ethanol production scenarios presented favorable environmental and economic impacts compared to gasoline.

Acknowledgements

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