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Jamaican bioethanol: an environmental and economic Life Cycle Assessment.

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Abstract:
E10 is a blend of 10 % bioethanol and 90 % gasoline that can be used in the engines of most cars without causing damage. Currently for the E10 blend Jamaica imports gasoline from Trinidad &Tobago and bioethanol from Brazil due to the bioethanol production in Jamaica is at an early stage. However, the country has great potential for bioethanol production. In order to assess the environmental and economic feasibility of bioethanol in Jamaica, this paper presents an economic and environmental Life Cycle Assessment for a case study in Jamaica in two different scenarios. The Baseline Scenario represents the use of E10 in the current conditions in which bioethanol comes from Brazil and gasoline from Trinidad & Tobago. Scenario I represents the use of E10 with bioethanol from Jamaica and gasoline from Trinidad & Tobago.
The comparative environmental Life Cycle Assessment revealed that the Baseline Scenario had better results than Scenario I in ten environmental categories. The economic assessment results in Scenario I were 7% higher than in the Baseline Scenario. Hence, the current context (Baseline Scenario) was identified as the scenario with the best economic performance. Therefore, the current situation in Jamaica (Baseline Scenario) scored better results than Scenario I from an environmental and an economical point of views.

Keywords: life cycle costing (LCC); life cycle assessment (LCA); biofuel; clean technology; sustainable development

Declarations:
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1. INTRODUCTION

The use of fossil fuels has been the basis for the development of modern society. However, this resource is being exhausted and now entails a transition towards a sustainable energy generation scheme (Chen, Xiong, Li, Sun, & Yang, 2019). In this new global scheme, biomass and biofuels have become a central issue for addressing the environmental hazards. Evidence suggests that biofuels are among the most promising alternative for replacing the use of fossil fuels (Basu, 2018), especially in the transport sector (Ballesteros & Manzanares, 2019).

The worldwide increase in biofuel production has principally been determined by several energy policies (European Parliament, 2009; Favretto, Stringer, Buckeridge, & Afionis, 2017; Leah & Hanna, 2017). Currently United States is the largest bioethanol producer, followed by Brazil and China with 45.34, 21.87 and 2.42 Gt in 2015 respectively (United States Energy Information Administration, 2018). In this context, bioethanol production in Latin American non-oil producing countries has a key role to play by reducing the dependence on fossil fuel imports. Moreover, biofuel production involves the implementation of agricultural and industrial processes and the development of smallholder agriculture. This results in an increase in the technological level of the country. The use of biofuels also reduces the Greenhouse Gas (GHG) emissions (World Energy Council, 2016). Furthermore, biofuels are a way to address energy security as they promote exports and compliance with environmental objectives (Rodríguez, 2011).

Jamaica imports around 90% of its total energy consumption. The Jamaican National Biofuels Policy 2010-2030 (Ministry of Energy and Mining, 2010) supports the promotion of bioethanol production to reduce the dependence of energy importations. Bioethanol production in Jamaica is at an early stage. However, the country has great potential for bioethanol production since there is availability of suitable land (50.000 ha) for the production of sugar cane (Ministry of Mining and Energy, 2010). In the last years, Jamaica has been an important trade partner for Brazil, being one of the main destinations of Brazilian ethanol (IEA, 2016).

This research work was conducted in a sugarcane factory (Everglades) in Jamaica. Everglades factory works with sugar from Long Pond and Hampden, both in the parish of Trelawny (Jamaica). Land available for cane cultivation is 527 ha. The planned sugarcane production is 9866 t/y, which has great potential to produce bioethanol. This ethanol could be used blended with gasoline in E10.

E10 is a blend of 10 % bioethanol and 90 % gasoline that can be used in the engines of most modern cars without causing damage. This case study location (Caribbean region) has regulatory frameworks to encourage the use of biofuels, such as policies on subsidies and tax breaks (Iriarte, Rieradevall, & Gabarrell, 2010). It is worthwhile noting that Everglades location has experienced complex social changes as a direct result of the transition from government to private ownership. The present research work provides the results of the second part (those related to bioethanol) of the "Biofuels Life Cycle Sustainability Assessment in Jamaica" project, conducted by the Organization of American State. For this purpose, the project gathered and analyzed the data from two sugar factories, namely Golden Grove in St. Thomas (cogeneration) and Everglades Farms in Trelawny (bioethanol). Results for the cogeneration part was previously published by Contreras-Lisperguer et al., (2018). To conduct this work, the authors followed the same principles of that research line.

By means of a case study, this research work aimed to investigate the environmental and economic impacts of bioethanol in two possible scenarios in order to evaluate overall sustainability of their processes and the feasibility of the bioethanol production in the Jamaican context. Two scenarios were considered for conducting an integrated environmental and economic impact assessment. The Baseline Scenario represents the current Jamaica situation with respect to E10. In this scenario both bioethanol from Brazil and gasoline from Trinidad & Tobago are imported. Whereas Scenario I represents a future perspective in which the bioethanol comes from a local sugarcane enterprise (Everglades). This case study assesses the feasibility of producing bioethanol in countries with potential for bioethanol production such as Jamaica.

There is a vast amount of literature on bioethanol in Latin America and the Caribbean region. Rico et al. (2010) stated that the consolidation of Brazilian bioethanol was achieved thanks to regulatory policies. Likewise, Velaquez et al. (2011) maintain that there is an unambiguous relationship between public expenditure in bioethanol production and the reduction of illness due to air pollution. Castillo et al. (2010) mentioned the need for considering environmental issues in Colombian bioethanol production.

Recent research studies indicates the interest for the triple bottom line (environmental, economic, social) of sustainable development is rising (Subramanian, Chau, & Yung, 2018). It has previously been analyzed the environmental and techno economic impacts of biofuels, more specifically of biodiesel (Jeswani & Azapagic, 2012). Several studies have performed a bioethanol Life Cycle Assessment (LCA). In this respect, Raman and Gnansounou (2015) only assessed the Climate Change and Fossil depletion indicators whereas Rathnayake et al., (2018) conducted an exhaustive LCA which analyzed all the Recipe Midpoint Hierarchist (H) indicators. Economic assessments of bioethanol have been conducted (Luo, Van Der Voet, & Huppes, 2009).

Despite this interest, no one, to the best of our knowledge, has studied the environmental and economic impacts of bioethanol in Jamaica through a whole Life Cycle Assessment. This Jamaican case study could provide an important benchmark to advance the understanding of the bioethanol sustainability in potential countries for its production.

2. METHODS

The purpose of this investigation is to compare the Baseline Scenario and Scenario I through an economic and an environmental Life Cycle Assessment. The environmental LCA was carried out based on the guidelines provided by ISO 14040-14044 standards (Technical Committe 207/SC5, 2006b, 2006a). With regard to the economic impacts, the Life Cycle Costing (LCC) was conducted following the SETAC principles (Swarr et al., 2011).

2.1. Environmental Life Cycle Assessment

The LCA was conducted following the ISO 14040 and ISO 14044 guidelines (Technical Committe 207/SC5, 2006a, 2006b), accomplishing their four phases: i.Goal and scope definition, ii. Inventory Analysis, iii. Impact assessment and iv. Interpretation. First, the goal and scope of the study was defined. In this phase, it was also defined the Functional Unit and the system boundaries. Consequently, the inventory was gathered and then the impact assessment phase and its interpretation were conducted.

The goal of the present LCA study is to compare the E10 blend in the Jamaica current situation and an alternative scenario where bioethanol comes from a local enterprise. To this end, two scenarios were assessed:

- Baseline Scenario: It consists in the use of E10 in the current conditions with bioethanol from Brazil and gasoline from Trinidad & Tobago.

- Scenario I: It consists in the use of E10 with bioethanol from a local enterprise (Everglades) and gasoline from Trinidad & Tobago.

Recipe midpoint Hierarchist (H) was the method used in this research work. This method contains factors according to the three cultural perspectives (individualist, hierarchist and egalitarian). The most common policy principles with regards to time-frame and other issues and the most common choice for scientific models. That is why is the selected option for this study. Mandatory LCA steps of classification and characterization were accomplished. Impact categories gathered by Recipe methodology are widely recognized by the scientific community (Goedkoop et al., 2009). All calculations were performed using the SimaPro software.

Assuming an engine of displacement 1.0 L with a manual gearbox as the source of vehicle propulsion, the average consumption for the 10 % bioethanol in the E10 blend is 0.012 L/km. With regard to 90 % of gasoline in the E10 blend, 0.108 L/km was assumed as consumption. Total reference average consumption was 0.12 L/km for a conventional car in Jamaica (INMETRO, 2014). Furthermore, the potentially bioethanol production in Everglades is 800000 L/y or $6.27 \cdot 10^2$ t/y. With this amount is possible to drive $6.67 \cdot 10^7$ km. Thus, the Functional Unit (FU) for the study is: *To drive* $6.67 \cdot 10^7$ *km in a conventional automobile in Jamaica using the E10 blend with anhydrous bioethanol for fueling motor.* Hence, $6.67 \cdot 10^7$ km is the reference flow for the functional unit and the inventory data were referenced to this quantity.

Concerning the Life Cycle Inventory (LCI), both scenarios were described in Table S1 (see supporting information spreadsheet) and Figure 1. In the Baseline Scenario (Figure 1.A) bioethanol is imported from Brazil whereas in Scenario I (Figure 1.B) bioethanol comes from the Everglades factory. In both scenarios, gasoline for blending with bioethanol is imported from Trinidad & Tobago. The same amount of bioethanol is used for blending with gasoline in Baseline Scenario and in Scenario I. In the use stage, it was considered the transportation of gasoline and bioethanol from their origins to Jamaica, and the combustion of the mixture in a conventional car in Jamaica.

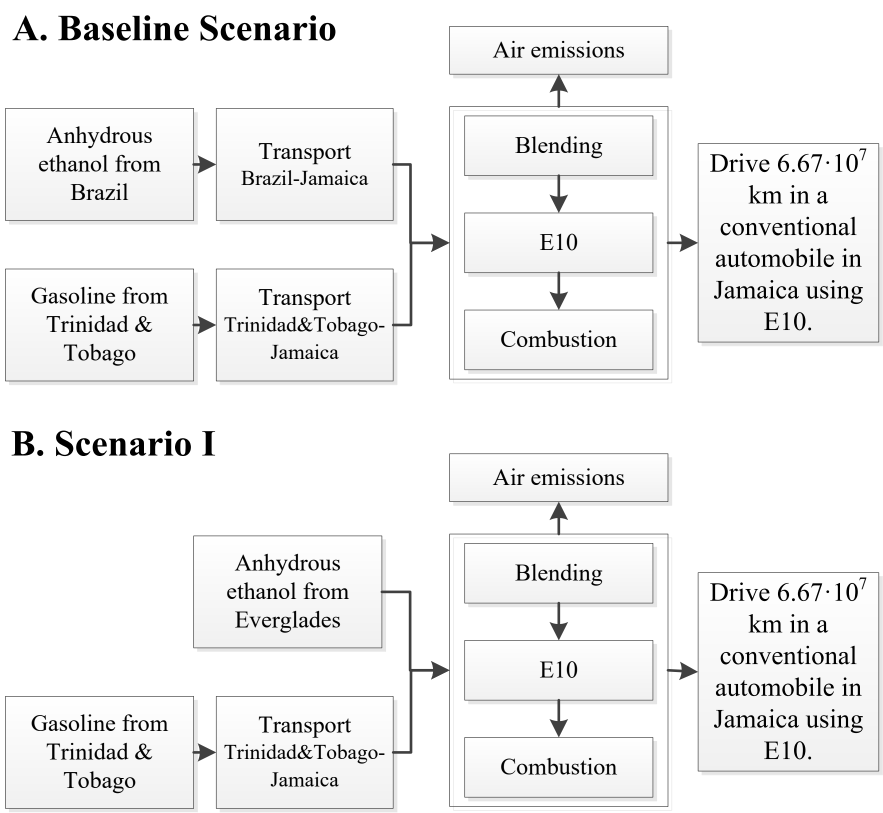

Figure 1. Graphical explanation of the Functional Unit. 1.A. Baseline Scenario. B. Scenario I.

In order to model the Baseline Scenario, bioethanol production from sugar cane in Brazil was taken from the Ecoinvent 3 database (Wernet et al., 2016). In this Ecoinvent item, the agricultural and industrial stages considered the upstream flows. For the aim of the study, the Ecoinvent data chosen for the bioethanol production in Brazil plays an important role. Ecoinvent modelled this dataset with ethanol production from sugar cane and molasse from sugar cane in Brazil. Hence, in terms on geographical, the inventory is modelled for Brazil. This dataset was already contained in the Ecoinvent database version 2. The technology is dewatering of ethanol, and the technology level is 3. In terms on temporal, the period starts in 01/01/2000 and the end date is 31/12/2018 with business-as-usual as macro-economic scenario.

In Ecoinvent 3, for dissolved chemicals, the traditional nomenclature of the chemical industry is to indicate the active substance and then add the water separately. In Table S1 it is possible to see that for driving $6.67 \cdot 10^7$ km then $6.27 \cdot 10^2$ t/y bioethanol are needed. In the Baseline scenario this amount of bioethanol has been considered without taking into account the Ecoinvent 3 guideline previously described since the solution state is 99.7%.

Instead, in Scenario I bioethanol was modelled with primary data gathered in the last three years in the Everglades factory. Figure 2 represents the processes for the Bioethanol production in Scenario I.

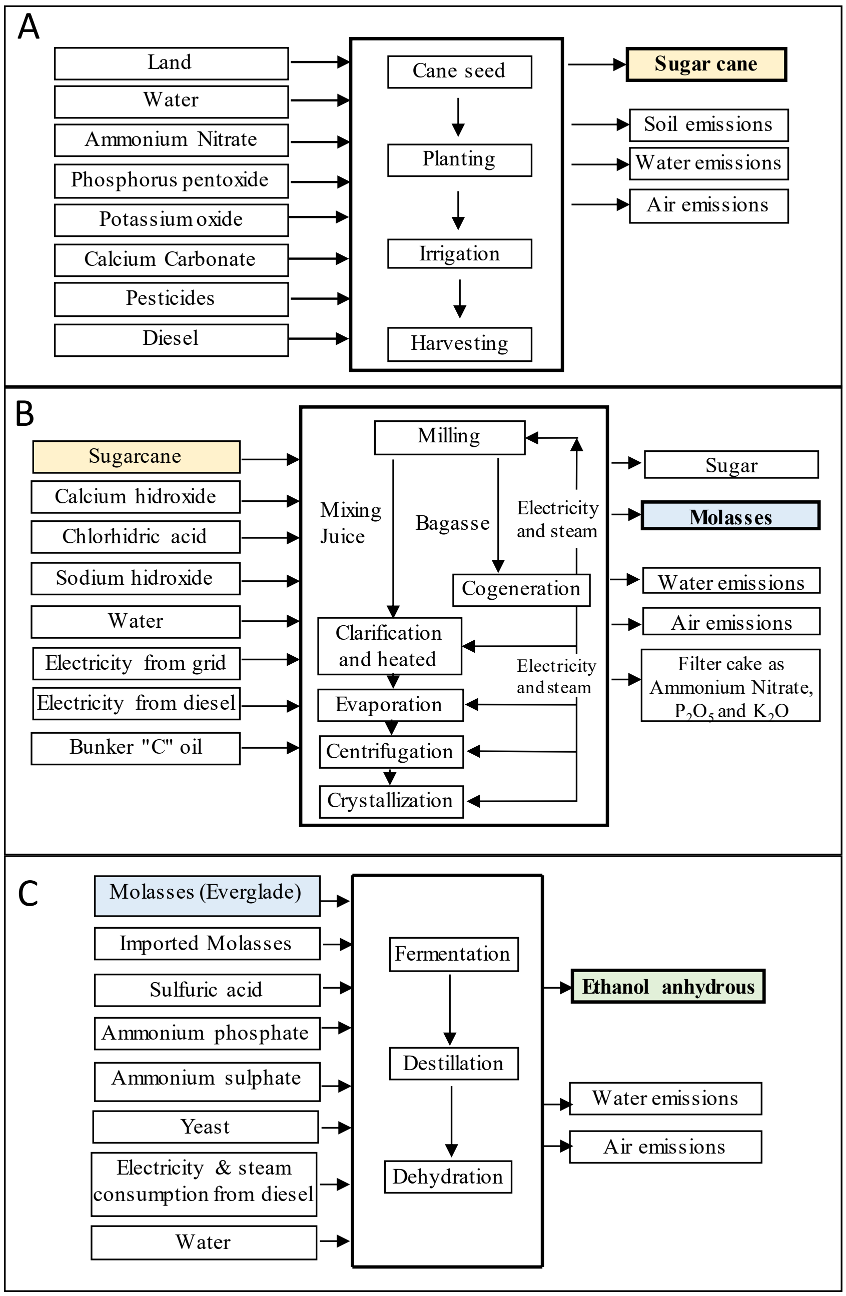

Figure 2. Flowchart of the bioethanol production in Scenario I. 2.A. Agricultural stage. 2.B. Molasses production. 2.C. Bioethanol production.

In the agricultural stage (Figure 2.A) the information was obtained from Everglades factory and completed with some research studies (Kubiak et al., 2008; Suppen, Rosa, Naranjo, & Kulay, 2013). The LCI for the agricultural stage is listed in Table S2 (see Supporting Information). Use of land, raw material and water consumption, transportation of materials in cane production, were reported by the Everglades local agricultural enterprise. Land available for cane cultivation is 527 ha. The planned sugarcane production is 9866 t/y. Fuel consumption was reported by Everglade company as well as some emissions. Water and soil emissions were estimated from literature (Kubiak et al., 2008; Suppen et al., 2013). Most processes were modeled in SimaPro using Ecoinvent except for some processes in which the USLCI and Agri-footprint databases were used. The methodology described by (Suppen et al., 2013) for estimating greenhouse gas emissions due to fertilizing activities, was used for calculating N_2O, NO and NH_3 emissions. The same reference was used for estimating discharges to water (P and NO_3). Herbicides consumption was reported by Everglades and revised with data from literature (Nemecek et al. 2007). Particularly for Merlin herbicide, calculations were made based on the product data sheet which indicates that Merlin is based on the active ingredient isoxaflutol (750 g/kg). The emissions of herbicides were estimated by using (Kubiak et al., 2008). Data related to solid waste generated at the production stage was offered by Everglades. The dataset of transport from Ecoinvent was used for modeling fertilizer and pesticide transportation considering that the average distance from Kingston to Everglade is 166 km. Consequently, a new dataset named sugarcane from Everglades was created.

The sugar manufacturing process (or molasses production) is showed in Figure 2.B. The molasses production stage LCI is detailed in Table S3 (see Supporting Information). with all inputs and outputs referred to the production of 1205.13 t of molasses. The allocation between sugar (80 %) and molasses (20 %) was economic. Furthermore, cogeneration by burning bagasse generates heat and consequently electricity. This electricity production does not satisfy all the sugar mill requirements. The rest of the demanded energy is imported from the public network. In that case, Everglades uses the Jamaican electricity (which is a mix composed by 7 % renewables and 93 % fossil fuels). The electricity mix composition in Jamaica was obtained from literature (Ministry of Energy and Mining, 2011). In the molasses production step, it is also produced filter cake. Filter cake may be used as a fertilizer directly applied on the fields reducing the environmental impact (George, Eras, Gutierrez, Hens, & Vandecasteele, 2010) . Regarding the emissions, detailed information for outputs to water, soil and air were estimated from literature. U.S Environmental Protection Agency provide a series of documents in which is described the procedure for having the amount of emissions when the input is known. The emissions, in the present research work, was calculated for the diesel, pesticides and the combustion of bagasse (EPA, 1996a, 1996b, 2009). The rest of emissions was estimated scaling up linearly the results of Contreras et al. (2009) study. The bioethanol production (Figure 2.C) uses the previously produced molasses and a significant amount of imported molasses as well as other feedstocks listed in the Table S4 (see Supporting Information). In this study, the hydrated bioethanol is dehydrated through molecular sieves generating a vinasses fluid (15 L/L bioethanol). In this study, we have considered an average of the impact for disposing vinasses in surface watercourses, our assumption is in accordance with an LCA study of bioethanol in Brazil (Caldeira-Pires et al., 2018).

2.2 Life Cycle Costing

Life cycle costing (LCC) mostly consider investment, operation, maintenance and end of life costs. This paper follows the methodology for LCC developed by SETAC Working Group (Swarr et al., 2011) building on an previous monograph (Hunkeler, Lichtenvort, & Rebitzer, 2008). LCC methodology is analogous to LCA being the Functional Unit and system boundaries definition equivalents. According to Hunkeler et al. (2008), there are three different types of life cycle costing methods: Conventional LCC is an economic assessment of the life cycle of a product, often excluding one or more life cycle phases, like the disposal phase; Environmental LCC is an economic assessment of the entire life cycle of a product, performed in parallel with an LCA study applying the same system boundaries but without monetization of environmental impacts in order to avoid double counting with LCC results; And societal LCC is an economic assessment of the entire life cycle of a product including external costs for society, like for instance through the monetization of environmental impacts. In the present research work the environmental LLC has been adopted for analysis. Since the environmental LCC has been applied the inclusion of externalities were left out.

This study carries out a comparative assertion of scenarios: Baseline scenario – current conditions of using E10 in Jamaica; and Scenario I – Jamaica sugar sector produces bioethanol with their current sugar industry conditions.

The economic LCI was modelled based on primary data from a survey conducted in the Everglades factory and with secondary data. The primary data was collected by a survey made for the sugarcane and sugar sector. The survey included all cost related to labour, materials, energy, maintenance, fuels, and operation in each unit process of the agricultural and industrial phase. The unit processes in the agricultural phase are soil correction, land preparation, planting, plantation management, ratoon management, hand cut harvesting, mechanical harvesting, cane transport. The unit processes in the industrial phase are industrial process and maintenance. To complement this information and obtain cost data for the following processes: distillation, international freight, import fuels, blending process, and distribution, were set some visits to interview partners from the Sugar Manufacturing Corporation of Jamaica Limited, Petrojam Limited, JB Ethanol, and The all-island Jamaica Cane farmers' Association. This economic LCI has a producer perspective since the results wanted to attain the sugar sector and the government agencies. The producer is focused on controlling production cost to achieve a sufficient rate of return for a given product. E10 life cycle model includes several actors: sugarcane producers, ethanol producers, input providers, gasoline producers, transport services, and final consumers. The capital costs for distillation and cogeneration are sunk costs, thus those were not taken into consideration in the life cycle cost. Additionally, because cogeneration cost is considered in this life cycle costing study, the internal steam and power generation costs in the industrial and distillation processes are not accounted for, only cost of the electricity from the external power grid, avoiding double counting of energy costs.

Scenario I represents the molasses-derived ethanol production in Jamaica with the current sugar production conditions. Scenario I considers agricultural, industrial, distillation and cogeneration phases for Jamaican bioethanol production with molasses locally produced (15%) and imported (85%). Furthermore, Scenario I includes imported gasoline from Trinidad & Tobago, distribution and use phases, elements in common to Baseline Scenario. Therefore, Table S5 (see Supporting

Information) summarized the economic LCI for the Scenario I and for the Baseline since there are some elements in common such as the imported gasoline. Flows are expressed in Jamaican dollars per ton (J$/t) of sugarcane, per L of E10 and related to the Functional Unit (FU). Regarding international freight, when ethanol and gasoline are imported, we used Free on Board (FOB) prices according to Petrojam, n.d. data. Ethanol price is J$59.62/L and Gasoline price is J$66.77/L.

In Scenario I, the unit processes in the agricultural phase are soil correction, land preparation, planting, plantation management, and hand cut harvesting, and all of them consider labour, materials, machinery, diesel, energy, and material costs in Jamaica dollar (J$) per sugarcane metric ton. This information is primary data gathered directly from Everglades information. The costs of the industrial stage are those relate to industrial activities, distillation, and cogeneration processes. The amount of molasses necessary for driving $6.67 \cdot 10^7$ km is 4000 t molasses. 85% of this molasses is imported and 15% is produced in Everglades. It is assumed that 20% of the costs in the industry and maintenance activities are related to molasses production. The converter factors for the reference flow (0.12 L ethanol/km) for Scenario I were 7.8 L bioethanol/t sugarcane in the industrial phase or 200 L bioethanol/t molasses. Distillation and cogeneration phases were modelled according with technical literature and adapted to the Jamaican context. In the Supporting Information it is possible to find their modelling assumptions (Table S9). However, for these two processes further assumptions were considered. For the distillation process, the final costs for the LCI were only those related to labour cost because the steam and power generation costs are associated with the internal cogeneration process costs. Additionally, the capital cost is a sunk cost, thus it is not taken into consideration in this study. In Scenario I of sugar industry, the cogeneration process uses diesel and bagasse as fuels, and bunker oil as a backup input. Thus, it considers all costs of power generation of these different fuels and the operation and maintenance. In the cogeneration process, the capital cost is also a sunk cost, thus it is not taken into consideration in this study. In Scenario I, the Jamaican production context, 20 % of the industry cost is related to molasses production. Following the market value criteria in the imported molasses cost, 72 % of total cost is related to the agricultural phase and 28 % to the industrial phase.

The Baseline Scenario economic LCI gathers Brazilian bioethanol, transports, imported gasoline from Trinidad & Tobago, distribution and use phases. In the Baseline Scenario, it is assumed that imported bioethanol is from Brazil, and the total cost is based on the average market price according to Petrojam data. Information for imported gasoline, imported ethanol, distribution (E10 transport to pump station) and use phases are based on Petrojam data (Petrojam, n.d.-b) and U.S EIA information (United States Energy Information Administration, 2011).

In addition to the information from Jamaican sugar sector to quantify the LCC inventory of Scenario I, we need to identify the cost related to the agricultural, industrial, cogeneration and distillation processes in Brazil (Baseline Scenario) to be capable of comparing with those costs in Jamaica. In this research work, we used the market value criteria to carry out different allocations. Table S6 (see Supporting Information) lists the share of costs of each process related to the Brazilian bioethanol (Caldeira-Pires et al., 2013). Regarding Brazilian bioethanol, Caldeira-Pires et al., (2013) stated that in Brazil the cost related to the agricultural phase represents 60.4 % and the industrial phase represents 39.6 %. Regarding the industrial phase costs, the cogeneration cost represents 1.07% and distillation is about 0.02%.

3. RESULTS

3.1. Environmental impacts

Table 1. LCA Results for both scenarios.

Potential Impact	**Acronym**	**Reference substance**	**Baseline**	**Scenario I**
Climate change	CC	kg CO2 eq	$1.33 \cdot 10^{7}$	$1.71 \cdot 10^{7}$
Ozone depletion	OD	kg CFC-11 eq	$1.27 \cdot 10^{0}$	$1.28 \cdot 10^{0}$
Terrestrial acidification	TA	kg SO2 eq	$3.51 \cdot 10^{4}$	$4.48 \cdot 10^{4}$
Freshwater eutrophication	FE	kg P eq	$1.44 \cdot 10^{2}$	$3.01 \cdot 10^{5}$
Marine eutrophication	ME	kg N eq	$3.97 \cdot 10^{3}$	$2.37 \cdot 10^{5}$

Human toxicity	HT	kg 1,4-DB eq	$3.10\cdot10^5$	$3.83\cdot10^5$
Photochemical oxidant formation	POF	kg NMVOC	$4.09\cdot10^4$	$4.34\cdot10^4$
Particulate matter formation	PMF	kg PM10 eq	$1.08\cdot10^4$	$1.52\cdot10^4$
Terrestrial ecotoxicity	TET	kg 1,4-DB eq	$1.96\cdot10^4$	$6.44\cdot10^3$
Freshwater ecotoxicity	FET	kg 1,4-DB eq	$6.37\cdot10^3$	$9.58\cdot10^3$
Marine ecotoxicity	MET	kg 1,4-DB eq	$1.32\cdot10^4$	$1.53\cdot10^4$
Ionising radiation	IR	kq U235 eq	$9.84\cdot10^5$	$1.01\cdot10^6$
Agricultural land occupation	ALO	m2a	$1.56\cdot10^5$	$6.61\cdot10^6$
Urban land occupation	ULO	m2a	$4.47\cdot10^4$	$1.92\cdot10^4$
Natural land transformation	NLT	m2	$9.95\cdot10^1$	$3.32\cdot10^4$
Water depletion	WD	m3	$3.41\cdot10^6$	$1.02\cdot10^7$
Metal depletion	MD	kg Fe eq	$1.05\cdot10^5$	$1.07\cdot10^5$
Fossil depletion	FD	kg oil eq	$6.66\cdot10^6$	$7.03\cdot10^6$

The specific objective of this part of this study is to evaluate an overall LCA comparative of both scenarios and examine their contribution analysis. Table 1 shows the results of a comparative LCA between Scenario I and the Baseline Scenario. 18 impact categories of the Recipe midpoint Hierarchist method were assessed. For the sake of briefness, impact categories will be named with acronyms listed in Table 1. Figure 3 shows that the most striking result to emerge from the comparative LCA is that the Baseline Scenario has better results than Scenario I in sixteen of the eighteen impact categories assessed (Figure 3 and Table 1). Only the TET and ULO impact categories get lower potential environmental impacts in Scenario I.

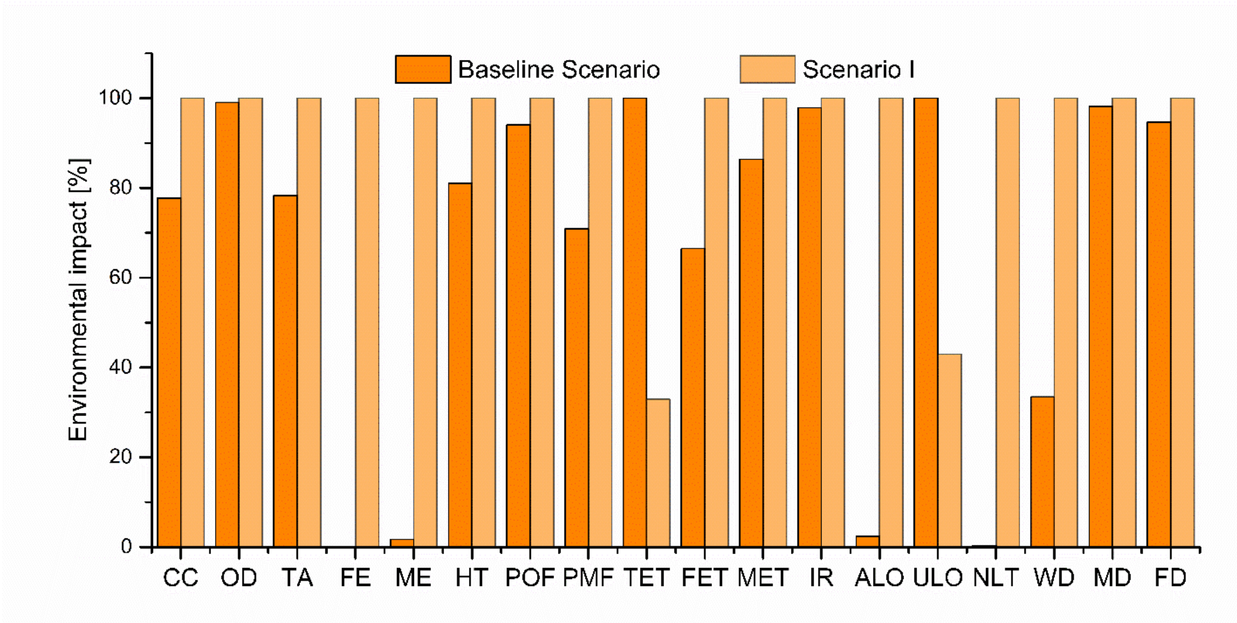

Figure 3. Comparative LCA Results. Recipe Midpoint Method Hierarchist.

Figure 4 shows the LCA of E10 biofuel in Jamaica in the Baseline Scenario. Use stage represents the E10 combustion in a conventional car in Jamaica, the gasoline is included in this contribution. Raw material contribution represents the transports both the gasoline from Trinidad & Tobago to Jamaica and the bioethanol transport from Brazil to Jamaica. As its name suggest, Brazilian bioethanol production represents the bioethanol production in Brazil. In the Baseline Scenario, most of the environmental impacts are highly influenced by the use stage except for FE, ME, TET, FET, ALO and ULO where Brazilian bioethanol production dominates to the impacts. The potential impact for the CC, OD, MET, IR and FD categories is mainly due to the use. Transports from Brazil and Trinidad &Tobago to Jamaica represent less than 10% of the impacts.

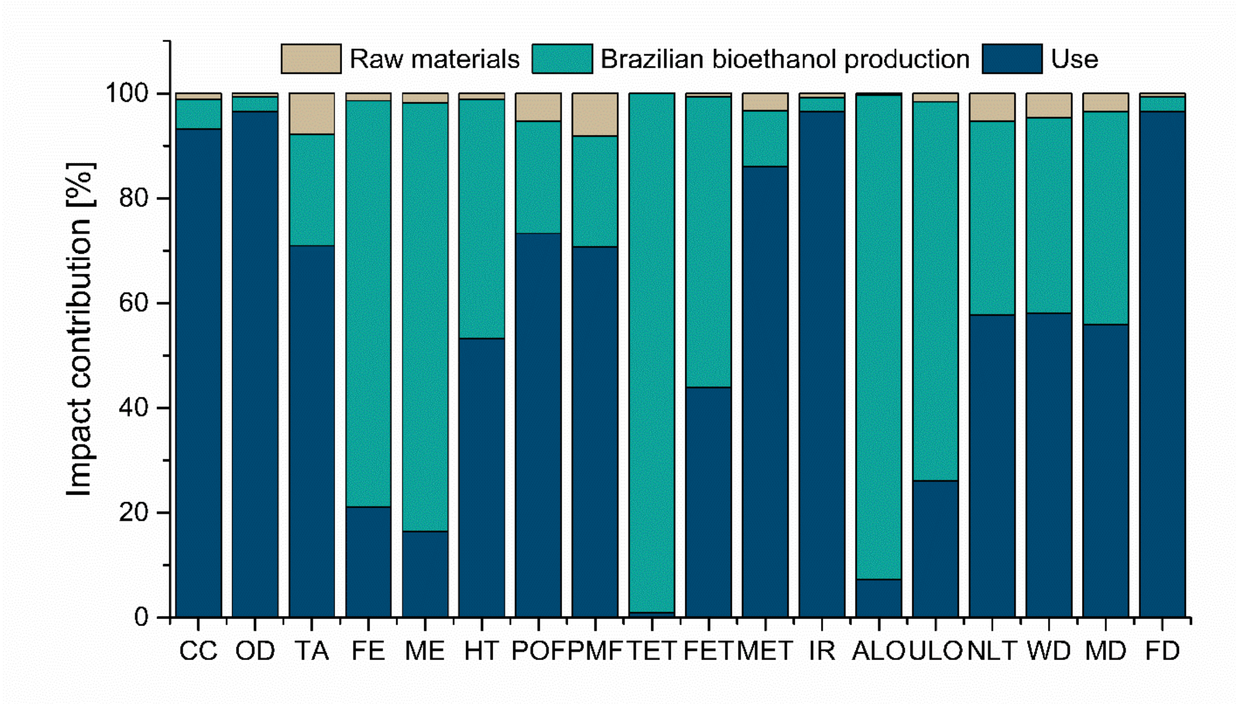

Figure 4. Environmental impact contributions for the Baseline Scenario.

In Figure 5 it is possible to find the Scenario I environmental profile. Figure 5.A shows the agricultural phase contributions for Scenario I. In this first step sugarcane is produced. The item *emissions* represents those emissions to soil, water and air, listed in the inventory (see Supporting Information Table S2). It is possible to distinguish that these emissions are the main contributor to TA, FE, ME, POF, PM, ALO and WD. The use of nitrogen fertilizer highly contributed to the CC, OD, HT, FET, MET, IR, ULO, NLT, MF and FD categories due to the big amount of fertilizer required in the Everglades crops. It is noticeable the contribution of other fertilizers like potassium in TET category. Regarding the use of diesel, this gets relevant contribution in OD, IR and FD. Pesticides contribution represents more than 10% in OD category. Calcium carbonate contribution is lower than 0.5% in all the assessed impact categories. Regarding the transport of pesticides and fertilizers from Kingston to the Everglades location, it is possible to see that its contribution is almost negligible.

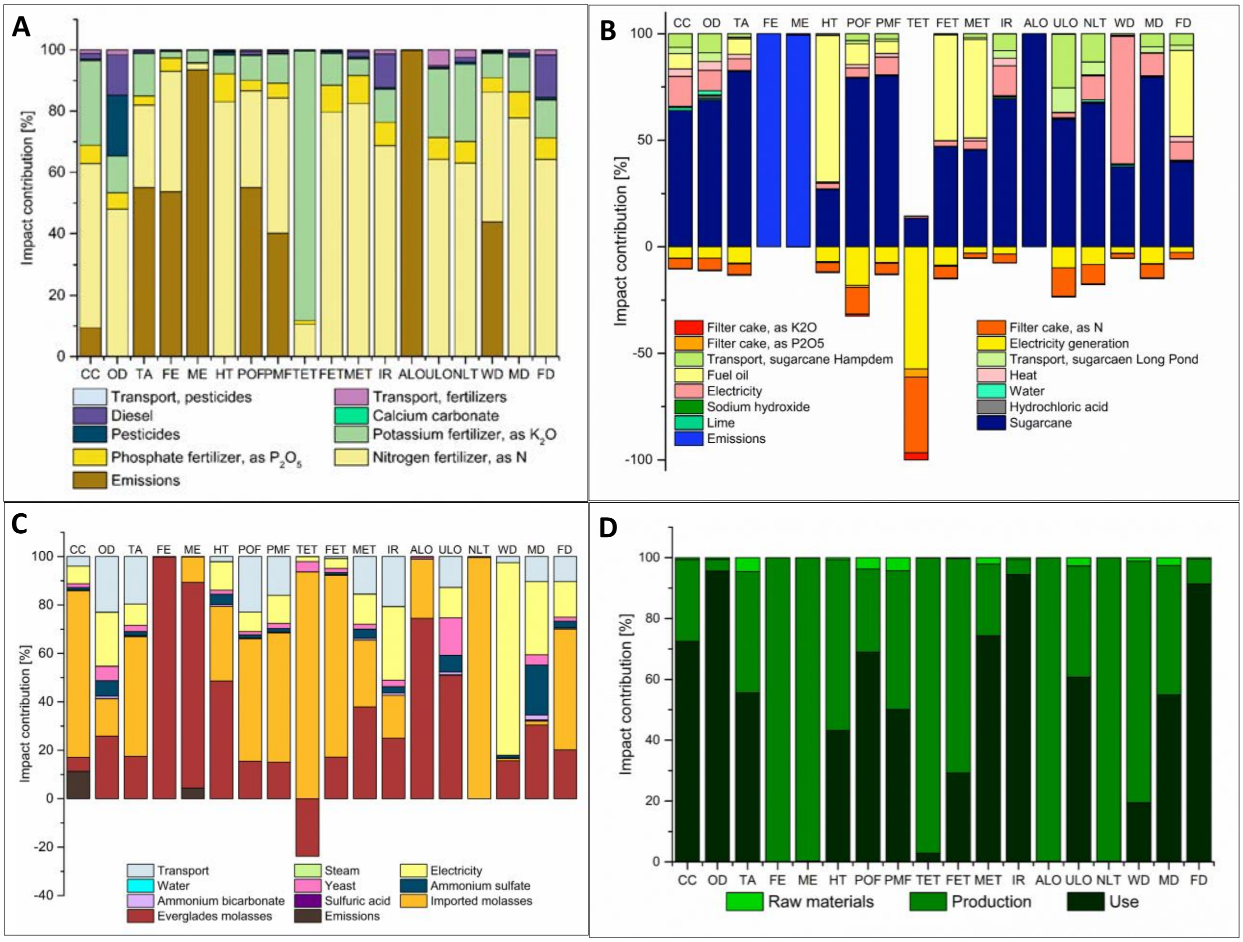

Figure 5. Environmental impact contributions for Scenario I. 5.A. Agricultural stage. 5.B. Molasses production. 5.C. Bioethanol production. 5.D. Functional Unit complete.

Figure 5.B shows the environmental contributions in the molasses production for the Scenario I. The emissions to soil, water and air are listed in Table S3 (Supporting Information). In this respect, it is possible to notice how these emissions are important in FE and ME categories. The use of fuel oil during sugar and molasses production generates a high level of sulphur dioxide and mostly affects to HT, FET, MET and FD. Lime barley represents 2% of the environmental impacts. Likewise, for sodium hydroxide and hydroclholic acid, environmental impacts do not get contributions higher than 1%. Water use contribution is almost negligible. Transport affects to ULO category significantly. There is a noticeable effect of the fuel oil in HT, FET and MET categories. More than 50% of WR is due to the electricity. Sugarcane production in the agricultural

stage carries its environmental impacts to this molasses production stage causing the highest contribution to the environmental impacts in CC, OD, TA, POF, PMF, IR, ALO, ULO, NLT and MD. In most impact categories (all unless FE, ME and ALO), it is possible to notice a positive contribution due to the use of filter cake (as N, as K_2O, and as P_2O_5) as fertilizer. Likewise, energy production and its auto-consumption produce positive results in most of categories being remarkable the positive contribution in TET. The positive contribution regarding the energy cogeneration with bagasse highlights how increasing the bagasse cogeneration in Everglades the impact will be lower. These aspects could promote the local bioethanol production in a more competitive way.

Figure 5.C presents the environmental impact contribution of bioethanol production in Scenario I. In most impact categories, the environmental impacts of are dominated by the imported molasses and its transport to Jamaica. However, in FE, ME, ALO and ULO molasses from Everglades represent the highest contribution since carry the environmental burden of previous processes downstream. The associated emissions to bioethanol production represent contributions around 10% in CC and ME. The used steam for heat does not obtained significant contribution to the environmental profile, neither water, sulfuric acid, yeast or ammonium sulfate.

Figure 5.D shows the environmental contributions of driving $6.67 \cdot 10^7$ km in a conventional car using bioethanol locally produced in Jamaica. In Scenario I the environmental profile is different from the Baseline Scenario (see figure 4). Use stage corresponds to the gasoline and the E10 combustion by an average car in Jamaica. Raw material contribution represents the transport of gasoline from Trinidad & Tobago. The production item represents the bioethanol production process with the Jamaican conditions. It was observed that the raw material stage presented negligible contributions in most of the categories. The Jamaican bioethanol production obtained the highest contributions to the FE, ME, TET and ALO categories. Those categories influenced by production are in turn mainly affected by the molasses contribution upstream. The use stage is the main contribution in CC, OD, TA, POF, PMF, MET, IR, ULO, MD and FD due to the emissions of the combustion of E10 in a conventional car in Jamaica.

In order to corroborate the accuracy of the results, we wanted to carry out an uncertainty analysis of the Ecoinvent datasets (see Figure S1, in the Supporting Material).

Every time, SimaPro selects random values from the uncertainty distribution per data input, calculates the LCA results and stores them. The stored LCA results of the iterations form an uncertainty distribution for the final outcome. It does so by repeating the comparison. Each time another value is selected for the transport and energy, as these were the factors specified with an uncertainty range. The different samples are chosen in such a way that all samples together conform to the distribution specified in the data. This is a Monte Carlo distribution.

The uncertainty analysis results showed that it is highly likely that the environmental impacts in the current conditions (Baseline Scenario) are lower than those of future scenario (Scenario I) in 10 out 18 impact categories. However, TET and ULO categories obtained lower environmental impacts in Scenario I than in the Baseline Scenario in all iterations. 6 environmental categories (MD, MET, FET, HT, OD and POF) obtained high levels of uncertainty. Hence, taking together these uncertainty results with those from Figure 3 (or Table 1) should be reformulated adequately as follows. The Baseline Scenario obtained lower environmental impacts in 10 out 18 categories: CC, TA, FE, ME, PMF, IR, ALO, NLT, WD and FD. Scenario I scored better than the Baseline Scenario in 2 out 18 environmental categories: TET and ULO. For those environmental categories with high levels of uncertainty (6 out 18: OD, HT, POF, FET, MET and MD) is not possible to determine if the Baseline Scenario is worse or better than the Scenario I from an environmental point of view.

3.2. Economic analysis

Table 2. Summary of the LCC results of driving $6.67 \cdot 10^7$ km with E10 in Jamaica.

Processes	Baseline	Scenario I
Agricultural phase	$2.80 \cdot 10^7$	$7.34 \cdot 10^7$
Industrial process	$1.60 \cdot 10^7$	$3.08 \cdot 10^7$
Cogeneration	$2.37 \cdot 10^6$	$1.71 \cdot 10^6$
Distillation	$4.63 \cdot 10^4$	$1.46 \cdot 10^5$
Industrial Phase	$1.84 \cdot 10^7$	$3.27 \cdot 10^7$

Subtotal (J$/FU)	**$6.48 \cdot 10^7$**	**$1.39 \cdot 10^8$**
Freight for fuels	$6.65 \cdot 10^6$	$3.91 \cdot 10^6$
Imported Gasoline 90 % vol	$4.67 \cdot 10^8$	$4.67 \cdot 10^8$
Distribution	$7.77 \cdot 10^7$	$7.77 \cdot 10^7$
Use phase	$2.78 \cdot 10^8$	$2.78 \cdot 10^8$
Total (J$/FU)	**$8.94 \cdot 10^8$**	**$9.65 \cdot 10^8$**

The LCC results identified the imported gasoline process as the main contributor, followed by the use phase, the distribution process and the agricultural activities in both scenarios. However, there was different share of cost contributions. The cost share of each process within the system boundary is shown in Figure 6.

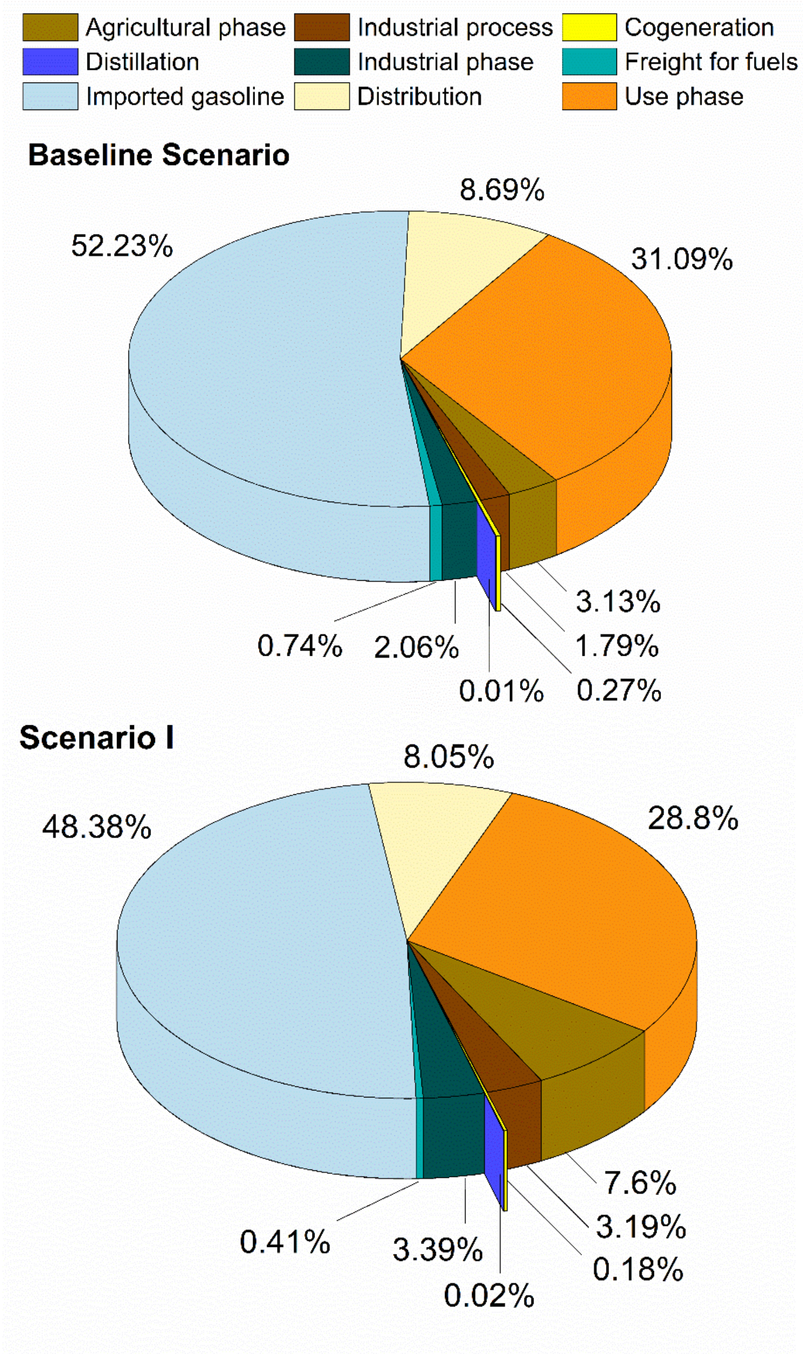

Figure 6. LCC results. Cost share of each process in the Baseline Scenario and Scenario I.

The current context of using E10 in Jamaica (Baseline Scenario) was identified as the scenario with the best economic performance related to the LCC of E10, mainly because the Jamaican sugarcane production costs are 163 % higher than in Brazil. Additionally, the cost of producing ethanol in Jamaica, with regards to the industrial phase, is 78 % higher than the Brazilian one. As shown in Table 2, the costs of the imported gasoline, the distribution and the use phase are the same for both scenarios, which confirms that the main difference between the scenarios is mainly associated with the total ethanol production costs. Table 2 revealed that $1.39\cdot10^8$ J$ are needed in Scenario I while only $6.48\cdot10^7$ J$ in the Baseline Scenario for the same Functional Unit. As described above, the Functional Unit is composed by the production stage but also the raw materials and the use stage. Hence, the difference in bioethanol production is reduced in the LCC results of E10 because the weight of the agricultural and industrial phases in the cost shares is lower than the weight of the other processes inside the system boundary such as gasoline and distribution processes and the use phase, as depicted in Figure 6. Thus, the difference in the total LCC results is reduced to 7%.

The imported gasoline process is the main contribution in the LCC of E10. Additionally, the industrial production of ethanol in Jamaica is quite low if compared with other industrial productivities using sugar molasses for bioethanol production. Rathnayake et al. (2018) reported an ethanol from molasses productivity of $5.33\cdot10^3$ L/d. Everglades could produce 800000 L/year. Considering hypothetically 365 days that Everglades works, the productivity will be lower $2.19\cdot10^3$ L/d. Furthermore, it is important to highlight that Everglades yield will be even lower since there are stops for operation and maintenance. Nowadays, results revealed that a factory as Everglades cannot compete against the large-scale Brazilian Bioethanol production. Thus, the Jamaican ethanol industry infrastructure must be improved to attain higher industrial productivity.

4. DISCUSSION

In reviewing the literature, no data was found on the environmental and economic impacts of producing bioethanol and its use in E10 blend in Jamaica. The first question in this study sought to determine the environmental impacts of Jamaican bioethanol production. Then the research follows with economic LCA assessments in a Life Cycle Sustainability Assessment (LCSA) perspective. As far as our knowledge, there are no LCSA studies with primary data for bioethanol production in Jamaica. Hence this is the main added value of our research work. This study did not use weighing factors within their economic and environmental pillars. One source of weakness in this study which could have affected the measurements of overall sustainability was the difficulties we found to assess the same Functional Unit than in those economic an environmental LCA for conducting a social LCA. However, we included some social aspects in this study (as Supplementary Material) because connecting the assessment of environmental and socio-economic issues may support more comprehensive sustainability assessment of impacts, benefits, and related trade-offs as stated by (Sala, Vasta, Mancini, Dewulf, & Rosenbaum, 2015). Moreover, we decide to conduct three separated assessments, two of them (economic and environmental) with identical system boundaries and other gathering, at least, the main part of our research (the Jamaican bioethanol production) but avoiding the weighting among them as proposed by Kloepffer (2008).

Very little has been published on Social Life Cycle Assessment of sugarcane for biofuels (Azapagic & Stichnothe, 2011; de la Rúa Lope & Lechón, 2017). Fokaides and Christoforou (2016) indicated the necessity of achieving the sustainability by considering the three interrelated pillars to get the promotion of biofuels over fossil fuels. However, that study only conducts the quantification of the environmental impact. Other studies have noted the importance of the social LCA on biofuels. Souza et al. (2018) proposed numerous social metrics approach in a case study in Brazil in which they integrate the SLCA and an input-output analysis to distinguish the social effects over different present and future sugarcane biorefinery supply chains. Mahbub et al. (2019) developed a framework to assess environmental, economic, and social impacts for a concrete application of biofuels. Mahbub et al. (2019) assume a functional unit from the biomass harvesting and included the use stage in vehicle operation. Moreover, in accordance with the methodology used in the present study, that study assessed, among others, CC and WD as environmental impacts, overall cost for the economic impact assessment and employment potential in the social impact.

In the present study, the authors present the results by means of two stand-alone assessment processes (economic and environmental) and an extra assessment including some social aspects (Supplementary Material). LCA and LCC are linked since both have the same functional unit (drive $6.67 \cdot 10^7$ km with E10 in Jamaica). Additionally, the SLCA presented in the Supplementary Material aimed to put the focus only on the effects of producing bioethanol in Jamaica.

Concerning the environmental LCA, it is somewhat surprising that local bioethanol (Scenario I) scored worse environmental performance than current situation with importations of bioethanol (Baseline Scenario). In Scenario I, in the agricultural phase of sugarcane production, the environmental impacts are dominated using fertilizers. This finding was also reported by (Foteinis, Kouloumpis, & Tsoutsos, 2011) in a study for bioethanol production from sugar beet crops in Greece. Foteinis et al. (2011) reported in their LCI similar amounts for consumed fertilizer per ha that in the present study. In turn, agricultural stage (see sugarcane item in Figure 5B) is the main contribution in the molasses production. This finding broadly supports the work of Gabisa et al. (2019) who highlighted the agricultural stage as the most contributing life cycle stage in the molasses production process. Furthermore, in the molasses production, the obtained benefits of recovering filter cakes as fertilizer accord with earlier observations (George et al., 2010). In the Baseline Scenario, the use stage is the contribution that produces higher impacts, globally, having the bioethanol production lower environmental impacts in the Brazilian case (Baseline scenario) than in the Jamaican case (Scenario I). One interesting finding to justify this is because industrial alcoholic fermentation processes in Brazil have produced Bioethanol since the beginning of the twentieth century. Hence, the production of bioethanol from sugarcane in Brazil is a mature technology well developed (Amorim, Lopes, de Castro Oliveira, Buckeridge, & Goldman, 2011). On the contrary, Jamaican production context is in the early beginning (Ministry of Energy and Mining, 2010). The sugarcane factory under study cannot produce bioethanol only with its local molasses production, this factory needs to import molasses to reach the proposed bioethanol production. The use of imported molasses for bioethanol production in Everglade and it transport by sea is necessary to produce bioethanol in Everglades and this fact impacts negatively. Brazilian bioethanol production does not import molasses since they are produced locally (Lopes et al., 2016) helping to reduce the environmental impacts of imported molasses. Sharma and Strezov

(2017) stated that bioethanol is an energy intensive process. The cogeneration process is an environmental credit for Everglade (see Figure 5.B). However, cogeneration does not satisfy the whole electricity consumption and it is necessary to get electricity from diesel and the national grid (based on oil consumption). In addition, during the production process, bunker oil is used for generating electricity in the boilers. The influence of electricity in LCA (see figure 5.B) has already been indicated in previous studies (Saga, Imou, Yokoyama, & Minowa, 2010; Silalertruksa & Gheewala, 2009). Moreover, the cogeneration process in Everglade have not used systems for pollution abatement systems making the cogeneration process less environmentally friendly than those systems whit technologies for pollution abatement. Furthermore, in spite that filter cake get beneficial contribution into the impacts, the rest of the wastes were not re-used affecting negatively to the impacts. For both scenarios, the combustion of E10 (i.e the use stage) get a big contribution in several categories, among them CC and HT in accordance with the results obtained by Gnansounou et al., (2015).

Regarding the economic impacts, an LCC has been conducted obtaining the overall cost as suggested by Mahbub et al. (2019). Actual conditions (Baseline Scenario) reported better economic results than a possible production of bioethanol in Jamaica (Scenario I). The production cost of sugarcane ethanol in Jamaica is higher than in Brazil. This result has different reasons:

- The first reason is because the average sugarcane yield in Brazil was around 70-80 sugarcane ton per hectare (de Oliveira Bordonal et al., 2018), depending the region where the sugarcane was produced. The sugarcane productivity in Jamaica in the data collection campaign of the present study was on average 52 t/ha sugar cane.

- Bioethanol in Scenario I is produced from molasses. However, sugarcane bioethanol can be produced from cane juice. The potential source of producing bioethanol in Jamaica is sugar molasses. On average, the industrial productivity for molasses-ethanol is 7.8-12 L/t sugarcane. This Jamaican molasses-derived bioethanol case study has a productivity equal to 7.8 L bioethanol/t sugarcane. However, if bioethanol is derived from sugarcane juice the productivity increased to about 80 L bioethanol/t sugarcane (Jonker et al., 2015). In Brazil, the sugarcane-juice ethanol share represented approximately 70%, and sugar-molasses ethanol share was only 30% of the total ethanol production (Walter & Dolzan, 2014). Hence, the second reason is because both molasses and cane juice are used to produce ethanol in Brazil. The Jamaica consumption of bioethanol as fuel is about $64 \cdot 10^6$ of L/y. If the sugar molasses production is used to produce bioethanol, Jamaica would fulfill only 27% of its demand. 12 L/t sugarcane was used to perform the calculations to get the most promising situation. However, if all sugarcane production is used to produce cane-juice bioethanol fuel, the country would fulfill all its demand and produce a surplus of bioethanol. Nevertheless, to obtain these results Jamaica should introduce industry where bioethanol fuel can be produced from both sugar molasses and cane juice.

- The third reason is because the total cost of the industrial phase is higher in Jamaica than in Brazil due to technological differences. In line with this, there are studies (Roy, Tokuyasu, Orikasa, Nakamura, & Shiina, 2012) which suggest that an adaptation of innovative technologies and renewable energy policy may help limit costs. Hence, innovative changes in the Jamaican sugarcane industry may help to mitigate the over cost of the Jamaican bioethanol production.

LCSA integrates environmental, social and economic impacts. In this regard, Sala et al. (2013) stated the importance of maintaining the balance between analytical and descriptive approaches. A recent study (Ekener, Hansson, Larsson, & Peck, 2018) about LCSA of biomass based and fossil transportation fuels noted that LCSA methodology still faces challenges to integrate the LCA, LCC with SLCA. Ekener et al. (2018) conducted an LCSA integrating the LCA and LCC results with the social impacts by means of a multi criteria decision analysis (MCDA) assuming values of different stakeholder profiles. Pesonen and Horn (2013) developed a methodology for harmonizing the LCSA with the Sustainability SWOT (Strengths, Weaknesses, Opportunities, Threats. (Halog & Manik, 2011). Halog and Manik (2011) stablishes an Integrated Systems Modelling for Life Cycle Sustainability Assessment. In spite of all of the works conducted for the integration of LCSA, further efforts are necessary towards the development of new integrative methodology (De Luca et al., 2017).

There are several interactions between environmental, economic and social part. Imported gasoline has the highest cost in the Baseline Scenario with a reduction of almost 4% in scenario I. There is a mismatch between cost and environmental performance since the main contributor to the LCC is not the main contributor in LCA for a future scenario (Scenario I). In both scenarios, the use phase represents more than 90% in some environmental categories, and on average, its contribution to an overall environmental issue will be more than 50%. However, in the economic impacts is around 30% in both scenarios. Freight for fuels is highly influent in several categories in the environmental analysis. Nevertheless, its economic cost is not representative. These findings may help scientific community and policy makers to understand the reality of the Jamaican bioethanol context. However, further studies, which take these variables into account, will need to be undertaken. A further study with more focus on the social impact of the whole functional unit is therefore suggested. Furthermore, despite these promising results, questions remain in terms on integration of the social, environmental and economic impact. In future investigations, it might be possible to use a multicriteria methodology to assess together the three pillars of the LCSA in an integrated methodology.

5 CONCLUSIONS

The purpose of the current study was to determine the environmental and economic impacts in two different scenarios: The Baseline Scenario represents the use of E10 in actual conditions with bioethanol imported from Brazil and gasoline from Trinidad & Tobago. Scenario I represents the use of E10 with bioethanol from Jamaica and gasoline from Trinidad & Tobago.

Regarding environmental impacts, LCA results revealed that for 10 out of 18 impact categories Baseline Scenario performs better compared to Scenario I whereas for 6 out of 18 it is not possible to draw conclusions about the environmental preferability of analyzed scenarios due to high uncertainty. In 2 out 18 impact categories the Scenario I performs better. Use stage represents the E10 (gasoline and bioethanol) combustion in a conventional automobile in Jamaica. This study has found that generally the use stage dominates the environmental impacts in both Scenario I and the Baseline Scenario. Furthermore, the LCA results for Scenario I revealed that the production of bioethanol in Jamaica had significant contributions in all the impact categories reaching contributions higher than 90% in OD, IR, and FD impact categories. In turn, the production of Jamaican bioethanol was highly dependent on the molasses both imported and locally produced. It is recommended to increase the bagasse cogeneration in the bioethanol production of Scenario I to lower the environmental impacts.

Concerning the economic impacts, the current Jamaican context (Baseline Scenario) showed lower life cycle cost than Scenario I. The overall LCC results differed 7%. This was mainly due to the cost-competitiveness of import ethanol and the technological gap in the sugar/ethanol and sugarcane industries between Jamaica and Brazil. The productivity of ethanol from sugarcane in Brazil is higher than in Jamaica since Brazil sugarcane bioethanol is produced both form molasses (7.8-12 L/t sugarcane) and cane juice (80 L/t sugarcane). Jamaican sugarcane technology is only based on bioethanol molasses impacting on its economy and its environment. Hence, it is recommended that before introducing the use of locally-produced ethanol fuel in the E10 blend in Jamaica, it is necessary some actions to improve the Jamaican sugar industry infrastructure and the sugarcane production performance. A mix structure in ethanol-sugar industry using molasses and cane-juice to produce bioethanol fuel could be an option to improve the bioethanol industrial productivity.

This work contributes to understanding the Jamaican situation of bioethanol through a case study. However, this study is limited due to a lack of integration of the results of every part (economic, social, and environmental) in a multicriteria decision-making tool. A natural progression of this work is to analyze other case studies in order to get a wider perspective. Notwithstanding these limitations, the study suggests that the current situation in Jamaica for the E10 blend, where bioethanol is imported from Brazil scored better than the E10 blend with local bioethanol from an environmental and economical point of view.

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