Environmental and economic analysis of bioethanol production from sugarcane molasses and agave juice

Maria Magdalena Parascanu[1], Nestor Sanchez[2], Fabiola Sandoval-Salas[3], Carlos Mendez Carreto[3], Gabriela Soreanu[4], Luz Sanchez-Silva[1*]

1 = Department of Chemical Engineering, University of Castilla-La Mancha, Ciudad Real, Spain

2 = Energy, Materials and Environmental Laboratory, Department of Chemicaland Biochemical Processes, Universidad de La Sabana, Campus Universitario Puente del Común, km. 7 Autopista Norte, Bogotá, Colombia

3 = Tecnologico Nacional de Mexico/ITS de Perote, Perote, Mexico

4 = Department of Environmental Engineering and Management, Technical University "Gheorghe Asachi" of Iasi, Iasi, Romania

*=corresponding author details: marialuz.sanchez@uclm.es

Abstract

In this article, sugarcane molasses and agave juice were compared as potential feedstocks for producing bioethanol in Mexico in terms of their environmental impact and economic factors. Life cycle assessment (LCA) using SimaPro was carried out to calculate environmental impacts by using a cradle-to-gate approach. A preliminary economic analysis was performed to determine the economic feasibility of the studied options. Also, capital goods costs were obtained using the Aspen Plus economy package. Moreover, a sensitivity analysis was involved to compare the environmental and economic viability of producing bioethanol from sugarcane molasses and agave juice. LCA results revealed that cultivation and fermentation were the most harmful stages when producing bioethanol from sugarcane molasses and agave juice, respectively. Furthermore, when it was derived from agave juice rather than sugarcane molasses, it had more environmental benefits. This was ascribed to the lower consumption rate of fertilizers, pesticides, and emissions given off from the former. Regarding financial aspects, the preliminary analysis showed that producing bioethanol was not economically viable when grid energy alone was used. However, if power from the grid is partially replaced with renewable energy, producing bioethanol becomes economically feasible, and sugarcane molasses is the most suitable feedstock.

Keywords: Bioethanol, Sugarcane bagasse, Agave bagasse, Life cycle assessment, Economic analysis

1. Introduction

Undoubtedly, climate change - mainly due to the increase in CO_2 emissions from fossil fuel combustion, industry, and transport - is a severe threat to life on our planet. For instance, about 3% of greenhouse gases (GHG) emissions are associated with transport (Oliver et al. 2017). Therefore, renewable energy poses an alternative for tackling these adverse effects (Sanchez et al. 2020b). Mexico, whose main source of energy is crude oil, is considered to be one of the largest contributors to CO_2 emissions in Latin America (Hanif 2017, Sarmiento et al. 2019).Hence, it is generally agreed that it must change from crude oil to renewable fuels if it is to overcome the unfavorable effects of climate change(Rendon-Sagardi et al. 2014). Bioethanol is one potential renewable fuel, whose combustion is more efficient than gasoline and, consequently, gives off fewer emissions of pollutants such as SOx, NOx and particulate matter (Zabed et al. 2017).

Bioethanol is produced from a wide range of materials and can be classified into first, second, and third generation. First generation bioethanol is produced from sugar and starchy feedstocks such as molasses and corn, while second and third generations are obtained from lignocellulosic materials and algae, respectively. Bioethanol production spans the following stages: physical pretreatment (i.e., crushing or chipping), hydrolysis (this is only required when both lignocellulosic and algae materials are employed as feedstock), fermentation, and distillation. For sugar materials, such as molasses, hydrolysis is not required since fermentable sugars, such as sucrose, glucose, and fructose, are freely available for metabolisation by microorganisms during fermentation under anaerobic conditions. Yeasts, such as *Saccharomyces cerevisiae¸* are the most widely used industrially, since they produce a large amount of ethanol and are highly tolerant to ethanol. (Sanchez et al. 2020a, Sanchez et al. 2020c).

Sugarcane and agave are some potential feedstocks that could potentially be used in Mexico to produce bioethanol and mitigate the impacts associated with climate change. For instance, sugarcane (*Saccharum officinarum L.*) is an essential crop which is primarily used in sugar production. However, it has become fundamental for producing a wide range of goods in the industry. As a result, economic interests in this crop have increased significantly in recent years (Gómez-Merino et al. 2017, Lopez-Bustamante 2015). In Mexico, about 57 million tons of sugarcane are produced annually (SAGARPA 2018b). In the extraction process, by-products such as bagasse, sugarcane press-mud,and molasses are also yielded (Dias et al. 2015). The latter is a by-product whose sugar content is 50%, which, in turn, is used to yield bio pesticides, pharmaceuticals, cellulose, acids, and bioethanol, amongst other products.

Moreover, agave, also known as *"maguey"*, is a native crop from Mexico and about 1.8 million tonnes of it are produced annually (SAGARPA 2018b). Nowadays, approximately 200 species are known and they have been classified into three groups: wild, semi-cultivated, and cultivated (Mandujano Bueno et al. 2018, Nava-Cruz et al. 2015, Trejo-Salazar et al. 2016). Among these, *Agave Salmiana* can grow in areas with low rainfall, low temperatures, and poor fertility soils; hence, it is considered to be economically viable. Furthermore, agave juice is well known for its ability to produce bioethanol by fermentation (Corbin et al. 2016, Tauer et al. 2004).

Although production is low in comparison to sugarcane molasses (1.8 million tons vs. 57 million tons), it has an outstanding economic, cultural, and social impact in Mexico(Pérez Hernández et al. 2016). Hence, it could potentially be used as a feedstock for producing bioethanol to mitigate GHG and to act as a driver for economic and social development in Mexico. Moreover, there is no land competition for food since agave grows on semi-arid lands where food crops cannot be cultivated. Additionally, there is still enough unused land where agave can be cultivated. For instance, in Jalisco and Oaxaca there are about 1.7 million and 60,000 hectares available respectively for cultivating agave, but at present it has only taken up 30% of this land (Núñez et al. 2011). In light of this, the environmental and economic benefits of the Mexican biofuel industry obtained from agave by-products were analyzed. This was performed by comparing it with a highly available feedstock such as sugarcane molasses. In order to assess the environmental benefits of agave crops, a life cycle assessment (LCA) was employed. This is an internationally standardized approach (International Organization for Standardization – ISO, i.e. ISO 14040 and ISO 14044) that enables environmental burdens associated with consuming resources and emissions to be assessed as well as the waste released in the chain of production (ISO14040 2006, ISO14044 2006).

To date, there are no studies in which the environmental impacts associated with bioethanol from both sugarcane molasses and agave juice are compared. However, several LCA studies on bioethanol yielded from both these raw materials have been published. For instance, Renouf et al. (2013) performed the LCA for ethanol production with different by-products from sugar extraction. They showed that sugarcane juice had the greatest impact on reducing non-renewable energy and global warming potential (GWP). In addition, Silalertruksa et al. (2017) evaluated the environmental impacts from a sugarcane biorefinery, showing that this could be reduced by integrating waste valorization. Papong et al. (2017) studied the environmental benefits of producing bioethanol from cassava and molasses in Thailand, concluding that using it as a transport fuel reduced GHG emissions. However, eutrophication potential (EP) increased as did water consumption potential (WCP) in comparison with gasoline. Furthermore, Yan et al. (2011) evaluated bioethanol production from *Blue Agave Tequilana Weber*. They proved that agave was the optimum choice for producing first-generation bioethanol in comparison to corn, switchgrass, and sugarcane in terms of energy and GHG balances (Yan et al. 2011).

In short, since both crops were profitable in Mexico, it was deemed beneficial to determine which was most beneficial in terms of the environment and economy. In light of this, the goal of this study was to compare the environmental burdens and economic feasibility of producing bioethanol from sugarcane molasses and agave juice on the basis of these chains of production in Mexico.

2. Methodology

2.1. Life cycle assessment

2.1.1. Definition of goal and scope

A LCA was carried out considering the cradle-to-gate approach, in which the following stages were evaluated: i) cultivation, ii) juice extraction, iii) fermentation, and iv) distillation. Bioethanol is characterized as being high in energy, 26.6 MJ/kg. For this reason, 1 MJ was selected as the functional unit (FU) (Consorcio 2012).

2.1.2. System boundaries and assumptions

The LCA carried out for the bioethanol production system analyzed the entire chain of production, from cultivating sugarcane and agave to producing bioethanol from sugarcane molasses and agave juice. The main inputs in fermentation are generated at the extraction stage at which point molasses and agave juice were produced. Figures 1 and 2 represent the system boundaries considered for producing biofuels from sugarcane molasses and agave juice, respectively, considering the main inputs and outputs corresponding to each stage.

The following assumptions were made in this approach:

✓ Chemical, fertilizer, pesticide, and energy production were included within the system boundaries as “market” dataset. A "market " data set collects all activities with the same reference product in a certain geographical region, including the average amount of transport related to this product within that area (Ecoinvent 2019).

✓ Transport of sugarcane and agave to the extraction plant were considered.

✓ The plant extraction and the bio-refinery plant were assumed to be in the same place.

✓ Capital goods, staff and buildings were excluded from this evaluation.

✓ The system boundary excluded the usage and end of life for sugar and bioethanol products.

2.1.3. Life cycle inventory analysis

The primary inventory data for cultivating and extracting sugarcane and agave cultivation, sugar, and molasses/agave juice fermentation stages are shown in Tables 1 - 3, respectively.

In this study, data collected for the raw material, utilities, and products at the cultivation stage were provided from a real plant in Mexico (Veracruz). However, air, water and soil emissions at this stage were calculated according to the Intergovernmental Panel on Climate Change (IPCC), Environmental Protection Agency (EPA) and Ecoinvent (EPA 2016, 2017, Klein et al. 2006, Nemecek &Kägi 2007). In addition, the input and output data for the extraction stage were taken from the literature (Consorcio

2012, Gamboa 2006, Livier 2004, Marín 2014, SAGARPA 2018a). The mass and energy balances for the biorefinery plants were estimated by simulating the entire process with Aspen Plus® V.9 software (Aspentech, Bedford, MA, USA). Finally, the background processes were considered from the Ecoinvent database (Ecoinvent 2019).

a. Block I: Agriculture stage

i. Sugarcane

In this study, a five-year cycle was assumed for producing sugarcane. In the first year, the soil was prepared (by harrowing, ploughing, and raking). Next, 20,000 kg/ha of compost were used for soil conditioning, which was transported 25 km from the "*La Gloria*" sugar refinery to the plot. Apart from compost, in order to make sugarcane productive, it is essential to use fertilizers and pesticides, as crop productivity depends on primary nutrients such as nitrogen, phosphorus and potassium (Meyer 2013). To obtain the greatest yields from fertilizers, these should preferably be used when the soil is humid, as this helps in the dilution and absorption of nutrients(Meyer 2013). Specifically, in this study, fertilization was performed annually, and fertilizers and pesticides were transported 7 km in a 3-tonne truck. The ones used were: Triple17 (300 kg/ha), urea (150 kg/ha), Allectus 300sc (12 kg/ha) and Engeo (12 kg/ha).

Furthermore, the crop was irrigated with a gravity-fed system, using water from a river located 2 km away from the plot. Harvesting was performed manually, and the sugarcane was transported by truck to the mill, which was 25 km away. Total yields per annum were as follows: 1st year 140 tons/ha, 2nd year 120 tons/ha, 3rd year 100 tons/ha, 4th year 90 tons/ha and 5th year 85 tons/year.

ii. Agave *Salmiana*

Agave *Salmiana*is is used for producing alcoholic and non-alcoholic drinks. In this research, a 6-year cycle was assumed for agave cultivation. In the first year, the soil was prepared by harrowing. Planting was carried out in a rectangle (plants placed 3 meters apart), which yielded an average of 1,200 plants/ha.

The main advantage of using this plant is that it can be grown on highly degraded soils that are poor in nutrients and water (Davis et al. 2011). Pruning, which consisted in removing the outer leaves, which were already adult and dry, was carried out every two years. Here, fertilization was performed manually every year, with 4 tons/ha of compost made up of glyphosate (3 kg/ha), bifenthrin (20-30 kg/ha), and copper sulphate (3 kg/ha) during the rainy season. In addition, throughout the cultivation period, the crops were rain-fed only. Agave yielded 1,200 plants/ha whose average weight was around 250 kg/plant.

b. Block II: Raw material processing stage

i. Sugar extraction

After transporting the sugarcane to the sugar extraction plant, it was weighed and then stored in baskets (Consorcio 2012). The sorted sugarcane was then transported in a conveyor belt system to choppers whose blades were used for splitting it. Next, it was crushed in six mills with three or four maces to extract the juice (Consorcio 2012). Meanwhile, water was added to extract the sucrose contained in the fibrous material, and the juice and bagasse were obtained at this point. The latter was evacuated in the fourth mill (Consorcio 2012). In order to reduce costs and the environmental impact, 50% of the bagasse was used as a fuel for generating electricity (Consorcio 2012). The rest was used as a raw material in thermochemical processes.

Subsequently, the resulting juice was weighed to define the proportion of calcium oxide to be added, and this mixture was heated to 102-105 °C. Afterwards, came clarification at which point the juice was purified, with all impurities removed in the form of insoluble calcium salts (Consorcio 2012). Sucrose was then recovered from these solid impurities by filtration, to obtain juice and a solid by-product (sugarcane press-mud) which can be used as compost (Consorcio 2012, Sanchez et al. 2017).

The filtered juice, whose sugar content was about 14 wt.%, was subjected to evaporation in an evaporation train to remove any excess water and to gain 60 wt.% solids (syrup) (Consorcio 2012). This syrup was then crystallized in three tanks in a vacuum. The liquid and solid phases were next separated by centrifugation to yield sugar and molasses (Consorcio 2012).

ii. Agave juice extraction

On maturity the agave plant was harvested by removing the leaves until the center of the plant (which is called the *pineapple*) was reached (L. Gutiérrez-Coronado et al. 2007). Firstly, this was cooked in an autoclave using pressurized saturated steam (Livier 2004). The cooking by-product (syrup) was then collected in a tank. Next, the cooked *pineapple* was ground to obtain cut agave and organic waste. The former was washed to extract the first syrup while the organic waste (wet bagasse) was sent to the second mill. The second and third milling were carried out under the same conditions as the first one in order to obtain syrup and bagasse (Livier 2004). The three syrups obtained were called agave juice, which were then stored in a tank and fermented to obtain bioethanol. At this extraction stage, 50% of the resulting bagasse and 10 kg of coal were used to produce the electricity needed (Consorcio 2012).

c. **Block III: Biorefinery plants**

In this paper, bioethanol produced from molasses and agave juice was yielded at various stages. During fermentation (first stage), microorganisms, the most commonly used of which were yeasts (e.g. *S. cerevisiae*) (Robak &Balcerek 2018), converted sugars (glucose and fructose) into bioethanol and CO_2 (Equation 1) (Lin &Tanaka 2006).

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad (1)$$

Distillation was the second stage and the aim of which was to obtain anhydrous bioethanol concentrated up to approximately 96%. The drawback to this was the large amount of energy used (Gavahian et al. 2016).

The final stage was dehydration in which anhydrous ethanol (i.e. 99.7 wt. %) was obtained by using molecular sieves (Robak &Balcerek 2018, Soreanu et al. 2004).

In this study, bioethanol production was simulated in Aspen Plus and using the Non-random two-liquid (NRTL) method. Table 4 shows the features of both the sugarcane molasses and agave juice employed in this study.

Table 5 gives a brief explanation of each block used for simulating bioethanol production. The flowsheet diagrams for obtaining bioethanol from sugarcane molasses and agave juice are shown in Figure 3.

The difference between simulations was water requirements. This must be added to prevent yeast cells dying on account of the high osmotic pressure of the fermentation culture (Jambo et al. 2016). Indeed, sugarcane molasses, whose sugar concentration was 48.7 wt.% (Table 4), needs to be diluted until 30 wt.% is reached, whilst agave juice does not as it is lower in sugars (i.e., 9.8 wt.%).

Fermentation was the first stage and was simulated by means of a RSTOIC at 30 °C. In the fermenter, sucrose was converted to ethanol to obtain 14 wt.% and 4.7 wt.% ethanol for molasses and agave juice, respectively. In this study, it was assumed that sucrose was converted into glucose and fructose at a rate of 100%, while the rate for converting glucose and fructose into bioethanol and CO_2 was assumed to be 85.7%. (Ghani &Gheewala 2018).

The resulting CO_2 was removed in Sep-CO_2 equipment, while the remaining stream was heated to 85 °C. After heating, distillation was performed with two rectification columns (Rectif1 and Rectif2). In the former, 15 stages were employed, while the latter used 50. Feeding for the first column occurred at the 6th stage, while for the second column, it was the 49th. From the first column, bioethanol was obtained with 50 wt.% and 45 wt.% for molasses and agave juice, respectively. In the second column, the bioethanol was purified at 94 wt.%, a value close to that for azeotropic bioethanol (95.6 %) (Valencia &Cardona 2014). The by-product obtained in the first distillation unit (vinasse) was considered to be an avoided product.

The distilled stream was heated to 115 °C and introduced into the dehydration zone, which is commonly carried out with molecular sieves. In this study, these were modeled as a separator column. The resulting stream (i.e., 99.9 wt.% ethanol) was cooled (Cooler2) to 50 °C whereas, the output streams (i.e. emissions, water, and ethanol) were cooled (Cooler1) to 70 °C. Moreover, steam and cooling water were employed as the heat source for both distillation columns. In this study steam was obtained by a water heater, while river water was used for cooling.

2.1.4. Impact assessment methodology

The LCA was carried out using the SimaPro 8 software, with the ReCiPe 2016 Midpoint (H) methodology to calculate the LCA results. The following impact categories were selected for determining the environmental performance of the bioethanol produced:

GWP, ozone depletion potential (ODP), photochemical oxidation formation potential - humans (HOFP), photochemical oxidation formation potential - ecosystems (EOFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), human toxicity potential - cancer (HTPc), human toxicity potential - non-cancer (HTPnc), fossil fuel potential (FFP) and WCP.

In the chain of production for bioethanol, different by-products were obtained. Therefore, economic allocations were used for the environmental burdens of co-products (Ecoinvent 2019). The economic allocation factors were:

- ✓ Sugar extraction: 80.6 % (0.58 €/kg) for sugar, 8.6 % (0.19 €/kg) for sugarcane molasses, 8.95 % (0.025 €/kg) for sugarcane press-mud and 1.85 % (0.01 €/kg).
- ✓ Juice extraction: 99.3 % (0.2 €/kg) for agave juice and 0.7 % (0.01 €/kg).
- ✓ Bioethanol production (molasses): 82.4 % (0.75 €/kg) and 17.6 % (0.025 €/kg).
- ✓ Bioethanol production (molasses): 57.4 % (0.75 €/kg) and 42.6 % (0.025 €/kg).

2.2. Preliminary costs analysis

A preliminary cost analysis was carried out to determine the economic feasibility of producing bioethanol from sugarcane molasses and agave juice. An economic evaluation was made using the percentages methodology (Hillstrom &Hillstrom 2002, Peters et al. 2003). The Aspen Plus® software was used for assessing the financial aspects related to equipment costs. In addition, the price of the storage tank was calculated according to its scale (Kalk &Langlykke 1986).The evaluation corresponded to V class evaluation economy. This approach is commonly used for screening alternatives and all cost estimations were accurate between 30% and 50% (Becerra et al. 2017, Proaño et al. 2020).

Furthermore, by observing the quantity of utilities needed in the process, water and energy costs could be estimated. The sale price of the products (bioethanol and vinasse) also had to be set. The financial indicators considered in this study were the following: net present value (NPV), internal rate of return (IRR) and payback.

3. Results

In this research, an environmental and economic analysis was performed to determine the most suitable crop for producing bioethanol. In this study, sugarcane molasses and agave juice were used as feedstock. The stages involved in converting these to bioethanol as well as the scenarios overall were compared. The conversion stages included cultivation, extraction, and biorefining. Moreover, an economic and sensitivity analysis of the bioethanol production stage was made to determine which of the two crops was more economical viable. In the following section, the environmental impacts for both feedstocks are shown.

3.1. Producing bioethanol from sugarcane molasses

In this section, the results for the ‘cradle-to-gate' analysis for producing bioethanol from sugarcane molasses are shown in Figure 4. In addition, the LCA results for each analyzed stage presented in Table 6.

According to Figure 4, sugarcane extraction showed the greatest results in almost all impact categories whose values were higher than 45%. It had the highest impact on HTPnc (47%) whereas bioethanol production showed the lowest contribution in all categories (<15%). Concerning GWP, significant differences were observed among stages according to Table 6. Thus, sugar extraction had the highest impact value (1.82 kg CO_2 eq) followed by sugarcane cultivation (1.04 kg CO_2 eq) and bioethanol production (3.99E-01 kg CO_2 eq). The results obtained for the former were mainly due to the high amounts of CO_2 given off (Table 2) and background processes (quicklime and coal production). Also, the GWP impact value obtained for sugarcane cultivation was associated with the GHG given off and the diesel used in transport (Table 1).

Like GWP, FEP and FFP showed the same tendency. In this respect, the values obtained at sugar extraction in terms of FEP and FFP were 9.38E-05 kg P eq and 3.19E -01 kg of oil eq, respectively. The SimaPro software identified that the main contributing factors to FEP at the second stage were background processes, such as coal production and emissions during these processes. In terms of sugar extraction, using and producing coal for obtaining energy and steam were found to be the factors which had most impact on FFP. Moreover, the negative impacts on both categories were also due to P_2O_5 emissions, the use of diesel, P-based fertilizers, and compost (Table 1).

The high environmental impact on cultivating sugarcane was due to emissions from organic and inorganic fertilizers, water, and the diesel used. In ODP, the most influential factors were N_2O emissions from N-based fertilizers and compost, and the CH_4 given off from transport from burning diesel (Table 1) (Papong et al. 2017). For HOFP and EOFP, the impacts with sugarcane cultivation (Table 6: 1.80E-03 and 1.85E-03 kg NO_x eq, respectively) were associated with NOx emissions from transport and background processes (energy and diesel production) (Table 1). NH_3 and NO_x emissions from cultivation (transport and using fertilizer and pesticide) were the main contributors to TAP. In addition, SO_x emissions from fertilizers and energy production (background processes) significantly contributed to this. Also, higher values were observed for HTPnc than for HTPc for sugarcane cultivation (Table 6). According to SimaPro's data, these impacts were mainly associated with background processes (fertilizer and pesticide production) and emissions (e.g., benzene, cadmium, nickel, chromium) (Silalertruksa et al. 2017). Finally, WCP was affected by the high amounts of water used in irrigation and preparing fertilizers (Table 1).

3.2. Producing bioethanol from agave juice

Figure 5 shows the results for the agave-to-bioethanol chain, considering the ten selected categories. Table 7 presents the LCA results for each stage under consideration in this research. All the impact values at each stage were calculated for 1 MJ of bioethanol produced.

According to Figure 5, bioethanol production contributed to the highest impact in all categories. The values obtained for this were: 72% (GWP), 57% (ODP), 81% (HOFP and EOFP), 79% (TAP), 60% (FEP), 61% (HTPc), 54% (HTPnc) 83% (FFP), and 85% (WCP). Additionally, both cultivation and juice extraction showed similar values in all categories, as shown in Figure 5.

As for agave, bioethanol production was the most environmentally damaging stage. This was associated with the low sucrose concentration and consequently low ethanol yield during fermentation, factors which affected performance. Therefore, a higher amount of both raw materials and utilities were required to produce 1 MJ of bioethanol from agave juice in comparison to sugarcane molasses.

The information generated by SimaPro software indicated that producing and using grid energy to produce bioethanol were the main explanatory factors behind this detrimental environmental impact (Table 3). Energy production, considered to be a background process, had a significant influence on almost all the categories analyzed (GWP, ODP, HOFP, EOFP, TAP, HTPc, HTPnc and FFP), mainly due to the large amount of emissions. For instance, NO_x emissions were observed to be primarily responsible for the values obtained in HOFP, EOFP and TAP. Also, CH_4 emissions (background processes) were detrimental to GWP and ODP (Nguyen &Gheewala 2008, Zhang et al. 2010). The high value of GWP (6.72E-01 kg CO_2 eq) was also due to the CO_2 given off when fermenting agave juice (Table 3) (Amores et al. 2013, González-García et al. 2012, Wang et al. 2013). Human toxicity categories were affected by emissions such as those from nickel, cadmium, chromium, and formaldehyde that were given off mainly in energy and chemical production. Raw materials such as coal, natural gas, and oil used in background processes were found to be the main components which influenced FFP. Also, the effect producing bioethanol had on FEP was related to agave cultivation and juice extraction, while WCP was affected by the water consumed at the last stage (Table 3).

At the cultivation stage, using fertilizers and transport had a high impact on ODP due to CH_4 and N_2O emissions. According to Table 7, the impact values for HOFP and EOFP were 6.42E-05 and 6.65E-05 kg NO_x eq, respectively, and these were attributed to NO_x emissions (Table 1) given off when raw materials, fertilizers and pesticides were being transported. Transportation, using fertilizers and compost made a significant contribution to TAP as they generated high amounts of NO_x and NH_3 (Table 1). In addition, background processes such as producing fertilizers and pesticides were harmful in terms of HTPc and HTPnc (Silalertruksa et al. 2017).

3.3. Producing bioethanol from molasses vs. agave juice

Figure 6 compares the relative environmental impacts for producing bioethanol from sugarcane molasses and agave juice. Table 8 shows the impact values for 1 MJ of bioethanol produced from sugarcane molasses and agave juice.

On comparing both scenarios, bioethanol produced from agave juice was seen to make a relatively minor contribution in all categories. However, in the previous analyses, impacts on producing bioethanol from agave juice were observed to be higher than those for molasses. Hence, agave juice is more environmental-friendly. This significant difference could be due to the different ways these raw materials are cultivated and processed. Therefore, in this way, molasses was seen to generate much higher impact values than agave juice (Tables 6 and 7) and, consequently, molasses were more harmful to the environment overall.

When converting sugarcane-to-bioethanol the amount of GHG emissions was 384% higher than those for agave-to-bioethanol. Indeed, GHG for sugarcane was 3.26 kg of CO_2-eq/MJ, while for agave; this figure was only 0.67 kg. GHG emissions, as well as using N-fertilizers, coal and energy, increased the value of GWP (Nguyen &Gheewala 2008, Pryor et al. 2017, Wang et al. 2012). In addition to CH_4 and N_2O, the data provided by SimaPro indicated that emissions of Halon-1211, Halon-1301, CFC-10 and CFC-12 were the most detrimental to the environment in terms of ODP (González-García et al. 2012). Also, the impact value obtained in this category could be linked to cultivation. At this point pesticides (which may contain CH_4 and halocarbon compounds) were used. In Table 8, it was observed that the impact value for ODP in molasses was higher than in agave juice. This may be because more pesticides were required, and more gases were given off to cultivate sugarcane than agave (Table 1).

According to Table 1 and 2, Global NO_x emissions in sugarcane-to-bioethanol were1.86E-05 kg/MJ of bioethanol, while in agave-to-bioethanol, they were 1.22E-04 kg/MJ of bioethanol, respectively. Moreover, NO_x, SO_x, NH_3, CO, and hydrocarbons were given off on producing and using fertilizers and pesticides, transport, burning coal and bagasse, and energy production were the main contributing factors to the following: HOFP, EOFP, TAP, as shown in Table 8 (Brizmohun et al. 2015, Costa et al. 2018, Ghani &Gheewala 2018, Ruiz et al. 2018).The higher amount of NO_x given off and greater consumptionof these feedstocks (i.e. coal, pesticides, and fertilizer) in sugarcane meant that bioethanol from this raw material had a greater environmental impact in terms of HOFP, EOFP and TAP than agave (Figure 6 and Table 8) (Brizmohun et al. 2015, Michailos 2018)

Figure 6 and Table 8 showed that in terms of human toxicity, values for sugarcane were up to approximately 70% higher than they were for agave (78% for HTPc and 89% for HTPnc). This may be because sugarcane is relatively more reliant on fertilizers, pesticides, coal, and diesel than agave. It was also on account of the high emissions given off with the former (Tables 1-3) (Ghani &Gheewala 2018, Han et al. 2019, Ruiz et al. 2018). Moreover, on producing energy, fertilizers, pesticides, chemicals, diesel, coal and compost (background processes), pollutants such as nickel, cadmium, chromium and formaldehyde (that damaged the environment in terms of HTPc and HTPnc) were given off (Brizmohun et al. 2015).

In sugarcane cultivation, considerably more fertilizers, pesticides and compost were used. Additionally, this process created the highest amount of wastewater ash and emissions (P_2O_5) (Table 1) all of which led to a greater impact on FEP than agave did

(Figure 6 and Table 8) (Brizmohun et al. 2015, Costa et al. 2018, Ghani &Gheewala 2018, Michailos 2018, Ruiz et al. 2018)

Finally, the raw materials used (coal, natural gas and oil) for producing diesel and chemical products were the main contributing factors to FFP (Table 8) (Brizmohun et al. 2015, Ghani &Gheewala 2018). Moreover, the water used in irrigation (sugarcane), preparing fertilizers and pesticides, extracting sugar and agave and producing bioethanol contributed to WCP (Table 8)(Papong et al. 2017). As observed in the other categories, as well as FFP and WCP, sugarcane had higher impact values than agave (Figure 6).

3.4. Recommendations for improving environmental performance

Several recommendations for making bioethanol from sugarcane molasses and agave juice more environmentally-friendly could be considered. One of the greatest challenges to meet is making the raw material more productive without damaging the ecosystem (Farahani &Asoodar 2017, Osei et al. 2003, Papong et al. 2017, Silalertruksa &Gheewala 2009, Steiner et al. 2007).

In this respect, soil quality must be improved by substituting inorganic fertilizers with organic ones, such as manure or compost (Osei et al. 2003, Steiner et al. 2007). Also, this would considerably reduce eutrophication (Silalertruksa &Gheewala 2009). Similarly, reducing organic waste and emissions into the atmosphere also improves the environmental performance at the cultivation stage. A decrease in CH_4, CO_2, N_2O, and NO_x emissions in turn reduces impact values in terms of GWP, HOFP, EOFP, TAP, among others (Silalertruksa &Gheewala 2009).

For sugar and agave juice extraction, coal-produced energy was primarily responsible for the negative environmental impact. In this respect, it is recommended substituting coal with another fuel or using renewable energy such as biomass or hydraulic energy (the most widespread in Veracruz, Mexico) (CEMAD 2016, Farahani &Asoodar 2017) as this reduces GHG emissions and environmental damage in sugar extraction.

Finally, to reduce the impact that bioethanol production has on the environment; the amount of grid energy consumed must be reduced. In this respect, as in the processing stage, it is recommended replacing grid energy with that generated from renewable sources (biomass or hydraulic). Using renewable energy at the ethanol production stage could help reduce GHG emissions. In this sense, a sensitivity analysis was carried out in which grid energy was increasingly replaced with renewable energy. The main results of these analyses can be seen in Figures 7 and 8 and in Table 9. The sensitivity scenarios are as follows:

- Base scenario: 100% grid energy and 0% renewable energy;
- Scenario 1: 75% grid energy and 25% renewable energy;
- Scenario 2: 50% grid energy and 50% renewable energy;
- Scenario 3: 25% grid energy and 75% renewable energy;
- Scenario 4: 0% grid energy and 100% renewable energy;

Figure 7 and 8 shows that by changing from the Mexican energy grid to renewables, most of these impacts will be significantly reduced. In this research, we assumed that renewable energy would not have an environmental impact. For instance, GWP would be reduced by almost 50%, if the energy came from renewable sources and sugarcane was employed to produce bioethanol. This reduction was based on the fact that the energy grid in Mexico was mainly oil-based (>60%), while renewables still accounted for under 20% (Sarmiento et al. 2019). A reduction in oil consumption would cause a fall in GHG emissions. However, a higher drop would be observed if agave was employed as the feedstock. The relatively higher drop for agave was associated with the energy consumption required to produce bioethanol. According to Figure 1 and 2, producing 1 MJ of ethanol from sugarcane and agave would require 1.25 and 1.90 MJ of energy, respectively.

Apart from this strategy, using vinasse as compost may significantly reduce environmental damage. It is also essential to capture and store any CO_2 given off on producing bioethanol by means of carbon capture and storage technology (CEMAD 2016, Farahani &Asoodar 2017, Laude et al. 2011, Silalertruksa &Gheewala 2009).

3.5. Comparison with other studies

As earlier mentioned, there is little research on producing bioethanol from agave (Yan et al. 2011); However, several articles concerning the environmental screening of bioethanol produced from sugarcane have been published. For instance, Farahani andAsoodar (2017) reported that sugarcane cultivation mainly contributed to acidification, ozone layer depletion, human toxicity and photochemical oxidation. In addition, sugar extraction mainly contributed to global warming potential. Moreover, Amores et al. (2013) demonstrated that sugarcane cultivation is the main hotspot in the life cycle since it affected almost all categories except eutrophication. Similarly, Silalertruksa andGheewala (2009) observed that it was the main contributing factor to the environmental impact in terms of global warming, photo oxidation, acidification, human toxicity and eutrophication.

As observed in this study, cultivation was not the main hotspot when producing bioethanol from sugarcane. In this paper, sugar extraction contributed to a greater extent of the environmental impact than cultivation and bioethanol production. Indeed, it accounted for at least 46% in all the categories assessed.

According to the literature review, global warming potential ranged between 0.016 and 400 kg CO_2 produced for 1 MJ of ethanol from sugarcane(Amores et al. 2013, Farahani &Asoodar 2017, Silalertruksa &Gheewala 2009, Valencia &Cardona 2014). Table 8 shows that around 3.26 kg CO_2-eq/MJ was given off when sugarcane molasses was the feedstock. In other words, it can be concluded that the observed carbon footprint quite similar for that previously reported in others research. These discrepancies in the research were ascribed to i) assessment models (e.g., CML and ReCiPe); ii) allocation method; iii) and inventory data.

Furthermore, when comparing the actual study with that of Ghani andGheewala (2018), some similarities can be observed. They studied four different scenarios for producing bioethanol from molasses, the first of which was based on very similar assumptions to those we made. Thus, they considered using inorganic fertilizers and freshwater irrigation for cultivation, bagasse and biogas (from treated wastewater from the bioethanol plant) to produce electricity. Cane waste was burned, wastewater was discharged into surface water and filter cake was used as fertilizer. As in this study, they used the ReCiPe 2016 midpoint methodology and the SimaPro 8.4 software to evaluate impacts. On comparing the results obtained for the five categories in this research and those by Ghani andGheewala (2018), similar values were observed in three of them (GWP, FEP and FFP). The differences seen in the other two (TAP and HTPc) might have been linked to the different assumptions made, such as burning cane waste and producing biogas (Ghani &Gheewala 2018).

As for the ethanol produced from agave, we reported a carbon footprint of 0.70 kg CO_2-eq/MJ, whose value was lower than that reported for sugarcane juice, as shown in Table 8**.** Considering the agave plant-to-bioethanol production chain, the main stage that contributed to the high environmental impact was producing bioethanol from agave juice. This was mainly attributed to energy consumption on purifying the bioethanol. This stage is known to be one of the main hotspot within the life cycle (Sanchez et al. 2021). However, Yan et al. (2011) reported that crop cultivation was the highest contributing factor to environmental impact in terms of GHG. Furthermore, they reported overall GHG emissions of 0.0044 kg CO_2-eq/MJ whose value was lower than that reported in this study (i.e. 0.70 kg CO_2-eq/MJ) and our value was higher due to the energy consumed from the Mexican grid.

3.6. Economic analysis

The parameters considered for carrying out the preliminary economic analysis were as follows: installation capacity of 1000 kg/h of raw material, operating time for the plant of 8000 h/year, total operating time of 15 years, and 50% of total costs would be invested in year zero. The inflation rate was 3.8%, the tax rate was 30% and the depreciation coefficient was 7% (FinancialredMéxico 2018, IPC 2018).

Table 10 shows the costs of equipment and utilities. Table 11 shows a summary of fixed capital, direct production costs and sales of bioethanol produced from molasses and agave juice.

Equipment costs of the biorefinery were provided by the Aspen Plus® economic package, and the storage tank in this study was to scale. Also, working capital was the raw material stock for ten days of production. The bioethanol production plant was assumed to be located in the same place as the agave sugar/juice extraction plant (Veracruz, Mexico), whereby the cost of the raw material was assumed to be zero. In addition, Table 11 shows prices for electricity, water, urea, ammonia sulphate and magnesium sulphate (Budimir et al. 2011, CFE 2019, CONAGUA 2019, SENER 2018).

Moreover, it was assumed that six workers, on an annual salary of 15,000 €/worker, were needed to operate the plant.

Furthermore, Table 11 shows that capital investment, fixed capital and working capital for producing bioethanol from molasses were 1,075,281 €, 860,225 € and 215,056 €, respectively, while for agave juice these figures were 1,036,068 €, 828,854 € and 207,214 €, respectively.

On analyzing the data provided by the Aspen Plus simulations, it was observed that from 1,000 kg/h of molasses, 170 kg/h of bioethanol and 1,080 kg/h of vinasse were produced. In comparison, from 1,000 kg/h of agave juice 45 kg/h of bioethanol and 990 kg/h of vinasse were produced. The vinasse obtained could not be directly applied to the field, although it could be used in conjunction with other residues from the sugar refinery, and in this way, it could be sold (Consorcio 2012). Both products were put on the market, with the following assumptions on price: 0.75 €/kg for bioethanol and 0.025 €/kg for vinasse (biocompost price) (Castañeda-Ayarza &Cortez 2017, Consorcio 2012).

The results obtained from this economic evaluation indicated that neither of the two-bioethanol production scenarios were profitable given that the VPN values obtained were negative (-1,521,947 € for molasses and -1,785,235 € for agave juice) and the time for seeing a return on investment was over 15 years. This might have been mainly due to the high amount of energy used to produce bioethanol which entailed high utility costs. In this study, all energy was assumed to be sourced from the grid, with 1600 kW used for sugarcane and 600 kW for agave.

Therefore, a sensitivity analysis was carried out in order to evaluate how reliable the project would be if part of the grid energy were replaced by renewable energy, assuming that the latter would cost zero because it would be generated at the plant itself. Energy percentages considered in the sensitivity analysis were the following (Table 12):

- Base scenario: 100% grid energy and 0% renewable energy;
- Scenario 1: 75% grid energy and 25% renewable energy;
- Scenario 2: 50% grid energy and 50% renewable energy;
- Scenario 3: 25% grid energy and 75% renewable energy;
- Scenario 4: 0% grid energy and 100% renewable energy;
- Scenario 5: NPV=0.

The sensitivity analysis showed that varying the energy source had a significant influence on all three economic parameters (Table 12). On analyzing the results, it was observed that if part of the grid energy were replaced with renewable energy, the two bioethanol production processes would become more economically viable. However, there were considerable differences between both scenarios as molasses were more profitable. So, producing bioethanol was only profitable with the ratios 17.1% grid energy and 82.9% renewable energy, and 73.5% grid energy and 26.5% renewable energy for agave juice and molasses, respectively. These considerable differences between both scenarios could be attributed to the lower yields for agave juice in comparison to that for molasses. Hence, producing bioethanol from sugarcane molasses and agave juice was economically viable, better results were achieved with the former.

Conclusions

This research aims to compare the environmental and economic performance of using sugarcane juice and agave juice as feedstocks to produce bioethanol in Mexico. On the one hand, producing bioethanol from agave juice had a less environmental impact than sugarcane juice. This was ascribed to the low consumption of pesticides, coal, and water throughout the whole chain. Among stages, bioethanol production contributed to a higher extent (>60%) than cultivation and juice extraction due to the low amounts of ethanol yielded in fermentation. On the other hand, the economic analysis revealed that neither of the feedstocks is feasible if the current Mexican energy grid is employed. However, if 26.5% of renewable energy is employed along the grid, then producing bioethanol from agave juice would be economical feasible. Briefly, using agave juice, rather than sugarcane molasses as a feedstock for producing bioethanol seems to be more promising from an environmental and economic point of view. On a final note, in Mexico it would be worthwhile creating robust policies to encourage the adoption of renewable energy.

Acknowledgments

The authors would like to thank the University of Castilla-La Mancha ,Spain for their financial support (UCLM "Plan Propio de I+D+i. (2016 / 14100)" Grant). The authors acknowledge the financial support given by the Castilla-La Mancha regional government (Project SBPLY/17/180501/000238).

Data availability

All data generated and analysed during this study have been included in this published article.

References

Amores MJ, Mele FD, Jiménez L, Castells F (2013): Life cycle assessment of fuel ethanol from sugarcane in Argentina. Int J Life Cycle Assess 18, 1344-1357

Becerra J, Figueredo M, Cobo M (2017): Thermodynamic and economic assessment of the production of light olefins from bioethanol. J Environ Chem Eng 5, 1554-1564

Brizmohun R, Ramjeawon T, Azapagic A (2015): Life cycle assessment of electricity generation in Mauritius. J Clean Prod 106, 565-575

Budimir N, Jarić M, Jacimovic B, Genic S, Jaćimović N (2011): Rectified ethanol production cost analysis. Therm Sci 15, 281-292

Castañeda-Ayarza JA, Cortez LAB (2017): Final and B molasses for fuel ethanol production and some market implications. Renew. Sust. Energ. Rev. 70, 1059-1065

CEMAD (2016): Marco jurídico de las energías renovables en Veracruz. Centro Mexicano de Derecho Ambiental, A.C. México. https://www.cemda.org.mx/, 86

CFE (2019): Precio Electricidad Industrial 2019, https://www.cfe.mx/Pages/Index.aspx

CONAGUA (2019): Sistema Nacional de Información del Agua, http://sina.conagua.gob.mx/sina/index.php

Consorcio C 2012: Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia; Capitulo II: Estudio ACV – Impacto Ambiental, https://www.minminas.gov.co

Corbin K, Betts N, Holst N, Jiranek V, Chambers D, Byrt C, Fincher G, Burton R (2016): Low-Input Fermentations of Agave tequilana Leaf Juice Generate High Returns on Ethanol Yields. BioEnergy Res. 9

Costa D, Jesus J, Virgínio e Silva J, Silveira M (2018): Life Cycle Assessment of Bioethanol Production from Sweet Potato (Ipomoea batatas L.) in an Experimental Plant. BioEnergy Research 11, 715-725

Davis SC, Dohleman FG, Long SP (2011): The global potential for Agave as a biofuel feedstock. GCB Bioenergy 3, 68-78

Dias MOdS, Maciel Filho R, Mantelatto PE, Cavalett O, Rossell CEV, Bonomi A, Leal MRLV (2015): Sugarcane processing for ethanol and sugar in Brazil. Env Dev 15, 35-51

Ecoinvent (2019): Encoinvent database, https://www.ecoinvent.org/

EPA (2016): GHG Inventory Guidance - Direct Emissions from Stationary Combustion Sources www.epa.gov/climateleadership

EPA (2017): Global Greenhouse Gas Emissions Data, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Farahani SS, Asoodar MA (2017): Life cycle environmental impacts of bioethanol production from sugarcane molasses in Iran. Environmental Science and Pollution Research 24, 22547-22556

FinancialredMéxico (2018): Porcentaje de depreciación fiscal ¿Cómo se calcula?, http://losimpuestos.com.mx/porcentaje-de-depreciacion-fiscal/

Gamboa RT 2006: Uso del agua en el ingenio Potrero, Instituto Politecnico Nacional, https://tesis.ipn.mx, 92 pp

Gavahian M, Farahnaky A, Sastry S (2016): Ohmic-assisted hydrodistillation: A novel method for ethanol distillation. Food Bioprod. Process. 98, 44-49

Ghani HU, Gheewala SH (2018): Comparative life cycle assessment of byproducts from sugarcane industry in Pakistan based on biorefinery concept. Biomass Conversion and Biorefinery 8, 979-990

Gómez-Merino FC, Trejo-Téllez LI, Salazar-Ortiz J, Pérez-Sato JA, Sentíes-Herrera HE, Bello-Bello JJ, Aguilar-Rivera N (2017): La diversificación de la agroindustria azucarera como estrategia para México. Agro productividad 10, 7-14

González-García S, Iribarren D, Susmozas A, Dufour J, Murphy RJ (2012): Life Cycle Assessment of two alternative bioenergy systems involving Salix spp. biomass: Bioethanol production and power generation. Appl. Energy 95, 111-122

Han D, Yang X, Li R, Wu Y (2019): Environmental impact comparison of typical and resource-efficient biomass fast pyrolysis systems based on LCA and Aspen Plus simulation. J Clean Prod 231, 254-267

Hanif I (2017): Economics-energy-environment nexus in Latin America and the Caribbean. Energy 141, 170-178

Hillstrom K, Hillstrom LC (2002): Encyclopedia of small business. Gale Group, Detroit, MI

IPC (2018): Inflacion de México en 2018, https://es.inflation.eu/tasas-de-inflacion/mexico/inflacion-historica/ipc-inflacion-mexico-2018.aspx

ISO14040 (2006): ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework.

ISO14044 (2006): ISO 14044: Environmental Management, Life Cycle Assessment, Requirements and Guidelines. International Standard Organization

Jambo S, Abdulla R, Azhar H, Marbawi H, Jualang Azlan G, Ravindra P (2016): A Review on third generation bioethanol feedstock. Renew. Sust. Energ. Rev. 65, 769

Kalk J, Langlykke A (1986): Cost estimation for biotechnology projects. Manual of industrial microbiology and biotechnology, 385-385

Klein C, Novoa R, Ogle S, Smith K, Rochette P, Wirth T, Rypdal K (2006): Capitulo 11: Emisiones de N2O de los suelos gestionados y emisiones de CO2 derivadas de la aplicación de cal y urea. . Directrices del IPCC de 2006 para los inventarios nacionales de gases de efecto invernadero. Editorial IGES, Japón. 425 p., 1-56

L. Gutiérrez-Coronado M, Acedo Felix E, I. Valenzuela-Quintanar A (2007): INDUSTRIA DEL BACANORA Y SU PROCESO DE ELABORACIÓN BACANORA INDUSTRY AND ITS PROCESS OF PRODUCTION, 5, 394-404 pp

Laude A, Ricci O, Bureau G, Royer-Adnot J, Fabbri A (2011): CO2 Capture and storage from a bioethanol plant: Carbon and energy footprint and economic assessment. Int J Greenh Gas Con 5, 1220-1231

Lin Y, Tanaka S (2006): Ethanol Fermentation from Biomass Resources: Current State and Prospects. Appl. Microbiol. Biotechnol. 69, 627-42

Livier RC 2004: Diseño preliminar del equipo necesario para la elaboración de bacanora, Universidad de Sonora, 115 pp

Lopez-Bustamante JF 2015: La caña de azucar (Saccharum officinarum) para la producción de panela. caso: nordeste del departamento de antioquia, Universidad Nacional Abierta y a Distancia, Medellin; Colombia, 1-70 pp

Mandujano Bueno A, Pons Hernández JL, Paredes Melesio R, García Meza P (2018): Diversidad genética de maguey (Agave spp.) en las sierras y llanuras del norte de Guanajuato. Revista mexicana de ciencias agrícolas 9, 511-523

Marín CB 2014: Análisis de la situación actual de las emisiones del Ingenio Central Progreso, Veracruz., Universidad Veracruzana. Facultad de Ingeniería Química.Región Xalapa., http://cdigital.uv.mx/handle/123456789/1270 82 pp

Meyer J (2013): Sugarcane Nutrition and Fertilization, pp. 117 to 168

Michailos S (2018): Process design, economic evaluation and life cycle assessment of jet fuel production from sugar cane residue. Environ. Prog. Sustain. Energy 37, 1227-1235

Nava-Cruz NY, Medina-Morales MA, Martinez JL, Rodriguez R, Aguilar CN (2015): Agave biotechnology: an overview. Crit. Rev. Biotechnol. 35, 546-559

Nemecek T, Kägi T (2007): Life Cycle Inventories of Agricultural Production Systems, 360 pp

Nguyen TLT, Gheewala SH (2008): Life cycle assessment of fuel ethanol from cane molasses in Thailand. Int J Life Cycle Assess 13, 301

Núñez HM, Rodríguez LF, Khanna M (2011): Agave for tequila and biofuels: an economic assessment and potential opportunities. GCB Bioenergy 3, 43 - 57

Oliver J, K.M S, Peters J (2017): Trends in global CO2 and total greenhouse gas emissions - 2017 Report, https://www.pbl.nl/sites/default/files/cms/publicaties/

Osei E, Gassman PW, Hauck LM, Jones R, Beran L, Dyke PT, Goss DW, Flowers JD, McFarland AMS, Saleh A (2003): Environmental benefits and economic costs of manure incorporation on dairy waste application fields. J. Environ. Manage. 68, 1-11

Papong S, Rewlay-ngoen C, Itsubo N, Malakul P (2017): Environmental life cycle assessment and social impacts of bioethanol production in Thailand. J Clean Prod 157, 254-266

Pérez Hernández E, Chávez Parga MdC, González Hernández JC (2016): Revisión del agave y el mezcal. Rev. Colombiana Biotecnol. 18, 148-164

Peters MS, Timmerhaus KD, West RE (2003): Plant Design and Economics for Chemical Engineers. McGraw-Hill Education

Proaño L, Sarmiento AT, Figueredo M, Cobo M (2020): Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: A system dynamics approach. J. Clean. Prod. 263, 121457

Pryor SW, Smithers J, Lyne P, van Antwerpen R (2017): Impact of Agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. J. Clean. Prod. 141, 137-145

Rendon-Sagardi MA, Sanchez-Ramirez C, Cortes-Robles G, Alor-Hernandez G, Cedillo-Campos MG (2014): Dynamic analysis of feasibility in ethanol supply chain for biofuel production in Mexico. Appl. Energy 123, 358-367

Renouf MA, Pagan RJ, Wegener MK (2013): Bio-production from Australian sugarcane: an environmental investigation of product diversification in an agro-industry. J Clean Prod 39, 87-96

Robak K, Balcerek M (2018): Review of Second Generation Bioethanol Production from Residual Biomass. Food Technol. Biotechnol. 56, 174-187

Ruiz D, San Miguel G, Corona B, López FR (2018): LCA of a multifunctional bioenergy chain based on pellet production. Fuel 215, 601-611

SAGARPA 2018a: 5to. Informe estadístico del sector agroindustrial de la caña de azúcar en México, zafras 2008-2009 / 2017-2018, https://www.gob.mx/conadesuca/es

SAGARPA 2018b: Resumen Nacional Intención de cosecha 2018 Ciclo: Perennes, http://infosiap.siap.gob.mx/opt/agricultura/intension/Intencion_cosechaPerenne_cultivo2018.pdf

Sanchez N, Ruiz R, Infante N, Cobo M (2017): Bioethanol Production from Cachaza as Hydrogen Feedstock: Effect of Ammonium Sulfate during Fermentation. Energies 10, 2112

Sanchez N, Ruiz R, Hacker V, Cobo M (2020a): Impact of bioethanol impurities on steam reforming for hydrogen production: A review. Int. J. Hydrogen Energy 45, 11923-11942

Sanchez N, Ruiz R, Hacker V, Cobo M (2020b): Impact of bioethanol impurities on steam reforming for hydrogen production: A review. IJHE 45, 11923-11942

Sanchez N, Ruiz R, Plazas A, Vasquez J, Cobo M (2020c): Effect of pretreatment on the ethanol and fusel alcohol production during fermentation of sugarcane press-mud. Biochem. Eng. J. 161, 107668

Sanchez N, Ruiz R, Rödl A, Cobo M (2021): Technical and environmental analysis on the power production from residual biomass using hydrogen as energy vector. Renew Energy 175, 825-839

Sarmiento L, Burandt T, Löffler K, Oei P-Y (2019): Analyzing Scenarios for the Integration of Renewable Energy Sources in the Mexican Energy System—An Application of the Global Energy System Model (GENeSYS-MOD). Energies 12, 3270

SENER (2018): Sistema de Información Energética, http://sie.energia.gob.mx/bdiController.do?action=cuadro&cvecua=IIIBC01

Silalertruksa T, Gheewala SH (2009): Environmental sustainability assessment of bio-ethanol production in Thailand. Energy 34, 1933-1946

Silalertruksa T, Pongpat P, Gheewala SH (2017): Life cycle assessment for enhancing environmental sustainability of sugarcane biorefinery in Thailand. J Clean Prod 140, 906-913

Soreanu G, Gagnon PL, Grégoire C, Marcos B, Heitz M (2004): Ethanol production by bioengineering. Environmental Engineering and Management Journal 3, 363-372

Steiner C, Teixeira WG, Lehmann J, Nehls T, de Macêdo JLV, Blum WEH, Zech W (2007): Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275-290

Tauer A, Elss S, Frischmann M, Tellez P, Pischetsrieder M (2004): Influence of Thermally Processed Carbohydrate/Amino Acid Mixtures on the Fermentation by Saccharomyces cerevisiae. J. Agric. Food Chem. 52, 2042-6

Trejo-Salazar R-E, Eguiarte L, Suro-Piñera D, Medellín R (2016): Save Our Bats, Save Our Tequila: Industry and Science Join Forces to Help Bats and Agaves. Nat. Areas J. 36, 523-530

Valencia MJ, Cardona CA (2014): The Colombian biofuel supply chains: The assessment of current and promising scenarios based on environmental goals. Energy Policy 67, 232-242

Wang L, Littlewood J, Murphy RJ (2013): Environmental sustainability of bioethanol production from wheat straw in the UK. Renew. Sust. Energ. Rev. 28, 715-725

Wang M, Han J, Dunn J, Cai H, Elgowainy A (2012): Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Ethanol From Corn, Sugarcane, and Cellulosic Biomass for US Use: Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Ethanol From Corn, Sugarcane, and Cellulosic Biomass for US Use. Environ. Res. Lett. 7, 45905-13

Yan X, Tan DKY, Inderwildi OR, Smith JAC, King DA (2011): Life cycle energy and greenhouse gas analysis for agave-derived bioethanol. Energy Environ. Sci. 4, 3110-3121

Zabed H, Sahu JN, Suely A, Boyce AN, Faruq G (2017): Bioethanol production from renewable sources: Current perspectives and technological progress. Renew. Sust. Energ. Rev. 71, 475-501

Zhang Y, McKechnie J, Cormier D, Lyng R, Mabee W, Ogino A, Maclean H (2010): Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas, and Wood Pellets in Ontario, Canada. Environ. Sci. Technol. 44, 538-44

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

Maria Magdalena Parascanu: investigation, writing and preparing original draft, data curation, editing.**Nestor Sanchez:** data curation, simulation,editing. **Fabiola Sandoval-Salas:** data curation, research. **Carlos Mendez Carreto:** formal analysis, research. **Gabriela Soreanu:** conceptualization, reviewing, supervision.**Luz Sanchez-Silva:**conceptualization, funding acquisition, visualization,project administration.

Conflict of interest

The authors declare there to be no conflict of interest.