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Original article

Development of indicators for the sustainability of the sugar industry

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ABSTRACT

Sustainable development has been highlighted widely in productive sectors such as the sugar industry with new paradigms and trends such restructuring of sugar mills in biorefineries and development of green chemical from byproducts, considering issues such as technology adoption towards sustainability, circular economy, climate change, value chain, sustainability assessment and decision making. Production of cane sugar is one of Mexico's main agro-industries; it conveys numerous positive socio-economic impacts and presents opportunities for productive diversification and enhanced profitability and competiveness. The sugar industry faces sustainability challenges due to the management of natural resources like soil, water, fossil fuels and agrochemicals, as well as the impacts of its greenhouse gas emissions and socio-economic constraints. However, sustainability of cane and sugar production cannot be assessed due to a lack of methodological frameworks for integrating economic and environmental indicators. We propose an index for Mexico's sugar agro-industry that facilitates the identification of those system components that impact sustainability. This index is based on a reduced number of indicators aggregated through a multi-criteria evaluation using the analytical hierarchy process (AHP). We apply this index to evaluate four sugar production systems in Mexico: producers of raw, refined, muscovado sugar and ethanol. Results show that systems with a high agro-industrial yield present better sustainability performance. This study is relevant because it provides quantitative information for decision makers towards a sustainable sugarcane agro-industry, based on the indicators used to build the sustainability index, to address actions as increase productive diversification by-products based, improve access to credit, irrigation, management practices and raw material quality reducing production costs, eliminate fossil fuel use in factories, make fertilizer application more efficient and reduce the area that is burned for manual harvest.

KEY WORDS: life cycle analysis; carbon footprint; multicriteria evaluation, AHP, decision makers

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1. Introduction

Human-induced environmental degradation is a growing challenge for modern societies. Global warming, ocean acidification, disruptions of the nitrogen cycle and biodiversity loss are just some examples of the current global environmental challenges (Rockström et al., 2009). In order to mitigate these negative impacts of human activities and achieve sustainability, it is necessary to modify the way in which economic and productive activities are developed, including agro-industrial systems (Ramankutty et al., 2018; de Oliveira Neto et al., 2018; Silva et al., 2018).

The area of sugarcane (*Saccharum* spp.) cultivation totalled 27 million hectares in the world (Heinrichs et al., 2017). With a production of nearly 6 mln t of sugar. Mexico is the seventh largest sugar producer worldwide since it has suitable conditions for the growth of sugarcane and presents opportunities for the development of biorefineries (Brambila-Paz et al., 2013; Eggleston & Lima, 2015; Martínez-Guido et al., 2015; Barrera et al., 2016; Sarker et al., 2017; Talukdar et al., 2017) (Fig. 1).

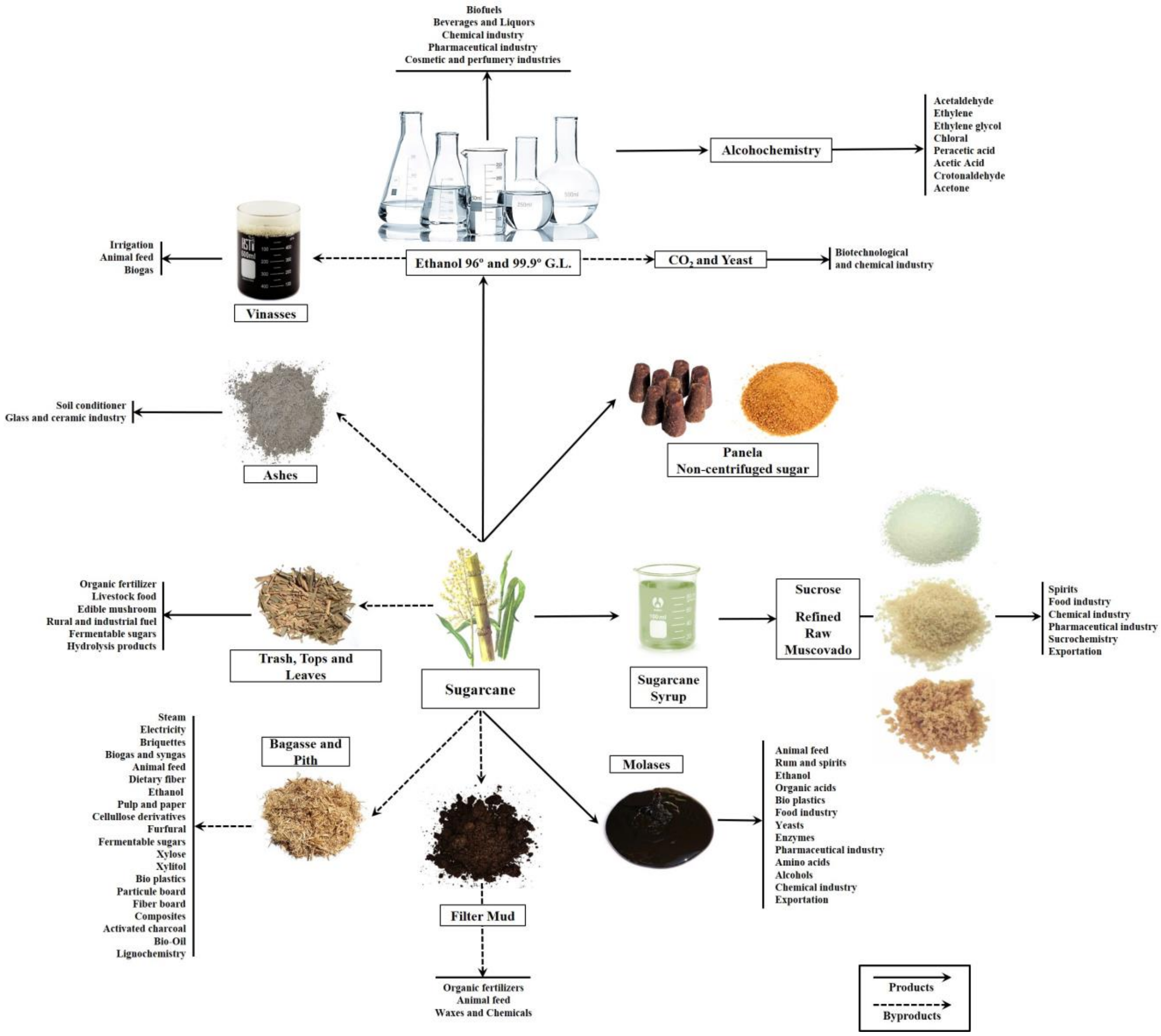

Fig. 1. Sugarcane biorefinery based on cane, products and byproducts

The sugar agro-industry represents 0.5% of Mexico's gross domestic product and provides significant full-time and temporary employment for more than 2.2 million people in 227 municipalities (9.2% of all municipalities in Mexico) with differentiated agro-ecological aptitude of cane cultivation and productivity (SENTÍES-HERRERA ET AL., 2014, 2017) (Fig. 2 and 3).

In the 2014/2015 season, the production was concentrated in 15 states and six different regions (Pacific, South east, Gulf of Mexico, Central Mexico, North east and North west) with 57 sugar mills and a harvested area of just over 783,515 ha with 53,602,636 t of raw material with a sugarcane yield of 68.409 tha^{-1}, with 7.639 t sucrose per hectare and a factory yield of 11.166%. However, the Mexican sucrose production in 2017/2018 was carried out in 51 operational sugar mills (CONADESUCA, 2018).

In Mexico, up to 400 million litres of ethanol can potentially be produced from molasses as an alternative for product diversification and climate change mitigation (GARCÍA ET AL., 2011, 2017). Evaluations have found opportunities for energy cogeneration that would allow sugar mills to sell electricity (RINCÓN ET AL., 2014). By producing ethanol to replace fossil fuels and generating electricity, and a lot of bioproducts, the sugar agro-industry can help reduce greenhouse gas emissions and have a positive impact on the environment (GRIGOLETTO-DUARTE ET AL., 2013; RENOUF ET AL., 2013; GARCÍA ET AL., 2016, 2017; HEINRICHS ET AL., 2017). Its high potential for job creation, economic development and sustainability should also be considered as productive options (DÍAS DE MORALES ET AL., 2015). The promotion and modernization of irrigation, the renovation of plantations, new varieties and the more efficient use of inputs as agrochemicals, manures, byproducts (filter mud, trash, bagasse and vinasse) fuels and management practices should be fostered in sugar cane growing areas (SANTILLÁN-FERNÁNDEZ ET AL., 2014) for economic competiveness (Fig. 4).

Fig. 2. Sugar Mills in Mexico

Fig. 3. Sugarcane producer regions in Mexico

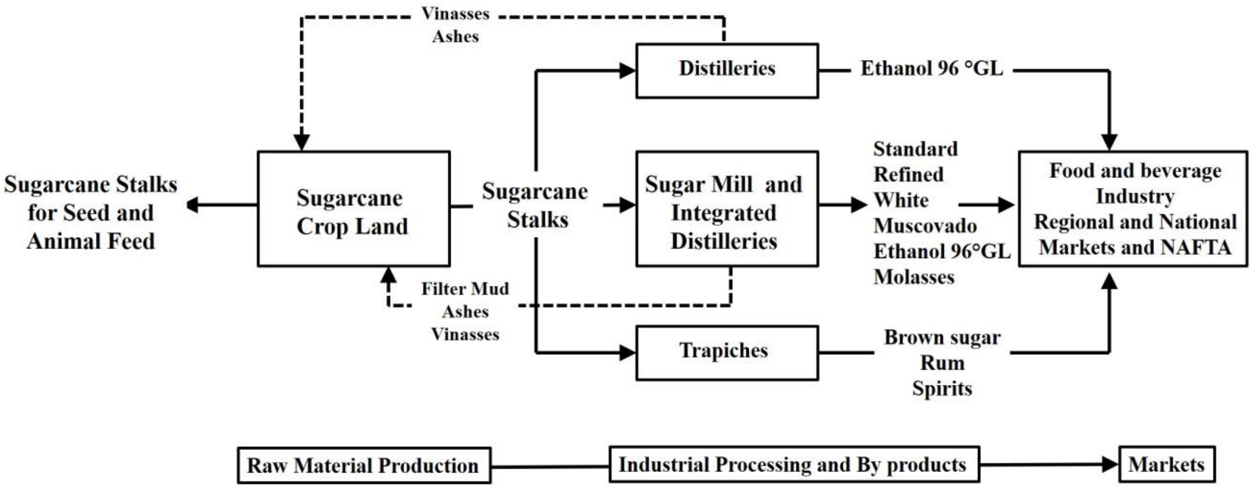

Fig. 4. Productive structure of the Mexican sugar industry

Sugar production, as a bio-based industry, is a complex system operating in a highly competitive environment and with opportunities to reduce its environmental impacts (Heinrichs et al., 2017). This means that managers have to make informed decisions, to be proactive and explore every opportunity and use multidisciplinary tools to improve production, reduce costs and enhance its sustainability (Shukla et al., 2017; Lang et al., 2017; Cardoso et al., 2018).

2. Sugar industry sustainability

Sustainability can be understood as a characteristic of dynamic systems that allows them to maintain themselves through time with no discernible end point (Büyüközkan & Karabulut, 2018; Loris, 2018). The sugar agro-industry faces many sustainability challenges due to its negative environmental impacts, such as land use change, soil degradation, high water consumption (Ingaramo et al., 2009), atmospheric pollution due to bagasse and trash burning (Finguerut, 2010; Schaffel & la Rovere, 2010; Mugica-Alvarez et al., 2015), biodiversity loss from monocultures (Grigoletto-Duarte et al., 2013) amongst others. There are also important socio-economic risks that have been associated to sugarcane cultivation: There have been reports of increased inequity in the rural sector, as well as low salaries and even exploitation of labourers (Grigoletto-Duarte et al., 2013; Leal et al., 2013; Nuffield, 2011).

For the sugar industry, sustainability evaluations have been made mainly for sugarcane bio-refineries with integrated sugar, ethanol and production of byproducts (Contreras et al., 2009; Chauhan et al., 2011; Silalertruksa et al., 2015; Tomei, 2015) in the context of developing countries. Two particular research reports focus on showing the sustainability of sugar cane ethanol and sugar production in Brazil at a regional level using data from greenhouse gas (GHG) mitigation, energy balance, land use change, emission of pollutants, water use, socio-economic aspects such as job creation and economic profitability. Goldemberg (2008) carried out a literature review to highlight the advantages of ethanol production from sugar cane, finding no negative effects in any of the environmental or socio-economic aspects analysed, and concluding that ethanol production in Brazil is sustainable. Likewise, Walter et al. (2011) evaluated this agro-industry focusing particularly on land use change impacts, Linnenluecke et al. (2018) in relation to climate change for the sugar cane industry and Amaya (2010) concluded that the sustainability aspects that can be emphasized in sugar cane processing are: 1) productivity (producing more with the same equipment), 2) efficiency (producing more with the same raw material, reducing losses and emissions), 3) energy (producing more with the same energy), 4) water (producing more with the same water), 5) chemicals (producing more with the same chemicals).

Separately, Pereira & Ortega (2010) evaluated the sustainability of ethanol production in Brazil considering GHG emissions, energy balance and the demand for land, water and certain materials. This study did not consider socio-economic aspects, so it cannot be considered as a sustainability evaluation within our framework. Additionally, their method does not contain an indicator integration that allows for different production alternatives to be classified.

Other types of studies can be found that are not proper sustainability evaluations but they do evaluate environmental, economic and social aspects (Büyüközkan & Karabulut, 2018; Gulisano et al., 2018). One of these studies by Chávez-Rodríguez

& NEBRA (2010) analyses GHG emissions, carbon footprint and water use in ethanol production from cane sugar in Brazil and ethanol from maize in the United States. This study compares each of the aspects studied but does not integrate the evaluations to obtain a grade. Results show better performance in two out of three cases evaluated for cane sugar in Brazil compared to gasoline. Other recent studies about bio-refineries evaluate different environmental impacts such as GHG emissions, fossil fuel use, water use and land for product diversification systems and technological optimization in the sugar agro-industry (CAVALETT ET AL., 2011; RENOUF ET AL., 2013).

In the case of the sugar industry in Mexico there are studies mainly to characterize the industry and its markets, AGUILAR-RIVERA (2012), RINCÓN ET AL. (2014), SENTÍES-HERRERA ET AL. (2014, 2017), ALEMÁN-NAVA ET AL. (2015) and SCHMITZ & LEWIS (2015), however, they lack specific methodologies to identify actions to improve the sustainability of the whole system.

Here we propose a sustainability index for the cane sugar agro-industry based on the conceptual frameworks mentioned above and using a number of criteria and reduced indicators that allow us to identify the system components that contribute the most towards the sustainability of this agro-industry. This paper is relevant because it provides quantitative information and a method that can be used to develop the sugar agro-industry more sustainably. This index is applied to four case studies in Mexico.

3. Materials and methods

The methodology employed in this study is based on theoretical frameworks for sustainability evaluation reported by NARDO ET AL. (2005), BUCHHOLZ ET AL. (2007), ELGHALI ET AL. (2007), WANG ET AL. (2009), ACOSTA-MILCH ET AL. (2011), GASPARATOS & SCOLOBIG (2012), GAN ET AL. (2017), and GNANSOUNOU ET AL. (2017). It is divided into three stages: 1) defining the group of criteria and sustainability indicators that will be evaluated by considering environmental, economic and social dimensions; 2) evaluating the indicators with a specific methodology; 3) integrating the indicators.

Sustainability indicators are developed as a simplified tool of communication, which helps to make political decisions for seeking sustainability. In order to achieve this goal, it is necessary to set a limited number of easy understandable indicators (CIEGIS ET AL., 2015; BÜYÜKÖZKAN & KARABULUT, 2018).

Indicators and sustainability indices were calculated for four agro-industrial production systems: Central Motzorongo and La Gloria in the state of Veracruz; Tamazula in Jalisco, and Emiliano Zapata in Morelos. These case studies were chosen according to data availability criteria, size of the sugar mills and how different production conditions are represented (GARCÍA ET AL., 2016) (Table 1). Note that these mills might not be a significantly representative sample of all mills in Mexico, since significant differences exist in levels of productivity, technology in cane production, in industrialized area, socio-economic conditions of growers and in net cane crushed.

3.1. Defining a group of indicators for the Mexican sugar industry and their specific methodologies

The sustainability criteria employed to construct an index for the Mexican sugar industry correspond to the different dimensions of sustainability: Environmental (E), socio-economic (SE) and technological (T). The last one is extremely important for industries. This study follows the methodology proposed by AZAPAGIC & PERDAN (2000), BUCHHOLZ ET AL. (2007), LIU (2014), COBULOGLU & BÜYÜKTAHTAKIN (2015), NIKODINOSKA ET AL. (2015), GAN ET AL. (2017) and GANI & HANTORO (2018). Rather than presenting a high number of indicators for the established criteria, a restricted number of structured criteria are selected so that relationships between impacts and outputs are clarified.

Fossil Fuel Consumption Indicator

One of the main current problems of productive processes is how much they depend on fossil fuels (ROCKSTRÖM ET AL., 2009). Fossil fuel use is proposed as an indicator that quantifies, within the production life cycle, how much fossil fuel (MJ) is used to produce 1 kg of sugar. This indicator has already been used in other sugar agro-industry studies (NGUYEN ET AL., 2008).

The specific methodology for calculating this indicator consists of quantifying all forms of fossil energy that are used during agricultural production, transport of sugar cane to the mill and industrial production. During agricultural production it is important to consider the energy required to produce agrochemicals (fertilizers and pesticides), energy for irrigation and energy used by agricultural machinery. During industrial production, energy used to generate vapour (which is used in sugar production) and fossil energy from electricity use and generation are considered. For the transport stage we consider fuel used for transport vehicles. All data for inputs of each agro-industrial system under study were obtained from field interviews and from the National "Cañeros" Union (UNC for its acronym in Spanish; UNC, 2015) and CONADESUCA (Committee for the Sustainable Development of Sugar cane). (2018) Specific coefficients for energy embedded in inputs, fuels and the Mexican electric grid were obtained from specific studies (FARREL, ET AL., 2006; EUROPEAN COMMISSION, 2011; GARCÍA ET AL., 2011).

Table 1. Sugar mills considered in this study (data from Conadesuca, 2018)

Indicators	Central Motzorongo	Tamazula	La Gloria	Emiliano Zapata	National average
Harvested cane area (ha)	17,886	11,375	16,93	10,288	777,078
Harvested cane (t)	1,323,222	1,045,183	1,469,006	1,018,370	53,308,643
Sucrose production (t)	143,752	120,481	164,851	139,99	5,970,373
Agroecological	High (2.14%)	High (35.64%)	High (94.66%)	High (97.15%)	High (20.07%)
Suitability for	Medium (55.38%)	Medium (59.12%)	Medium (3.91%)	Medium (2.81%)	Medium (56.34%)
Sugarcane	Low (42.49%)	Low (5.24%)	Low (0.26%)	Low (0.05%)	Low (23.59%)
Irrigation (%)	27.32	100	89.70	100	30
Farm size (ha/grower)	5.2	3.71	2.64	1.79	3
Green harvest (%)	7.361	0	2	3.102	6.9
Mechanized harvest (%)	5.644	51.229	10.287	11.498	16.786
Varieties	Mex 69-290 (51.57%) CP 72-2086 (19.51%) CP 44-101 (7.27%) CP 70-1527 (7.74%) ITV 92-1424 (3.63%)	AT-MEX 96-40 (25.1%) ITV 92-1424 (20.25%) CP 72-2086 (46.74%) L 69-321 (4.21%)	Mex 69-290 (47.58%) CP 72-2086 (12.5%) Mex 91-662 (6.44%) LGM-92-156 (10%) RD 75-11 (15.2%)	CP 72-2086 (37.45%) ITV 92-1424 (39.8%) Mex 79-431 (8.4%) MY 55-14 (6.55%) Mex 69-290 (4.56%)	CP 72-2086 (31.9%) Mex 69-290 (25.5%) Mex 79-431 (6.9%)
Yield (t cane ha^{-1})	73.980	91.883	86.769	98.986	68.601
Price per ton of cane (USD t^{-1})	40.72	44.98	41.52	50.44	42.40
Cane cutters (#)	2,892	589	2,568	918	68,365
Factory efficiency (%)	83.820	80.497	83.548	84.643	82.744
Factory yield (%)	10.877	11.488	11.194	13.728	11.175
Sugar mil products	Raw Muscovado Compost Hydrolyzed bagasse	Raw Refined Compost Ethanol	Raw Ethanol Compost Cogeneration	Raw Compost	Raw Refined Muscovado Compost Ethanol Cogeneration
Sucrose losses (%)	2.085	2.776	2.197	2.479	2.322
Oil per ton of sugar (L)	1.150	0	0	0	4.801
Steam consumption per kilogram of cane	0.572	0.509	0.556	0.571	0.527
Electricity generation per ton of cane (kWh)	15.829	22.069	86.194	16.013	23.204
Productivity index, cane area (ha) per produced sugar (t)	0.124	0.095	0.102	0.073	0.130

Carbon Footprint Indicator

Evaluating GHG emissions, or the carbon footprint (CF) of this industry, is the second indicator to be considered. This corresponds to the environmental criterion of sustainability and its units are kg CO_2 equivalent kg $sugar^{-1}$ (CHAUHAN ET AL., 2011). The CFs of the systems under study were obtained from GARCÍA ET AL (2016). System borders and production stages are the same as those considered for the Fossil Fuel Use indicator. Methodology details and all data for the case studies can be found in GARCÍA ET AL. (2016).

Water Use Indicator

The water required for producing 1 kg of sugar cane varied from 89 to 118 kg. This measures the amount of cubic meters of water required to produce 1 kg of sugar, and includes water used for irrigation and cane processing (SANTILLÁN-FERNÁNDEZ ET AL., 2014). The water use indicator was calculated according to the Hydric Footprint (HF) methodology created by HOEKSTRA & CHAMPAGAIN (2008). The HF includes green, blue and grey waters. Green water is rainwater that evaporates and is transpired (evapotranspiration) during plant growth in crops used for production of ethanol and other biofuels. Blue water is superficial (lakes and rivers) and subterranean water used for crop irrigation and factory processing. Grey water is necessary to dilute pollutants from industrial processes to environmentally safe levels. We decided to consider total water use as the sum of green and blue water used in the process, in accordance with FINGERMAN ET AL. (2010) and MEKONNEN & HOEKSTRA (2011).

To estimate the volume of green water, evapotranspiration was calculated using the CROPWAT software developed by the FAO (FAO, 2014a) and yearly average precipitation was obtained from FAO meteorological stations reported in CLIMWAT (FAO, 2014b). Water use during the industrial stages considered was 59 m^3/ton of sugar cane.

Agro-industrial Yield

The Agro-industrial Yield indicator is defined as kg of sucrose per hectare. It is calculated by multiplying raw material production (tonnes of sugar cane per hectare) by factory productivity (kg of sugar per ton of sugar cane). Data were obtained from the UNC (2015).

Human Development Index (HDI)

The sugar agro-industry represents important social benefits such as job creation and local development. However, reliable data for direct and indirect job generation are difficult to obtain. Hence the Human Development Index (HDI) was included as a social dimension that measures development conditions such as income, gender gaps, public infrastructure, education, location and other factors (NEUMAYER, 2001; CILINGIRTÜRK & KOÇAK, 2018). This indicator is calculated at a local scale, and data were obtained from the UNDP (2014) for each municipality where the sugar mills under study are located.

Production cost

The economic cost per raw material unit indicator is expressed in Mexican pesos and USD per ton of sugar cane (\$ ton^{-1}). Data for the study systems was obtained from UNC (2015) and CONADESUCA (2015) for the 2014/2015 harvest season.

Product Diversification

An integrated production of sugar with co-generation, ethanol and byproducts as *Potential Production Processes* (NGUYEN ET AL., 2015) could offer a viable solution to a sustainable sugar cane industry (MONCADA ET AL., 2013). Since 1970, sugar cane producing countries, have adopted product diversification and reconversion policies and include introducing other crops in sugar cane lands, elaborating non-traditional products from sugar cane such as panela and rum, high quality molasses and fodder in sugar mills, and higher use of by-products such as bagasse, molasses, filter mud, vinasses, trash and harvest residues. Product diversification in the sugar agro-industry is a highly complex project that has been evaluated as a competitive techno-economic alternative in several sugar economies to increase incomes and counter volatile global sugar prices. Production costs and environmental impacts are diminished when residues and sub-products are converted into raw materials for new productive cycles such as cogeneration of ethanol. A product diversification index is suggested as one of the main indicators (Table 2).

Table 2. Diversification index factors (Aguilar-Rivera, 2014)

Sugarcane crop field	Sugar mill
Sugarcane productivity (tha^{-1})	Sugar mill yield (factory yeld (%)
Farms with access to credit (%)	Sucrose recovery rate (%)
Irrigation (%)	Total time loss (%)
Ratoon (%)	Sucrose% cane
Income diversification (%)	electricity sold (KWh t $cane^{-1}$)
Farm size (ha)	Petroleum consumed in sugar mill (L t $cane^{-1}$)
Land tenure (% public)	Production of co-products and byproducts (#)

Using data available at the conceptual design stage, the framework of sustainability index can be applied to assess the sustainable development of the sugar industry *as sustainable, potentially sustainable, weak sustainability and potentially unsustainable.*

3.2. Constructing the index

Indicators, or indices, can be designed using the analytical hierarchy process (AHP) proposed by Saaty (1990, 2008, 2013) because it integrates criteria and objectives incorporating subjective judgment and information in a single indicator. Each criterion is weighted, based on its importance; the sum of the weights is normalized to unity. For each criterion, the alternative solutions are assigned scores based on quantitative or qualitative considerations. The decision outcome is then determined by the weight placed on each criterion and the numerical scores assigned to each alternative (Schaidle et al., 2011). The AHP consists of three fundamental stages: 1) Structuring a complex problem as a hierarchy of objectives, criteria and alternatives; 2) Comparing elements in each hierarchical level by pairs to each element of the previous level; 3) Vertical synthesis of judgements about the different hierarchy levels (Yakovleva et al., 2012; Cobuloglu & Büyüktahtakin, 2015; Veisi et al., 2016). The AHP is particularly effective for those cases when there are multiple options and when the criteria have different units and scales (Nikodinoska et al., 2015). The multi-criteria decision method is employed to determine weights of criteria and related sub-criteria (Subramanian & Ramanathan, 2012). It is necessary to determine the relative importance of each factor and criteria considering that they are part of a hierarchy in a real decision-making situation and answering a complex question (Schaidle et al., 2011). This comparison by pairs then leads to constructing the Saaty matrices (A=akl), through which the corresponding priority vectors are estimated (w1...wk...wn). Saaty developed a scale from one to nine to perform these comparisons and determine the relative weight of each pair of factors, where 1 shows that both attributes have similar importance and 9 shows that the first attribute is absolutely more important than the second one (Ishizaka & Labib, 2009, 2011) (Fig. 5).

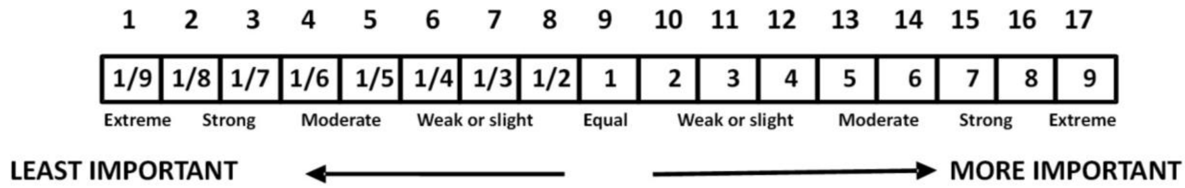

Fig. 5. Hierarchical scale of 17 relative importance of the construction of the comparison matrix between factor pairs or variables (Aguilar et al., 2012)

Accordingly, a matrix with the following structure is generated (Saaty matrix):

$$A_k = \begin{bmatrix} a_{11k} & a_{12k} & \cdots & a_{1nk} \\ a_{21k} & a_{22k} & \cdots & a_{2nk} \\ \cdots & \cdots & a_{ijk} & \cdots \\ a_{n1k} & a_{n2k} & \cdots & a_{nnk} \end{bmatrix}$$

where a_{ijk} represents the value obtained from comparing attribute *i* and attribute *j* for individual *k*.

This square matrix combines two fundamental properties: the main diagonal is composed of ones (a_{ijk}=1 for all *i*), and reciprocity is verified by comparing each pair (if a_{ijk}=x, then a_{jik}=1/x).

Values attributed to all pair comparisons represent how they are weigthed: $a_{ijk}=w_{ik}/w_{jk}$ for all values of *i* and *j*. The Saaty matrix can therefore also be expressed as:

$$A_k = \begin{bmatrix} \frac{w_{1k}}{w_{1k}} & \frac{w_{1k}}{w_{2k}} & \cdots & \frac{w_{1k}}{w_{nk}} \\ \frac{w_{2k}}{w_{1k}} & \frac{w_{2k}}{w_{2k}} & \cdots & \frac{w_{2k}}{w_{nk}} \\ \cdots & \cdots & \frac{w_{ik}}{w_{jk}} & \cdots \\ \frac{w_{nk}}{w_{1k}} & \frac{w_{nk}}{w_{2k}} & \cdots & \frac{w_{nk}}{w_{nk}} \end{bmatrix}$$

When all total priorities for all alternatives have been obtained, the AHP allows the error or inconsistency of the paired matrix to be evaluated. If the value is less than 10% it is considered acceptable and robust (Saaty, 1990, 2008; Subramanian & Ramanathan, 2012). A schematic diagram of the sustainability index for the sugar industry is shown in Fig. 6.

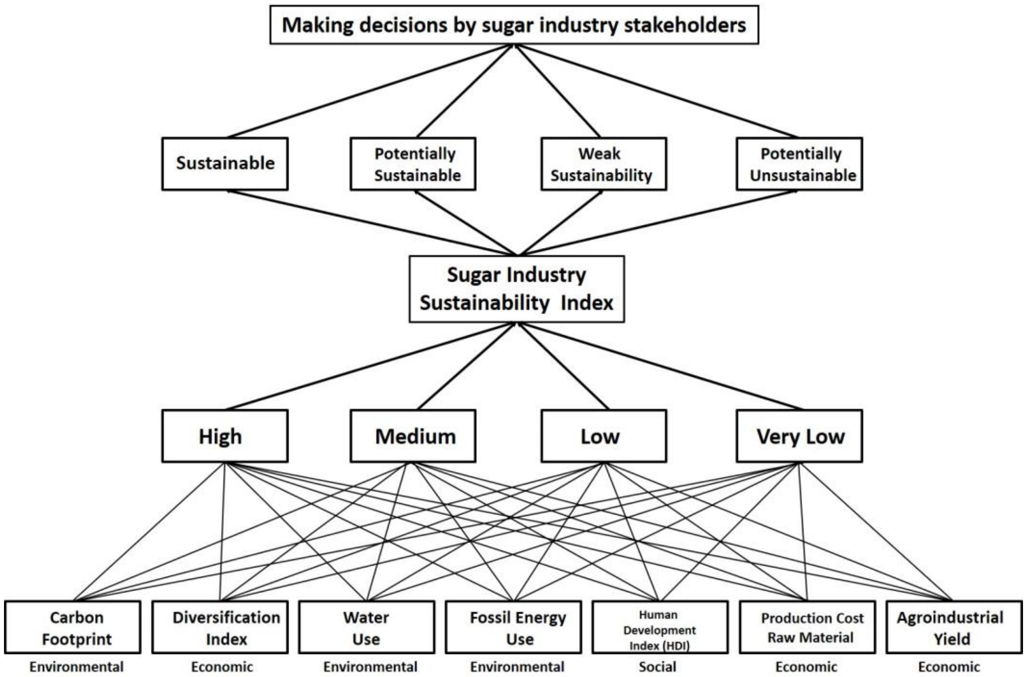

Fig. 6. Sustainability index framework

3. Results and discussion

3.1. Sustainability Indicators

A group of variables and factors were selected to construct a sustainability index for the sugar agro-industry (Table 3). These indicators were chosen because they clearly show the regional and sectorial importance of the sugar agro-industry as a productive activity. The list of indicators provided above was used for the AHP analysis. Integration of indicators and multi-criteria evaluation were followed by the solution to the Saaty matrix (Table 3), factor normalization, weighing and combining relative importance and generating the evaluation tool for each sugar mill Procedures and algorithms available in the *Expert Choice®* software were used to calculate the weight of each factor according to the Saaty scale (ISHIZAKA & LABIB, 2009) (Table 4 and 5) and *Sustainability evaluation tool* integrating factor that determines sustainability (Table 6).

Table 3. Results of sustainability indicators

Sustainability indicators	Central Motzorongo	La Gloria	Tamazula	Emiliano Zapata
Agroindustrial Yield (t. sucrose ha^{-1})	7.022	9.329	14.890	14.545
Diversification Index (1 = high, 0 = null)	0.901	0.861	0.739	0.710
Production Cost (Mexican Peso ton $cane^{-1}$)	348.220	337.34	219.480	289.980
(USD $ ton $cane^{-1}$)	19.350	18.740	12.190	16.110
HDI (sugar mill municipality)	0.747	0.849	0.696	0.696
Water Use (blue water)	0.065	0.392	0.720	0.867
Fossil Fuel Use (MJ fossil kg $sugar^{-1}$)	4.800	3.000	4.600	4.000
Carbon Footprint (kg CO_2 kg $sugar^{-1}$)	0.630	0.450	0.570	0.480

Table 4. Saaty matrix

	Agroindustrial Yield	Cost	HDI	Diversification Index	Water Use	Carbon Footprint	Fossil Energy use
Agroindustrial Yield	1	4	8	2	8	9	8
Cost	$\frac{1}{4}$	1	4	2	8	7	5
HDI	$\frac{1}{8}$	$\frac{1}{4}$	1	5	2	3	2
Diversification Index	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{5}$	1	5	2	3
Water Use	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{2}$	$\frac{1}{5}$	1	2	3
Carbon Footprint	$\frac{1}{8}$	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	1	3
Fossil Energy Use	$\frac{1}{8}$	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1

Table 5. Relative weight of indicators

Indicator	Weight	Indicator
Agroindustrial Yield	0.330	Economical
Diversification Index	0.241	Economical
Cost	0.191	Economical
HDI	0.102	Social
Water Use	0.057	Environmental
Fossil Energy Use	0.048	Environmental
Carbon Footprint	0.032	Environmental

Table 6. Sustainability evaluation tool

Criteria	Factors	Unit	Value and normalization			
			1 (High)	0.75 (Medium)	0.50 (Low)	0.25 (Very low)
E	Agroindustrial Yield	t sugar ha^{-1}	>12.5	9.51–12.5	7.51–9.5	<7.5
			0.33	0.2475	0.165	0.0825
E, T, SE	Diversification Index	–	>0.8	0.79–0.65	0.64–0.55	<0.55
			0.241	0.18075	0.1205	0.06025
SE	Production Cost of Raw Material	USD t^{-1}	< 14	14–19.5	19.5–23	>23
			0.0525	0.039375	0.02625	0.013125
E, T, SE	Human Development Index (HDI)	–	>0.85	0.84–0.75	0.74–0.66	<0.65
			0.102	0.0765	0.051	0.0255
E, T	Water Use	m^3 kg $sugar^{-1}$	<0.25	0.25–0.5	0.5–1.0	>1.0
			0.057	0.04275	0.0285	0.01425
E, T	Fossil Energy Use	MJ kg $sugar^{-1}$	<0.25	0.25–0.5	0.5–1.0	>1.0
			0.048	0.036	0.024	0.012
E	Carbon Footprint	kg CO_2 e kg $sugar^{-1}$	< 0.25	0.25–0.50	0.50–0.75	>0.75
			0.032	0.024	0.016	0.008

E - Enviromental, T - Technological, SE - Socioeconomic

3.2. Indicator results

There are important differences in the kind of factors that determine sustainability for sugar mills and the sugar cane supply zone (Table 7). For economic sustainability, the factors that integrate it have an overall weight of 0.762, because the sugar industry is an agro-industrial system, therefore, has worked with the use of various inputs, fossil fuels and technologies, the agro-industrial yield is the most important factor because the Mexican sugar industry has been structured since 1900 for the production of this unique product (sugar), therefore, productive diversification based on productive industrialization of byproducts, as an option to reduce the risk of international sugar markets, and the reduction of the production cost of raw materials, will contribute significantly to the socio-economic sustainability.

Table 7. Sustainability score from the sugar industry

Sustainability	Score
Economical	0.762
Environmental	0.137
Social	0.102

The factors that integrate environmental sustainability have a low value (0.137) which is the result of indicators from the processing of raw materials, production inputs, and obtaining sugar and ethanol in sugar mills, because this agro-industry has an energy ratio input/output between 8.3 to 10.1 (Alckmin–Governor & Goldemberg–Secretary, 2004; Klimiuk & Pawłowski, 2016; Rathore et al., 2016), however, in the short term, the sugar industry should eliminate practices like harvesting with burning, optimize the use of agrochemicals and fuels, integrate pest and disease control, irrigation and management of rain water, organic fertilizers, agricultural practices, introduce new varieties to do more with less inputs and minimize the generation of greenhouse gases to transit to environmental sustainability

In social sustainability, the value of 0.102 is explained by the fact that the sugar mills have been established for more than 50 years in areas of sugar cane supply, and they had created a collective culture in the inhabitants and producers that only sugar cane and sugar mill are sustainability factors. The Mexican government through public policy has failed to develop an infrastructure for sustainability at regions, municipalities and sugar cane areas.

The Agro-industrial Yield indicator (t. sucrose ha^{-1}) presents better performance in Tamazula and Emiliano Zapata systems, while La Gloria and Motzorongo show much lower productivity. This is basically due to differences in agricultural yield, which averages 106 tons of cane per hectare in the first two cases and 89 and 64 t of cane ha^{-1} respectively in La Gloria and Motzorongo mills over the last 10 years (UNC, 2015).

Regarding the productive diversification indicator obtained from Aguilar (2014), it is clear that Motzorongo and La Gloria mills achieved a higher score. This is explained by the advantages they present with regards to the number of goods they produce (raw and muscovado, manures from filter mud and trash hydrolysed bagasse from Motzorongo and refined sugar and ethanol in La Gloria). The cane Production Cost indicator is lower for Emiliano Zapata and Tamazula mills. In general, the main production cost components correspond to the harvesting stage and fertilizer purchase and application.

The human development index (HDI) groups health, education and income indicators, and presents higher values for La Gloria and Motzorongo mills. However, it is difficult to ascertain whether this value is due to the agro-industrial activities themselves or whether it derives from other productive activities. Likewise, it is not possible to conclude that this difference is due to the more intensive use of manual labour, mainly for harvesting activities. For the social dimension it will be necessary to generate and systemize any information about jobs created specifically by this agro-industry.

The Water Use indicator is higher for the Tamazula and Emiliano Zapata mills, the systems with higher agricultural yields. It is important to note that values indicated in Table 3 correspond to the use of blue water only, which is mainly used for irrigation. Fig. 7 shows total consumption considering blue and green water (rain). Total consumption is higher for Motzorongo mill, mainly because of its low agricultural yield. Lower consumption of blue waters means that this mill is not competing strongly with other uses of water such as human consumption or irrigation of other crops.

The Fossil Fuel Indicator showed that La Gloria and Emiliano Zapata mills have lower energy consumption levels. In all cases, the agricultural stage presents the highest consumption of fossil fuels of all production stages (Fig. 8), followed by the industrial stage, and then the transport stage. Fossil energy is mainly used during diesel consumption for agricultural labour, transporting sugar cane to the factory, production of fertilizers (mainly nitrogenous fertilizers), and cogeneration in mills. Energy use for irrigation is important in La Gloria and Tamazula, and not so relevant in the other mills because Motzorongo has a smaller irrigation area and Emiliano Zapata uses gravity fed irrigation. La Gloria mill presents the lowest consumption of fossil energy because their latest ten-year average shows no fossil fuel use during their industrial stage. This suggests that this mill has taken steps to increase their process efficiency so that their heat requirements are totally fulfilled by the use of bagasse. During the last few years, this tendency has been observed in most sugar mills in Mexico.

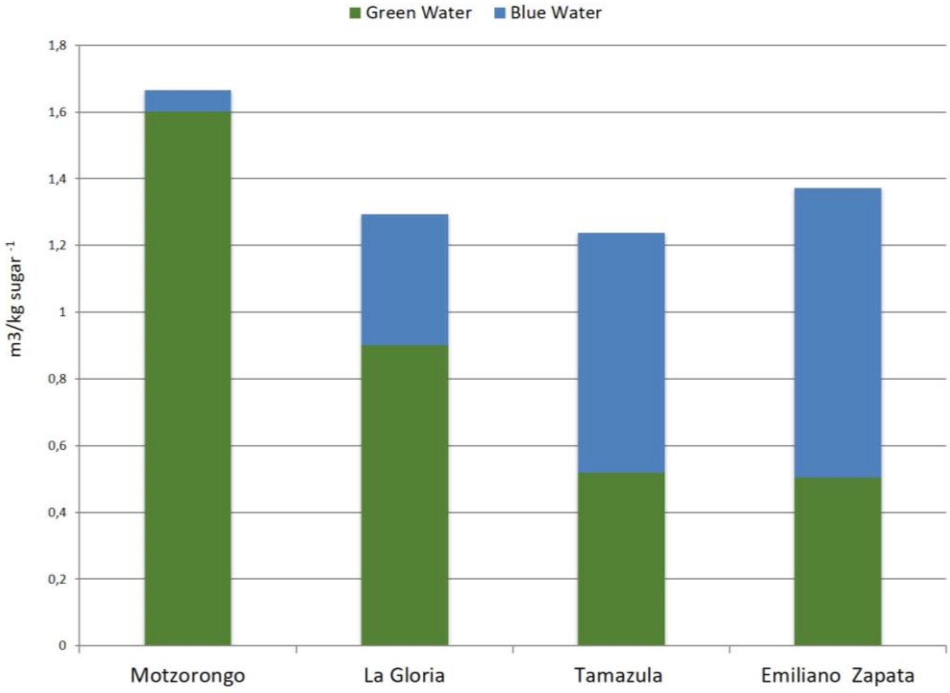

Fig. 7. Water Use Indicator

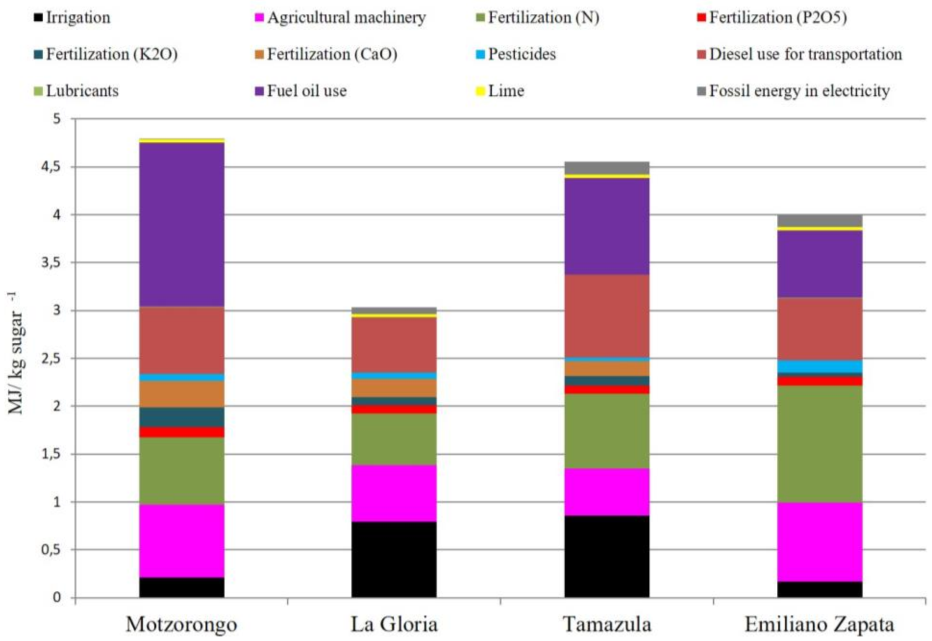

Fig. 8. Components of the Fossil Fuel Use indicator

The Carbon Footprint Indicator was obtained directly from the research of GARCÍA ET AL., (2016) in the Mexican sugar industry. La Gloria and Emiliano Zapata mills have the lowest GHG emissions per kilogram of sugar produced. Just as was described for the Fossil Fuel Use indicator, the agricultural stage presents higher GHG emissions compared to the transport and industrial stages (59 to 74%

of total emissions). In general, the main emission components are fertilizer production and application, use of diesel fuel for agricultural labour, emissions from sugar cane burning for harvest, and consumption of fuel in the factory. García et al., (2016) developed a sensitivity analysis for system parameters, showing that agro-industrial yield has the biggest influence in CF values. Actions aimed at increasing agro-industrial yield (mainly field yield), increasing fertilizer use, diminishing the burned area for manual harvest and eliminating use of fuels in the factory are important for reducing the CF of the sugar agro-industry.

3.3. Sustainability Index

Agro industrial Yield, Diversification Index and Raw Material Production Cost represent 62.35% of total sustainability for all sugar mills included in this study. Tables 8 and 9 and Fig. 9 shows that Emiliano Zapata, La Gloria and Tamazula mills have medium to high sustainability values and Motzorongo's is low.

Table 8. Sustainability index for all case studies (1=high, 0=null).

Sugar Mill	Sustainability Index	
Central Motzorongo	0.58137	Weak sustainability
Tamazula	0.67075	Potentially sustainable
La Gloria	0.68312	Potentially sustainable
Emiliano Zapata	0.71662	Sustainable

Table 9. Sustainability factors of sugar mills

Sustainability/sugar mill	Tamazula	La Gloria	Central Motzorongo	Emiliano Zapata
Economical	73.92%	69.27%	58.45%	72.19%
Environmental	41.24%	57.48%	62.04%	47.08%
Social	50.00%	75.00%	50.00%	100.00%

Fig. 9. Sustainability values of sugar mills

The proposed methodology shows great potential as a valuable complement to classic economic approaches (Brown et al., 2013; Munda, 2016) by quantifying the relative sustainability performance with socio-economic and environmental data from the sugar industry. This approach can be used across the sugar industry in different performance, geographical and temporal boundaries and production technologies to generate a specific sustainability indicator with regards to goals and objectives embedded in the idea of sustainable development.

Emiliano Zapata and La Gloria presented the largest global sustainability index for the mills analyzed here. Of the three components, economic, social and environmental, Tamazula has the highest economic sustainability, Central Motzorongo the highest environmental sustainability and Emiliano Zapata the highest social sustainability. However, Tamazula needs specific actions to improve their environmental and social performance; Central Motzorongo needs actions to increase the profitability of the sugar business and La Gloria needs actions to increase the three aspects of sustainability

The quest for sugar industry sustainability reflects a crucial paradigm shift for the 21st century: 1) new and innovative ways of revitalizing and diversifying the local sugar industry through value-added products, 2) the transition from environmental management to systems design coming up with solutions that integrate environmental, social, and economic factors to radically reduce the use of chemical and fossil inputs, 3) increasing health, equity, and quality of life for all stakeholders according to the 17 Goals and 169 targets of The 2030 Agenda for Sustainable Development (SDGs).

It is essential, as strategic actions for this group of sugar mills, to apply precision agriculture techniques to sugar cane production with the use of basic meteorological data such as precipitation, temperature and evapotranspiration to obtain the potential of soil humidity, along with remote sensing techniques through the Normalized Difference Vegetation Index (NDVI) and GIS to increase the irrigated area with low carbon technologies such as solar energy to obtain a profitable cane yield mainly in Motzorongo with low sustainability. It is necessary to introduce new sugar cane cultivars with easy adaptability to meteorological and edaphic conditions, to eliminate the practice of sugar cane burning during the harvest period because is extend at least in the 90% crop acreage in four sugar mills analyzed and generate pollutants as monoxide carbon (CO), nitrogen monoxide (NO), sulfur dioxide (SO_2) and particulate matter (PM) among others, the soil nutrients are released and this affects the soil health and the good development of the cultivation in the next crop period. (Mugica-Álvarez et al., 2018)

Likewise, the production of organic manures from filter mud, trash, bagasse, ashes and vinasses will be an important nutritional source for the soil. Besides, for Tamazula, La Gloria and Emiliano Zapata mills, with sustainable cane sugar yield (> 90 t ha^{-1}), can join the energetic matrix thought the cogeneration and ethanol production maximizing the use of energy contained in sugarcane with bagasse and trash (leaves and tops) as fuel according the international experiences (Bechara et al., 2018).

5. Conclusions

We propose a systematic framework sustainability index for benchmarking the sugar agro-industry in Mexico. This index is based on a limited group of indicators that were aggregated through a multi-criteria evaluation using the analytical hierarchy process (AHP). The index was used to evaluate four sugar production systems in Mexico. Results show that systems with greater agro-industrial efficiency and a higher diversification index have better sustainability performance. Many actions can be taken to improve sustainability, and the main ones are to increase product diversification, improve access to credit and irrigation and improve raw material quality. It is also important to reduce production costs, increase irrigation efficiency, eliminate fossil fuel use in factories, make fertilizer application more efficient and reduce the area that is burned for manual harvest. This study is relevant because it provides quantitative information to develop the sugar agro-industry more sustainably. Future work must focus on developing more and better indicators, particularly for the social dimension, as well as building new models for indicator integration and weighting.

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References

Acosta-Milch L., Lucht W., Bondeau A., Beringer T. 2011. Integrated assessment of sustainability trade-offs and pathways for global bioenergy production: Framing a novel hybrid approach. *Renewable and Sustainable Energy Reviews*, 15: 2791–2809.

Aguilar Rivera N., Galindo Mendoza M.G., Contreras Servín C., Fortanelli Martínez J. 2012. A methodological approach to sugar mill diversification and conversion. *Ingeniería e Investigación*, 32, 2: 23–27.

Aguilar-Rivera N. 2014. Diversification index of the sugar agroindustry in Mexico *Agricultura, sociedad y desarrollo*, 11, 4: 441–462.

Alckmin-Governor G., Goldemberg-Secretary J. 2004. *Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil*. Government of the State of São Paulo.

Alemán-Nava G.S., Meneses-Jácome A., Cárdenas-Chávez D.L., Díaz-Chavez R., Scarlat N., Dallemand J.F., Ornelas-Soto N., García-Arrazola R., Parra R. 2015. Bioenergy in Mexico:

Status and perspective. *Biofuels, Bioproducts and Biorefining*, 9, 1: 8–20.
Amaya A. 2010. Sugarcane research and technology transfer—strategies for the next decade. *Proceedings – International Society of Sugar Cane Technologists*, 27.
Azapagic A., Perdan S. 2000. Indicators of sustainable development for industry: a general framework. *Process Safety and Environmental Protection*, 78, 4: 243–261.
Barrera I., Amezcua-Allieri M.A., Estupiñan L., Martínez T., Aburto J. 2016. Technical and economical evaluation of bioethanol production from lignocellulosic residues in Mexico: Case of sugarcane and blue agave bagasses. *Chemical Engineering Research and Design*, 107: 91–101.
Bechara R., Gomez A., Saint-Antonin V., Schweitzer J.M., Maréchal F., Ensinas A. 2018. Review of design works for the conversion of sugarcane to first and second-generation ethanol and electricity. *Renewable and Sustainable Energy Reviews*, 91: 152–164.
Brambila-Paz J.D.J., Martínez-Damián M.Á., Rojas-Rojas M.M., Perez-Cerecedo V. 2013. Real options, biorefineries and bioeconomy: the case of bioethanol and sugar. *Agrociencia*, 47, 3: 281–292.
Brown D.G., Verburg P.H., Pontius R.G., Lange M.D. 2013. Opportunities to improve impact, integration, and evaluation of land change models. *Current Opinion in Environmental Sustainability*, 5, 5: 452–457.
Buchholz T.S., Volk T.A., Luzadis V.A. 2007. A participatory systems approach to modeling social, economic and ecological components of bioenergy. *Energy Policy*, 35: 6084–6094.
Büyüközkan G., Karabulut Y. 2018. Sustainability performance evaluation: Literature review and future directions. *Journal of Environmental Management*, 217: 253–267.
Cardoso T.F., Watanabe M.D., Souza A., Chagas M.F., Cavalett O., Morais E.R., Bonomi A. 2018. Economic, environmental, and social impacts of different sugarcane production systems. *Biofuels, Bioproducts and Biorefining*, 12, 1: 68-82.
Cavalett O., Junqueira T.L., Dias M.O.S., Jesus C.D.F., Mantelatto P.E., Cunha M.P., Franco H.C.J., Cardoso T.F., Filho R.M., Rossell C.E.V., Bonomi A., 2011. Environmental and economic assessment of sugarcane first generation biorefineries in Brazil. *Clean Technologies and Environmental Policy*, 14: 399–410.
Chauhan M.K., Chaudhary S., Kumar S. 2011. Life cycle assessment of sugar industry: A review. *Renewable and Sustainable Energy Reviews*, 15, 7: 3445–3453.
Chávez-Rodríguez M.F., Nebra S.A. 2010. Assessing GHG Emissions, Ecological Footprint, and Water Linkage for Different Fuels. *Environmental Science & Technology*, 44: 9252–9257.
Ciegis R., Ramanauskiene J., Startiene G. 2015. Theoretical reasoning of the use of indicators and indices for sustainable development assessment. *Engineering Economics*, 63, 4: 33–40.
Cobuloglu H.I., Büyüktahtakın İ.E. 2015. A stochastic multi-criteria decision analysis for sustainable biomass crop selection. *Expert Systems with Applications*, 42, 15: 6065–6074.
Conadesuca. 2015. Sistema de Información de Costos de Producción de Caña de Azúcar. Secretaría de Agricultura, Ganadería, Desarrollo Rural y Pesca. México.
Conadesuca. 2018. Sistema de Información de Costos de Producción de Caña de Azúcar. Secretaría de Agricultura, Ganadería, Desarrollo Rural y Pesca. México.
Contreras A.M., Rosa E., Pérez M., Van Langenhove H., Dewulf J. 2009. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. *Journal of Cleaner Production*, 17, 8: 772–779.
de Oliveira Neto G.C., Pinto L.F.R., Amorim M.P.C., Giannetti B.F., de Almeida C.M.V.B. 2018. A framework of actions for strong sustainability. *Journal of Cleaner Production*. 196: 1629–1643.
Eggleston G., Lima I. 2015. Sustainability issues and opportunities in the sugar and sugar-bioproduct industries. *Sustainability*, 7, 9: 12209–12235.
Elghali L., Clift R., Sinclair P., Panoutsou C., Bauen A. 2007. Developing a sustainability framework for the assessment of bioenergy systems. *Energy Policy*, 35: 6075–6083.
FAO (Food and Agriculture Organization). CROPWAT model (Online). Available at: http://www.fao.org/nr/water/infores_databases_cropwat.html. 2014a.
FAO. CLIMWAT for CROPWAT. Available at: http://www.fao.org/nr/water. 2014b.
Fingerman K.R., Torn M.S., O'Hare M.H., Kammen D.M. 2010. Accounting for the water impacts of ethanol production. *Environmental Research Letters*, 5: 014020 7.
Finguerut J. 2010. Sustainability in sugarcane processing in Brazil. *Proceedings – International Society of Sugar Cane Technologists*, 27.
Gan X., Fernandez I.C., Guo J., Wilson M., Zhao Y., Zhou B., Wu J. 2017. When to use what: Methods for weighting and aggregating sustainability indicators. *Ecological Indicators*, 81: 491–502.
Gani F.Q., Hantoro R. 2018. An ANP (Analytic Network Process)-based Multi-Criteria Decision Approach for The Selection of Sugar-Cane Industry Development. *IPTEK Journal of Proceedings Series*, 1: 54–58.
García C.A., Fuentes A., Hennecke A., Riegelhaupt E., Manzini F., Masera O. 2011. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. *Applied Energy*, 88: 2088–2097.
García C.A., García-Treviño E.S., Aguilar-Rivera N., Armendáriz C. 2016. Carbon footprint of sugar production in Mexico. *Journal of Cleaner Production*, 112: 2632–2641.
Gasparatos A., Scolobig A. 2012. Choosing the most appropriate sustainability assessment tool. *Ecological Economics*, 80: 1–7.
Gnansounou E., Alves C.M., Pachón E.R., Vaskan P. 2017. Comparative assessment of selected sugarcane biorefinery-centered systems in Brazil: A multi-criteria method based on sustainability indicators. *Bioresource technology*, 243: 600–610.
Goldemberg J. Teixeira C.S., Guardabassi P. 2008. The sustainability of ethanol production from sugarcane. *Energy Policy*, 35: 2086–2097.
Grigoletto-Duarte C., Gaudreau K., Gibson R.B., Malheiros T.F. 2013. Sustainability assessment of sugarcane-ethanol production in Brazil: A case study of a sugarcane mill in Sao Paulo state. *Ecological Indicators*, 30: 119–129.
Gulisano G., Strano A., De Luca A.I., Falcone G., Iofrida N., Stillitano T. 2018. Evaluating the Environmental, Economic, and Social Sustainability of Agro-Food Systems through Life Cycle Approaches. *Sustainable Food Systems from Agriculture to Industry*: 123–152.
Heinrichs R., Otto R., Magalhães A., Meirelles G.C. 2017. Importance of Sugarcane in Brazilian and World Bioeconomy. [in:] S. Dabbert, I. Lewandowski, J. Weiss, A. Pyka (eds) *Knowledge-Driven Developments in the Bioeconomy*. Springer, Cham: 205–217.
Hoekstra A., Chapagain A. 2008. *Globalization of Water: Sharing the Planet's Freshwater Resources*. Blackwell Publishing.
Ingaramo A., Heluane H., Colombo M., Cesca M. 2009. Water and wastewater eco-efficiency indicators for the sugar cane industry. *Journal of Cleaner Production*, 17, 4: 487–495.

Ishizaka A., Labib A. 2009. Analytic hierarchy process and expert choice: Benefits and limitations. *OR Insight*, 22, 4: 201–220.
Ishizaka A., Labib A. 2011. Review of the main developments in the analytic hierarchy process. *Expert systems with applications*, 38, 11: 14336–14345.
Klimiuk E., Pawłowski A. 2016. Biofuels and sustainable development. [in:] *Biomass for Biofuels*. CRC Press: 11–22.
Lang T., Schoen V., Hashem K., McDonald L., Parker J., Savelyeva A. 2017. The Environmental, Social, and Market Sustainability of Sugar. [in:] D. Barling (ed.) *Advances in Food Security and Sustainability*, 2, Elsevier: 115–136.
Leal M.R.L., Nogueira L.A.H., Cortez L.A. 2013. Land demand for ethanol production. *Applied Energy*, 102: 266–271.
Linnenluecke M.K., Nucifora N., Thompson N. 2018. Implications of climate change for the sugarcane industry. *Wiley Interdisciplinary Reviews: Climate Change*, 9, 1: e498.
Liu G. 2014. Development of a general sustainability indicator for renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, 31: 611–621.
Martínez-Guido S.I., González-Campos J.B., Ponce-Ortega J.M., Nápoles-Rivera F., El-Halwagi M.M. 2015. Optimal reconfiguration of a sugar cane industry to yield an integrated biorefinery. *Clean Technologies and Environmental Policy*: 1–10.
Mekonnen M.M., Hoekstra A.Y. 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15, 5: 1577–1600.
Moncada J., El-Halwagi M.M., Cardona C.A. 2013. Techno-economic analysis for a sugarcane biorefinery: Colombian case. *Bioresource technology*, 135: 533–543.
Mugica-Álvarez V., Hernández-Rosas F., Magaña-Reyes M., Herrera-Murillo J., Santiago-De La Rosa N., Gutiérrez-Arzaluz M., González-Cardoso G. 2018. Sugarcane burning emissions: Characterization and emission factors. *Atmospheric Environment*, 193: 262–272.
Mugica-Alvarez V., Santiago de la Rosa N., Figueroa-Lara J., Flores-Rodríguez J., Torres-Rodríguez M., Magaña-Reyes M., 2015. Emissions of PAHs derived from sugarcane burning and processing in Chiapas and Morelos México. *Science of the Total Environment*, 527: 474–482.
Munda G. 2016. Multiple Criteria Decision Analysis and Sustainable Development. [in:] S. Greco (ed.) *Multiple Criteria Decision Analysis*, Springer, New York: 1235–1267.
Nardo M., Saisana M., Saltelli A., Tarantola S., Hoffman A., Giovannini E. 2005. *Handbook on constructing composite indicators*. OECD Statistics Working Paper.
Neumayer E. 2001. The human development index and sustainability—a constructive proposal. *Ecological Economics*, 39, 1: 101–114.
Nguyen T.L.T., Gheewala S.H., Garivait S. 2008. Full chain energy analysis of fuel ethanol from cane molasses in Thailand. *Applied Energy*. 85: 722–734.
Nguyen T.T., Kikuchi Y., Noda M., Hirao M. 2015. A New Approach for the Design and Assessment of Bio-based Chemical Processes toward Sustainability. *Industrial & Engineering Chemistry Research*, 54, 20: 5494–5504.
Nikodinoska N., Mattivi M., Notaro S., Paletto A. 2015. Stakeholders' appraisal of biomass-based energy development at local scale. *Journal of Renewable and Sustainable Energy*, 7, 2: 023117.
Pereira C.L.F., Ortega E. 2010. Sustainability assessment of large-scale ethanol production from sugarcane. *Journal of Cleaner Production*, 18: 77–82.
Ramankutty N., Mehrabi Z., Waha K., Jarvis L., Kremen C., Herrero M., Rieseberg L.H. 2018. Trends in global agricultural land use: implications for environmental health and food security. *Annual Review of Plant Biology*, 69: 789–815.
Rathore D., Nizami A.S., Singh A., Pant D. 2016. Key issues in estimating energy and greenhouse gas savings of biofuels: challenges and perspectives. *Biofuel Research Journal*, 3, 2: 380–393.
Renouf M.A., Pagan R.J., Wegener M.K., 2013. Bio-production from Australian sugarcane: an environmental investigation of product diversification in an agro-industry. *Journal of Cleaner Production*, 39: 87–96.
Rincón L.E., Becerra L.A., Moncada J., Cardona C.A. 2014. Techno-Economic Analysis of the Use of Fired Cogeneration Systems Based on Sugar Cane Bagasse in South Eastern and Mid-Western Regions of Mexico. *Waste Biomass Valorization*, 5: 189–198.
Rockström J., Steffen W., Noone K., Persson Å., Chapin III F.S., Lambin E.F., Nykvist B. 2009. A safe operating space for humanity. *Nature*, 461: 472–475.
Saaty T.L. 1990. How to make a decision: the analytic hierarchy process. *European Journal of Operational Research*, 48, 1: 9–26.
Saaty T.L. 2008. Decision making with the analytic hierarchy process. *International journal of services sciences*, 1, 1: 83–98.
Saaty T.L. 2013. The modern science of multicriteria decision making and its practical applications: the AHP/ANP approach. *Operations Research*, 61, 5: 1101–1118.
Santillán-Fernández A., Santoyo-Cortés V.H., García-Chávez L.R., Covarrubias-Gutiérrez I., Merino A. 2016. Influence of drought and irrigation on sugarcane yields in different agroecoregions in Mexico. *Agricultural Systems*, 143: 126–135.
Santoyo-Castelazo E., Azapagic A. 2014. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production,* 80: 119–138.
Sarker T.C., Azam S.M.G.G., Bonanomi G. 2017. Recent advances in sugarcane industry solid by-products valorization. *Waste and Biomass Valorization*, 8, 2: 241–266.
Schaidle J.A., Moline C.J., Savage P.E. 2011. Biorefinery sustainability assessment. *Environmental Progress & Sustainable Energy*, 30, 4: 743–753.
Schmitz T.G., Lewis K.E. 2015. Impact of NAFTA on US and Mexican Sugar Markets. *Journal of Agricultural and Resource Economics*, 40, 3: 387–404.
Sentíes-Herrera H.E., Gómez-Merino F.C., Valdez-Balero A., Silva-Rojas H.V., Trejo-Téllez L.I. 2014. The Agro-Industrial Sugarcane System in Mexico: Current Status, Challenges and Opportunities. *Journal of Agricultural Science*, 6, 4: 26–54.
Sentíes-Herrera H.E., Trejo-Téllez L.I., Gómez-Merino F.C. 2017. The Mexican sugarcane production system: History, current status, and new trends. *Sugarcane: Production systems, uses and economic importance*: 39–71.
Shukla S.K., Yadav S.K. 2017. Sustainability of smallholder sugarcane growers under changing climatic scenario. *Current Advances in Agricultural Sciences (An International Journal)*, 9, 2: 197–203.
Silalertruksa T., Gheewala S.H., Pongpat P. 2015. Sustainability assessment of sugarcane biorefinery and molasses ethanol production in Thailand using eco-efficiency indicator. *Applied Energy*, 160: 603–609.
Silva M., Marques P., Coelho L., Nestler H., Castro P., Galhano C. 2018. Promoting Sustainability Through Agro-industrial Waste Valorisation. [in:] F. Alves, W. Leal Filho, U. Azeiteiro (eds) *Theory and Practice of Climate Adaptation*. Springer, Cham: 363–373.
Subramanian N., Ramanathan R. 2012. A review of applications of Analytic Hierarchy Process in operations

management. *International Journal of Production Economics*, 138, 2: 215–241.
Talukdar D., Verma D.K., Malik K., Mohapatra B., Yulianto R. 2017. Sugarcane as a Potential Biofuel Crop. [in:] Ch. Mohan (ed.) *Sugarcane Biotechnology: Challenges and Prospects*. Springer, Cham: 123–137.
Tomei J. 2015. The sustainability of sugarcane-ethanol systems in Guatemala: Land, labour and law. *Biomass and Bioenergy*. 82: 94–100.
UNC (Unión Nacional de Cañeros A.C.). 2015. Estadísticas de la agroindustria azucarera.
Veisi H., Liaghati H., Alipour A. 2016. Developing an ethics-based approach to indicators of sustainable agriculture using analytic hierarchy process (AHP). *Ecological Indicators*, 60: 644–654.
Walter A., Dolzan P., Quilodrán O., de Oliveira JG., Da silva C., Piacente F. Segerstedt A., 2011. Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. *Energy Policy*, 39: 5703–5716.
Wang J.J., Jing Y.Y., Zhang C.F., Zhao J.H. 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, 13, 9: 2263–2278.