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Sustainability assessment of ethanol production from two crops in Mexico

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ABSTRACT

First generation ethanol production from two crops, sugarcane and sorghum in four modalities, could be done considering the sustainability level of each modality. We studied two ethanol production modalities from sugarcane, the first from molasses while the second from direct juice; as well as two ethanol production modalities from sorghum, one from a high crop yield and the other from a medium crop yield. To find the modality with the highest sustainability, we developed a sustainability index integrated by six indicators applied in all lifecycle stages of each crop modality considering: greenhouse gas emissions (GHG), land use, water use, energy balance, ethanol production costs and the number of employments generated. We found that sensitivity analysis shows water use is the most sensitive indicator although this sensitivity to the weight factor of each indicator is not large enough to produce significant changes. We also found that production of sugarcane ethanol from direct juice has the highest sustainability index; therefore it would be the most sustainable modality, especially in Mexican regions where abundance of rainwater takes place. It requires 52% less blue water, involves 10.6 times less land use, has 28% less Greenhouse Gas emissions, generates 11% more employments, and its unit costs are 3.5% lower than sugarcane ethanol from molasses –this last one being the current modality Mexico uses to produce ethanol.

1. Introduction

Energy sources diversity, mitigation of GHG emissions and other pollutants that have a negative impact on the environment and inhabitants's health are some of the features an energy system must have to be sustainable [1,2]. In this regard, the renewable energy sources have been considered as alternatives which can meet these characteristics [3]. Bioenergy is the final energy obtained from organic matter produced by living organisms known as biomass [4,5]. Bioenergy is a highly versatile modality of energy, as it produces heat, electric power, and liquid-based fuels for transportation. Its sustainable production and use can be renewable, may have a lower impact on the environment, can minimize the emissions of Carbon Dioxide equivalent (CO_{2e}), and can also be socially and economically beneficial, for instance, by diversifying rural economies and providing employment opportunities throughout supply chains [6].

One sort of bioenergy that can be used to modify the energy system – particularly in the transport sector – is ethanol, an alcohol which production derives from the fermentation and distillation of raw materials containing sugars or starch, and it is used as a fuel or blended with gasoline for spark-ignition vehicles [7]. Ethanol can be classified as a first or second generation fuel depending on the raw material used in its production [8]. Nevertheless, the technology used to produce second-generation ethanol, which uses residues containing lignocellulosic biomass as raw material, is just starting to be financially competitive [5,9].

Since the transport sector in Mexico is highly dependent on gasoline and current gasoline imports represent 48% of the country's consumption [10], the debate on the convenience of using ethanol in this Mexican sector has reignited in recent years [11–13]. In 2014, a paper titled "Analysis and Proposal for the Anhydrous Ethanol Blending in the Gasoline Sold by PEMEX" was published, aiming to introduce gasoline-ethanol blends in some cities of the country [14]. Under the Energy Sector Program 2013–2018 PEMEX launched a

Abbreviations: CO_{2e}, Carbon Dioxide equivalent; CONACyT, Consejo Nacional de Ciencia y Tecnología; DGAPA, Dirección General de Asuntos del Personal Académico; EJDE, Direct Juice-Ethanol; EMB, Molasses-based ethanol; FAO, Food and Agriculture Organization; GHG, Greenhouse Gases; GJ, Gigajoule; ha, hectare; IEPS, special tax on production and services; IFEU, Institute for Energy and Environmental Research; kg, kilogramme; L, Liter; LCA, Life Cycle Assessment; MXN, Mexican Peso; N_2O, Nitrous oxide; PEMEX, Petróleos Mexicanos; RED, European Renewable Energy Directive; SIAP, Sistema de Información Agroalimentaria y Pesquera; SEN, National Electrical System; t, Tonne; TJ, Terajoule; UNAM, Universidad Nacional Autónoma de México; USD, US Dollar; VIOCS, Vinculo Informático para la Obtención de Costos de Producción; WF, Water footprint

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bidding to acquire anhydrous ethanol to blend with regular gasoline [15,16].

It is of relevance to acknowledge that first-generation ethanol can pose negative environmental impacts [5]. Particularly, the following effects have been alerted: 1) CO_2 emissions increase due to land use change [17] , 2) biodiversity-loss-related effects due to the deforestation growth, and 3) the impacts due to the use of monocultures can pose a food safety threat when competing for food growing soils, which can also cause soil erosion and water resources depletion [5]. Ethanol has also generated doubts on how to mitigate GHG and as a replacement for fossil fuel. Several analyses on GHG emissions and energy balances focusing on the life cycle [18–26] have been conducted, showing different results, which were contradictory at times. Therefore, it is relevant to analyze how the first-generation biofuels are produced in order to identify the chief aspects affecting sustainability.

Different analysis proposing methods to assess and analyze energy and the bioenergy's sustainability exist in literature [27–32]. Overall, sustainability assessment must be conducted by considering environmental, economic and social aspects. Similarly, the methods present two highly relevant stages in the assessment process. The first one implies a sustainability criteria definition and their indicators, while the second stage involves indicator integration aspects, where multi-criteria methods [27,28,33], fuzzy logic [29,34], or else, the sustainability index creation can be used [35].

It is well known that any sustainability assessment method must consider all its life span, that is, from the extraction of raw material, transport, production, delivery, use and reutilization, to the final waste disposal [36].

The development and use of indicators turn out to be useful tools to assess the processes sustainability in a system as well as to benchmark one or more modalities that generate the same product [27,37–41]. In this regard, sustainability criteria and indicators have been developed to differentiate sustainable biofuels from those which are not [27,28,40,42].

The ethanol production sustainability in Brazil has been assessed by various authors, among them Smeet [43] assessed sugarcane ethanol production sustainability in Brazil, with a set of 17 sustainability criteria searching for existing bottlenecks to attain the Dutch sustainability certification of the sugarcane ethanol production [43]. There are other proposals [7,44,45] aiming to show or recommend ethanol production´s regional-level sustainability improvements in Brazil by collecting data on the GHG mitigation, energy balance, change in the land use or demand for land, air pollutant emissions, water use and other materials at times, and by considering or not socio-economic aspects such as jobs-creation and profitability. There are also other types of analyses found in literature which despite of not being sustainability assessments, they evaluate environmental, economic and social aspects [46–48].

This paper´s main aim is to present a sustainability analysis based on the bioenergy´s conceptual frameworks by using first-generation ethanol technologies and a sustainability index comprising a reduced number of criteria and indicators which allow the identification of the system´s components contributing to its sustainability in a critical manner. An overall approach presenting the social, environmental and economic dimensions is conducted in parallel with the study of all the production system´s elements (raw material production, conversion technology and transportation stages) emphasizing the effects of the ethanol production with two different raw materials.

2. Analyzed crops and first-generation ethanol production technologies

2.1. Sugarcane and grain sorghum growth potential

Since the corn use for biofuel production is legally prohibited in Mexico [12], the other two raw materials highly viable for the ethanol production with first-generation technologies identified herein are sugarcane and grain sorghum. These materials are also the ones to be used for the production of ethanol which shall be blended with gasoline in the storage depots.

As per the analysis [49] in which the technical potential for new cultivation land areas in Mexico for sugarcane and grain sorghum was computed, the sustainable growth of sugarcane cultivation is estimated to attain 2.9 additional millions hectares per year, considering that currently this country grows about 750 thousand sugarcane hectares. As for the grain sorghum, the potential cultivation area could increase 2.6 additional millions hectares on yearly basis, considering that its current cultivation area is 1.8 million hectares, out of which about 75% is seasonal [49].

Four first-generation ethanol production scenarios or modalities are analyzed and evaluated in this paper are described below:

2.1.1. Molasses-based ethanol (EMB)

It is the most widely used sugarcane non-fuel ethanol production process in Mexico [50]. The process starts with sugarcane juice production, which is immediately clarified and concentrated. Subsequently, it is crystallized up to three consecutive times to obtain sugar and molasses products. The quality of molasses obtained from the second and third crystallization is poorer but they have about a 50% of fermentable material. After molasses have been obtained, yeasts are used for their fermentation and the resulting product goes through a distillation process to obtain hydrated ethanol. This is considered as a high-yield ethanol modality. The process includes the sugar and ethanol production from a third crystallization known as produced syrup or molasses. Bagasse is exclusively used in the steam generators to supply the steam demand for sugar production and distillery, residual fuel oil is seldom used. Despite of power being co-generated, it is not enough to fully meet the process demand, see García et al [51].

2.1.2. Direct juice-ethanol with power co-generation (EDJE)

The ethanol production from sugarcane juice in autonomous distilleries is a process which implies grinding the cane, extracting juice, and subsequently treating, concentrating, fermenting and distilling it for the production of hydrated ethanol at 96%. Bagasse is exclusively used in steam generators to supply the required process steam for the distillery. Power which meets the internal demand is co-generated and the surplus is exported to the national electricity system grid [51].

2.1.3. High and medium sorghum

this process start with the grain sorghum grinding to later add purified water and create a mix, then a hydrolysis to release sugars in sorghum is conducted. Afterward, sugars are fermented and later on distilled to obtain ethanol. This crop might turn out to be relevant in the ethanol production since it requires few supplies in the field and can have two harvesting periods throughout the year despite of this activity not being carried out. The dry grinding is considered as an industrial ethanol production technology. Natural gas is the mostly used fuel in the industrial manufacturing, while the power demand is met from the National Electricity System grid. It is worth mentioning that the difference between High and Medium Sorghum modalities lies in their agricultural yield, since the first one implies a greater mechanization and use of synthetic fertilizers. Table 1 displays the field and industry yields.

Lastly, an additional dehydration process using molecular sieves is conducted on the hydrated ethanol obtained from the aforementioned methods to obtain anhydrous ethanol, which is the only one under this form that can be mixed with other gasolines [52].

3. Methodology

The below methodology is proposed for the sustainability assess-