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Bioenergy Potential, Energy Crops, and Biofuel Production in Mexico

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The negative impact of burning fossil fuels on the global climate, uncertainty over the long-term price of fossil fuels—caused in part by geopolitics and pending decisions on the exploration of oil shale and gas, tar sands and arctic oil reserves, and in part by uncertainty over future regulations on greenhouse gas emissions—and the increasing global demand for energy resulting from population growth and economic development drive the need to deploy renewable energy on a large scale. Mexico is a promising country in the development of renewable energy due to its warm and sunny climate, which supports solar energy generation and crop cultivation throughout the year, and its relative abundance of agricultural land that is suitable for energy crops, but not for food crops, thus minimizing competition between food and energy production. With a well developed infrastructure of roads, ports, and industrial centers, and a relatively low cost of labor, Mexico is among the most relevant emerging bioeconomies.

In a recent study, Alemán-Nava et al. [1] reported the current use and future potential of renewable sources in the production of renewable energy, which included solar, hydroelectric, geothermal and wind energy, and bioenergy. However, these alternative sources of energy have not yet been fully exploited in Mexico. According to the Mexican Ministry of Energy (SENER) and the National Energy Balance databases [2], in 2014, Mexico produced 8826 PetaJoule (PJ = 10^{15} J) of energy from the following sources: fossil fuels 91.31% (crude oil 63.42%, natural gas 23.56%, coal 3.44%, and condensates from natural gas production 0.89%), nuclear energy 1.14%, and renewables 7.56% (hydroelectric 1.59%, geothermal 1.47%, solar 0.10%, wind 0.26%, biomass 4.12%, and biogas 0.02%); these statistics indicate that fossil fuels still dominate, and that biomass represents only a small proportion of the total.

While there are multiple renewable alternatives for the generation of electricity, biofuels are currently the only alternative source of liquid transportation fuels, and while the market share of electric cars is expected to increase, airplanes and ships will continue to require liquid fuels. Biomass is among the most promising feedstocks for the production of biofuels in Mexico, since the net emissions of CO_2 are substantially lower compared to the use of both fossil and first-generation biofuels, there is an abundance of biomass, and large-scale biomass production and processing has potential to generate opportunities in different commercial sectors and can contribute to sustainable regional economic development [3, 4]. Furthermore, in recent years, Mexico has made significant changes in public policies to enhance its development of renewable energies. For example, in 2005, the Law on the

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Sustainable Development of Sugarcane Crop was promulgated and gives the necessary guidance for the use of this energy crop [5]. In this context, the Mexican Congress approved the Law and Development of Bioenergetics in 2008 to promote the use of biofuels as bioethanol and biodiesel [6]. The Mexican government and the Energy Regulatory Commission published and approved the Mexican official standard "NOM-016-CRE-2016" allowing for the blending and sale of up to 5.8% (*v*/*v*) of ethanol anhydrous oxygenate in regular and premium gasoline sold by the national oil company Petróleos Mexicanos (PEMEX). The official standard does, however, not include the three major metropolitan areas: Mexico City, Guadalajara, and Monterrey [7, 8].

Valdez-Vazquez et al. [9] studied the distribution and potential bioenergy resources from agricultural activities in Mexico and estimated that in 2010, 75.7 million ton of dry biomass was produced from 20 different crops. The main sources of crop residues were sorghum stover, corn residues (corn stover and corncobs), wheat straw, sugarcane bagasse, agave bagasse, and coffee pulp. They concluded that the identification of the municipalities in which the potential of biomass is high enables accurate estimates of the availability and capacity of bioenergy production from crop residues [9]. Agave recently gained attention in Mexico because of its great potential as bioenergy feedstock, with as major advantage its ability to grow in semi-arid and arid lands due to its great water use efficiency [10, 11]. Additionally, agave bagasse is already available in large quantities as a residue from the production of alcoholic beverages such as tequila and mezcal. Thus, this biomass can be readily used as raw material for biofuel production [12].

The biomass in Mexico can be converted into biofuels, biochemicals, and biomaterials that are co-produced via biomass upgrading in a second-generation biorefinery [13, 14]. However, there are still several technological barriers that limit the full potential of this approach and that are the topics of active research.

We are, therefore, pleased to introduce this special issue of Bioenergy Research on Bioenergy in Mexico. This issue is promoted by the Mexican Thematic Network on Bioenergy (http://rtbioenergia.org.mx). This network belongs to a group formed by the National Council of Science and Technology, CONACYT, Mexico, and is focused on addressing aspects of science, technology, and innovation in bioenergy to stimulate their sustainable large-scale use in Mexico. The articles in the special issue showcase some of the ongoing projects related to bioenergy in Mexico. The special issue contains nine articles about various aspects of the use of different raw materials, including blue agave bagasse, *Agave tequilana* biomass and corncobs; biomass pretreatment; enzymatic hydrolysis of cell wall polysaccharides; biofuel production (bioethanol and hydrogen); economic and energy efficiency analysis of the production of high value-added compounds and biofuels; and strategies for optimizing distributed systems of biomass conversion under uncertainty scenarios. For this reason, this special issue "Bioenergy in Mexico" will inform the readers of the trends and developments in the use of biomass for the production of biofuels in Mexico.

Hernández-Meléndez et al. [15] describe the characterization of different types of blue agave bagasse from large-scale processing in the tequila industry. This biomass was pretreated using an alkaline extrusion process and subsequent enzymatic hydrolysis under moderate conditions. They concluded that the fibrous blue agave bagasse is suitable for alkaline extrusion pretreatment due to its high-crystalline cellulose content. Velázquez-Valadez et al. [16] studied the synergistic effect of a blend of enzymes on the *Agave tequilana* Weber bagasse pretreated using an alkaline-oxidative process. This study demonstrates the efficient alkaline-oxidative pretreatment on *Agave tequilana* Weber bagasse, and the modification of the crystalline structure of cellulose. Moreover, the use of an enzyme blend increases the yield of fermentable sugars compared with the use of a single enzyme. Montiel et al. [17] evaluated the thermo-mechano-chemical process (extrusion pretreatment) and enzymatic saccharification of blue agave bagasse using commercial preparations of enzymes. The results demonstrated that blue agave bagasse can be saccharified efficiently, increasing 73% (69.5 g/L) over the standard process. The concentration of ethanol was 30.8 g/L, representing 78.5% of the theoretical maximum. Farías-Sánchez et al. [18] studied the production of fermentable sugars and hydrogen-rich gas from *Agave tequilana* biomass. They performed a process simulation to determine the optimum process and operating conditions for effective production of H_2. The production of fermentable sugars was 71.1 g/L and 23.3 mol of H_2 from 271.5 g of *Agave tequilana* biomass. Orencio-Trejo et al. [19] reviewed the most recent information on the cellulolytic enzymes obtained from novel cellulolytic strains of Bacillus and Paenibacillus, especially on the various isoenzymes and their kinetic parameters in enzymatic hydrolysis. Orencio-Trejo et al. [20] are the first to report on the production of cellulases and xylanases from a Mexican strain of the fungal species *Talaromyces stollii* and used them for the enzymatic hydrolysis on corn and sorghum stover pretreated with dilute acid at 121 °C for 60 min. The efficiency of enzymatic hydrolysis of pretreated corn and sorghum stover using the enzymes produced by *T. stollii* was higher compared to that using a commercial enzyme preparation derived from *Trichoderma reesei*. Pedraza et al. [21] established a sequential process—thermochemical pretreatment and enzymatic saccharification—using corncobs as raw material and to subsequently produce ethanol from both C5 and C6 sugars, using the ethanologenic strain *Escherichia coli* MS04. The enzymatic hydrolysis yield following pretreatment was 86% (85 g/L), and after this process, the sugars were fermented at 37 °C. They reported an ethanol concentration of 35 g/L, representing a yield greater than 80% of the theoretical value. Santibañez-Aguilar et al. [22] evaluated the financial risk of biofuel supply chains in Mexico under uncertainty scenarios. This study presents a mathematical model for the optimal planning of a distributed system of biorefineries, considering the uncertainty associated with the supply chain operation. They concluded that the distribution of the uncertain data could significantly affect the selection of raw materials, products, and interconnections between supply chains. Also, the proposed approach is demonstrated through its application to the production of biofuels in Mexico, considering various raw materials and products. Romero-García et al. [23] used the biochemical platform of a biorefinery for the production of biofuels (ethanol) and value-added compounds (antioxidants) from olive tree prunings as feedstock. The authors of this study discuss the economic aspects of using olive tree prunings as raw material for producing value-added compounds in small amounts versus large quantities of biofuels. They concluded that taking into consideration aspects other than economic factors, such as sustainability or life cycle analyses (LCA), may stimulate the emerging bioeconomy.

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