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Ethanol from biomass: A comparative overview

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A R T I C L E I N F O

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A B S T R A C T

This work provided an overview of the ethanol production processes from sugarcane, corn and sugar beet in terms of energy indicators, carbon emissions and economic aspects. A description of the bioethanol production process for each feedstock is first presented, providing the basis for the comparative assessment. In general, best indicator values are achieved with sugarcane as feedstock, which allows the lowest requirements of fossil inputs for ethanol production. The cogeneration system of sugarcane biorefineries can provide the energy self-sufficiency to them through the burning of the main coproduct (bagasse). The coproducts of corn and sugar beet ethanol production are normally used as fertilizers or animal feed, and thus, external energy is required for those coproducts conversion usually at the expenses of fossil fuels burning. Energy consumption in the industrial phase of corn ethanol production is even higher when compared to sucrose-based ethanol, since additional steps to convert starch to glucose are required. Such higher energy use supplied by fossil sources contributes to its lowest GHG reduction potential among the biomasses, being sugarcane the most sustainable in this aspect. Average production costs for sugarcane ethanol are also more attractive: around 50–60% lower than those for corn ethanol and 20–30% lower than those for sugar beet ethanol. Although sugarcane seems to be the most advantageous biomass for ethanol production, larger subsides are provided to corn and sugar beet ethanol (especially in USA and EU), contributing to keep USA in the worldwide leadership of ethanol production, even with the less sustainable feedstock.

1. Introduction

Biofuels are seen as sustainable sources to replace fossil fuels, bringing benefits to the environment due to natural resources preservation and greenhouse gases (GHG) mitigation. Although this is a known information worldwide, the consumption of fossil sources has been steadily increasing over the years: above 84% more fossil-fuel carbon emissions were reported from the 1980's to nowadays, being an increase of about 7% just in the beginning of the current decade [1]. The lower initial investments on infrastructure required for the fossil-based power systems when compared to the renewable technologies ones [2] contribute to keep these numbers. Fortunately, the awareness of the global warming issue boosts the attempts to change this scenario through the research and development on GHG emission mitigation technologies, looking also for their cost-effectiveness. The main efforts normally focuses on advancing technologies that enable the decrease of energy consumption while increasing energy conversion/utilization efficiency, as well as the search for fuels with lower carbon content and technology systems able to capture/store CO_2 [3]. In this scenario, bioethanol has been recognized as a viable contender to replace fossil-based fuels in many countries.

The main impact of the bioethanol allocation is in the transport sector. According to IPCC [4], 14% of global GHG emissions in 2010 came from fossil fuel burning (including road, rail, air, and marine transportation), with baseline CO_2 emissions projected to approximately double by 2050. This is a reflection of the increased global passenger and freight activity that should be supported by mitigation measures (e.g., fuel carbon and energy intensity improvements, infrastructure development, behavioral change and comprehensive policy implementation) in order to avoid environmental deterioration, and consequently, affect people's quality of life. Among the alternative fuels within the mitigation options, bioethanol offers an immediate solution because there is no need of modification of the current transport infrastructure, as well as the ethanol combustion engines are already known and widespread.

In this paper, we provide a comparative overview of ethanol from the representative biomasses of the three main worldwide producers: United States of America (USA), European Union (EU) and Brazil. The

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Table 1
World fuel ethanol production ranking and the respective main biomass sources for the year 2015 (modified from [6]).

Country	Ethanol production in 2015 (mi m^3)	% increase (2009–2015)[a]	Main sources
United States	56.05	35%	Corn
Brazil	26.85	8%	Sugarcane
European Union	5.25	33%	Sugar beet
China	3.08	50%	Corn/wheat
Canada	1.65	50%	Corn/wheat
Thailand	1.26	25%	Sugarcane/cassava
Argentina	0.80	35%	Sugarcane
India	0.80	8%	Sugarcane
Rest of the world	1.48	33%	n.a.

[a] Period considered since the international economic crisis.

aspects of energy, emissions and economics were investigated and discussed, in an attempt to bring more recent data for the analyses. Such analyses involved the whole production chain, involving the agricultural and industrial phases, as well as some possibilities for improving the scores of ethanol scenario from the assessed biomasses.

2. Biomass to ethanol: sources and conversion processes

World has been experiencing a continuous increase in biofuel production driven by the targets set by many countries to replace fossil fuels aiming the climate-change mitigation as well as energy security. Important growth in such production has occurred in the Organization for Economic Co-operation and Development (OECD) countries in the last years, predominantly the USA and the EU countries, except by Brazil (non-member country of OECD), which has pioneered the development of an economically competitive national biofuel sector based largely on sugarcane [5]. The subsidies and policies support in the OECD countries were the most important boosters to keep USA and EU at the top list of bioethanol producers (Table 1), while Brazil is within this position especially due to huge availability of sugarcane, a very productive biomass for ethanol production (Section 3). Even though, a considerable drop of 19.5% in Brazilian production occurred in 2011, resulting from the international economic recession of 2009 that caused decrease on investments in this field. Allied to this, three years of crop compromised by climate issues, debts caused by harvest mechanization and exemption policies on gasoline prices contributed to the stagnation of the sector in Brazil, which has affected bioethanol world production (Fig. 1). By still in a recovering process from the crises, Brazil is now responsible for 28% of world ethanol production, behind USA with the expressive portion of

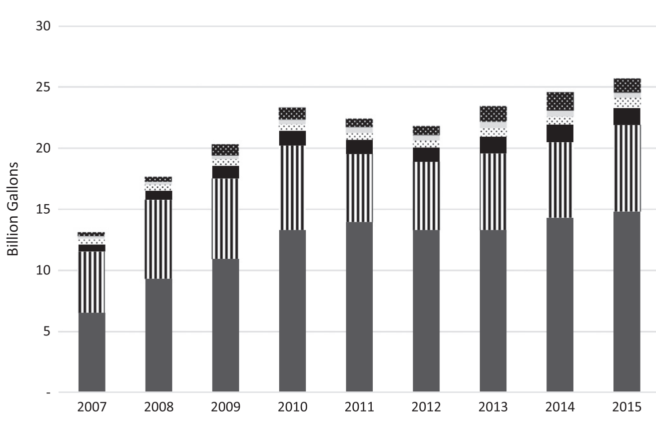

Fig. 1. Global ethanol production by country/region from 2007 to 2015 [7].

58%; EU comes in third place with 5% of world ethanol production.

A wide range of biomasses can be used to produce ethanol since they have considerable sugar content or materials that can be converted into sugar such as starch or cellulose. The most used nowadays are based on sucrose (e.g. sugarcane, sugar beet, sweet sorghum) or starchy feedstocks (e.g. corn, cassava, wheat, rye), being corn, sugar beet and sugarcane among the most productive crops worldwide, either in terms of ethanol yield or in terms of productivity per area. Corn is most ubiquitous crop with the third largest extent in the world [8]; the highest cultivation intensity is located in the USA Corn Belt due to optimum climate conditions. On the other hand, sugarcane and sugar beet keep the highest crop yields among all feedstocks, although their cultivation occurs in very opposed climate conditions: year-round warmth for sugarcane and cooler temperatures for sugar beet [5,8]. In the case of ethanol from sugarcane, Brazil is taken as reference, where an extensive and highly competitive ethanol program has been developed, even with few subsidies. EU leads ethanol production from sugar beet, where France emerged and still remains as the first producer, followed by Germany [9,10]. Recent restrictive measures by EU on bioethanol imports created an opportunity for domestic producers to expand their production and make use of their capacity, contributing to the increase from 55% to 62% of capacity use for bioethanol production [10].

The next sections will approach in detail the ethanol production steps according to the assessed feedstocks (corn, sugarcane and sugar beet) aiming to provide the basis for understanding the comparative overview.

2.1. Maize (Corn)

Maize, or corn, is a grain plant (C4 group) from the Family Poaceae (grass family) and the genus *Zea*, originated in Mexico but widespread to all continents [11]. Maize crops currently occupy about 147 million hectares worldwide [12], being extensively used as human or animal food due to their nutritional properties. The period of growth and development of this grain is limited by water, temperature and solar radiation. Drought, extreme temperatures (lower than 10 °C and higher than 30 °C) and low light intensity affect negatively corn productivity.

Taking as basis the world largest maize ethanol producer (USA), harvesting process is carried out mechanically, where the corn cob is separated from culm so that grains are extracted while cob with straw are left in the fields to improve soil fertility. The grains are transported to the corn mills via truck or rail and can be stored in silos prior their processing. Most ethanol plants' storage tanks are sized to allow storage of 7–12 days' production capacity [13,14]. Conveyors send then the grains to the processing plant, being initially screened to remove debris before milling.

There are two production processes of ethanol from corn: dry milling and wet milling. The initial treatment of the grain differs the processes, but both involves a previous hydrolysis to break down the chains of starch (polymer of a-glucose) for obtaining glucose syrup (d-glucose isomer) (Eq. (1)), which can be converted into bioethanol by yeasts [3,15,16].

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow n\ C_6H_{12}O_6 \quad (1)$$

The wet milling process was the most commonly used up to the 1990's, but nowadays, the dry milling is dominant in the country due to the lower capital costs associated to this technology, accounting for almost 90% of total USA ethanol production [17,18]. In the dry milling process, the whole corn kernel is ground into a powder and mixed with water to form a mash, in which liquefying enzymes (amilase) are added to break down the starch into simple sugars. Ammonia is also added for pH control and as nutrient for the yeast in the posterior fermentation step. The mash is then cooked to avoid bacterial contamination and