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Research review paper

Technological trends, global market, and challenges of bio-ethanol production

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A B S T R A C T

Ethanol use as a fuel additive or directly as a fuel source has grown in popularity due to governmental regulations and in some cases economic incentives based on environmental concerns as well as a desire to reduce oil dependency. As a consequence, several countries are interested in developing their internal market for use of this biofuel. Currently, almost all bio-ethanol is produced from grain or sugarcane. However, as this kind of feedstock is essentially food, other efficient and economically viable technologies for ethanol production have been evaluated. This article reviews some current and promising technologies for ethanol production considering aspects related to the raw materials, processes, and engineered strains development. The main producer and consumer nations and future perspectives for the ethanol market are also presented. Finally, technological trends to expand this market are discussed focusing on promising strategies like the use of microalgae and continuous systems with immobilized cells.

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1. Introduction

The beginning of this century is marked by the large incentive given to biofuel use in replacement of gasoline. Several countries worldwide, including Brazil, United States, Canada, Japan, India, China and Europe, are interested in developing their internal biofuel markets and established plans for use of these biofuels. Such interests are mainly motivated by 1) the rising oil prices and recognizing that the global oil reserves are exhausting fast, 2) concern about fuel emissions, 3) the requirements of the Kyoto Protocol and the Bali Action Plan on carbon emissions, and 4) the provision of alternative outlets for agricultural producers.

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Ethanol, as a clean and renewable combustible, is considered as a good alternative to replace oil (Bai et al., 2008; Almeida and Silva, 2006). Although the energy equivalent of ethanol is 68% lower than that of petroleum fuel, the combustion of ethanol is cleaner (because it contains oxygen). Consequently, the emission of toxic substances is lower (Krylova et al., 2008). Bio-ethanol use as a transportation fuel can also help in reducing CO_2 buildup in two important ways: by displacing the use of fossil fuels, and by recycling the CO_2 that is released when it is combusted as fuel. By using bio-ethanol instead of fossil fuels, the emissions resulting from fossil fuel use are avoided, and the CO_2 content of fossil fuels is allowed to remain in storage. Burning ethanol instead of gasoline reduces carbon emissions by more than 80% while eliminating entirely the release of acid-rain-causing sulfur dioxide (Lashinky and Schwartz, 2006).

This review presents a discussion of current and promising technologies for ethanol production from agricultural products and crops. The market and evolution of worldwide nations on the production of this biofuel are also considered in a subsequent section. Future trends and perspectives to expand this market are discussed mainly emphasizing promissory strategies like the use of microalgae and continuous systems with immobilized cells.

2. Historical background

The use of ethanol as an automotive fuel has a long history. The first prototypes of internal combustion engines built in the nineteenth century by Samuel Morey in 1826 and Nicholas Otto in 1876 were able to use ethanol as fuel (Demirbas et al., 2009). The first car produced by Henry Ford in 1896 could use pure ethanol as fuel and in 1908 the Ford Model-T, the first car manufactured in series, was a flexible vehicle able to use ethanol as a fuel, in the same way as gasoline or any mixture of both (Solomon et al., 2007). The use of bio-ethanol for fuel was widespread used in Europe and the United States until the early 1900s. After the First World War there was a decrease in demand for ethanol, because it became more expensive to produce than petroleum-based fuel, however there was an interest (e.g., from General Motors Corporation and DuPont) in ethanol as both an antiknock agent (i.e., octane enhancer) and as possible replacement for petroleum fuels (Demirbas et al., 2009; Balat and Balat, 2009; Solomon et al., 2007).

Brazil had a pioneering program to produce alcohol for automobile since 1927, when it has installed the first pump alcohol that continued until the early years of the next decade (Bray et al., 2000; Balat and Balat, 2009). However, the fuel ethanol market was revived in the 1970s when, for economic reasons as the global oil crisis and problems in the international sugar market due to overproduction, the National Alcohol Program (ProAlcool) was created in Brazil in 1975. This program was based on the sugarcane use as raw material, and was intended to target the large-scale use of ethanol as a substitute for gasoline (Goldemberg et al., 2008). With substantial government intervention to increase the supply and demand for ethanol, Brazil has developed institutional capacities and technologies for the use of renewable energy in large scale. In 1984, most new cars sold in Brazil required hydrated bio-ethanol (96% bio-ethanol + 4% water) as fuel. As the sugar-ethanol industry matured, policies evolved, and the ProÁlcool program was phased out in 1999, permitting more incentives for private investment and reducing government intervention in allocations and pricing. Although Brazilians have driven some cars that run exclusively on ethanol since 1979, the introduction of new engines that let drivers switch between ethanol and gasoline has transformed what was once an economic niche into the planet's leading example of renewable fuels. Widespread availability of flex-fuel vehicles (promoted through tax incentives) combined with rising oil prices have led to rapid growth in bio-ethanol and sugarcane production since 2000. Today, more than 80% of Brazil's current automobile production has flex-fuel capability (Kline et al., 2008).

In the United States, the combination of raising taxes, a concerted campaign by major oil producers and availability of cheap petrol effectively extinguished ethanol as a transport fuel in the early part of the 20th century (Rossillo-Calle and Walter, 2006). The desire to promote the production and use of bio-ethanol restarted in the early of 1980, largely to revitalize the farming sector at a time of oversupply of agricultural produce (Johnson and Rosillo-Calle, 2007). The United States rebuilt its fuel ethanol industry more gradually than Brazil, and is nowadays the world leader in its production and usage (RFA, 2010). A blended fuel E85 (85% bio-ethanol and 15% gasoline) is used in vehicles specially designed for it. Government has been promoting the development of this blend and several motor vehicle manufacturers including Ford, Chrysler, and GM, have increased the production of flexible-fuel vehicles that can use gasoline and ethanol blends ranging from pure gasoline all the way up to E85.

Currently ethanol is the main bio-fuel used in the world and its use is increasingly widespread, the worldwide prospects are the expansion of the production and consumption of ethanol (Bastos, 2007).

3. Current technologies for ethanol production

3.1. Raw-materials and processes

The biotechnological processes are responsible for the vast majority of ethanol currently produced. About 95% of ethanol produced in the world is from agricultural products (Rossillo-Calle and Walter, 2006). Ethanol production from sugar crops such as sugarcane and sugar beet account for about 40% of the total bio-ethanol produced and nearly 60% corresponding to starch crops (Biofuels Platform, 2010).

Fuel ethanol can be produced from direct fermentation of simple sugars or polysaccharides like starch or cellulose that can be converted into sugars. Thus, carbohydrate sources can be classified into three main groups: (1) simple sugars: sugarcane (Leite et al., 2009; Macedo et al., 2008); sugar beet (Içoz et al., 2009; Ogbonna et al., 2001); sorghum (Yu et al., 2008; Prasad et al., 2007a; Mamma et al., 1995); whey (Dragone et al., 2009; Silveira et al., 2005; Gnansounou et al., 2005; Domingues et al., 2001) and molasses (Roukas, 1996); (2) starches: grains such as maize (Persson et al., 2009; Gaspar et al., 2007); wheat (Nigam, 2001); root crops such as cassava (Kosugi et al., 2009; Rattanachomsri et al., 2009; Amutha and Gunasekaran, 2001); (3) lignocellulosic biomass: woody material (Ballesteros et al., 2004), straws (Silva et al., 2010; Huang et al., 2009), agricultural waste (Lin and Tanaka, 2006), and crop residues (Hahn-Hägerdal et al., 2006).

Ethanol production is usually performed in three steps: (1) obtainment of a solution of fermentable sugars, (2) fermentation of sugars into ethanol and (3) ethanol separation and purification, usually by distillation–rectification–dehydration (Demirbas, 2005). The step before fermentation, to obtain fermentable sugars, is the main difference between the ethanol production processes from simple sugar, starch or lignocellulosic material (Fig. 1). Sugar crops need only a milling process for the extraction of sugars to fermentation (not requiring any step of hydrolysis), becoming a relatively simple process of sugar transformation into ethanol. In this process, ethanol can be fermented directly from cane juice or beet juice or from molasses generally obtained as a by-product after the extraction of sugar (Içoz et al., 2009). In brief, the process of ethanol production from sugarcane consists of preparing, milling of cane, fermentation process and distilling–rectifying–dehydrating. Currently ethanol fermentation is carried out mainly by fed-batch processes with cell recycle, and a small part is produced through multi-stage continuous fermentation with cell recycle (Bastos, 2007).

In processes that use starch from grains like corn, saccharification is necessary before fermentation (Fig. 1). In this step, starch is