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Bioethanol production from renewable sources: Current perspectives and technological progress

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ABSTRACT

Bioethanol is an attractive biofuel having potential for energy security and environmental safety over fossil fuels. To date, numerous biomass resources have been investigated for bioethanol production, which can broadly be classified into sugars, starch and lignocellulosic biomass. However, conversion of biomass into ethanol varies considerably depending on the nature of feedstock, primarily due to the variation in biochemical composition, and so, only a few feedstocks have been exploited commercially. In recent years, the conversion process of biomass has been improved significantly, even though most of these achievements are yet to be implemented in commercial facility. All the major steps in a typical conversion process, particularly fermentation of sugars that is the common step for all biomass, are greatly influenced by microorganisms. A traditional yeast, *Saccharomyces cerevisiae*, and a bacterial species, *Zymomonas mobilis*, are widely used in the ethanol fermentation technology. Many factors affect ethanol production process, and the final yield is directly associated with the optimum conditions of these attributes. This review paper presents an overview on the first and second generation bioethanol production with a particular attention to the potential of various biomass sources, technological approaches, role of microorganisms and factors affecting ethanol production process.

1. Introduction

Energy security and environmental safety are two major issues in the current world that have boosted the demand for an alternative and eco-friendly energy source. It has been anticipated that fossil fuels reserve will be exhausted by next 40–50 years due to rapid increase in the consumption rate of these non-renewable fuels [1]. More importantly, the burning of fossil fuels contributes to the emissions of greenhouse gases as well as global warming that causes climate change, rise in sea level, loss of biodiversity and urban pollution [2–4]. Bioethanol is one of the most promising alternatives to fossil fuels, which can be produced from various renewable sources rich in carbohydrates. Many countries, such as USA, Brazil, China, Canada and several EU member states have already proclaimed commitments to bioethanol programs as attempts to reduce the dependence on fossil fuels, where the former two countries have shown the largest commitments thus far. In response to the current demand, global bioethanol production has been increased over time as shown in Fig. 1a. United states produces the highest amount of ethanol, which has been estimated to be more than half of the total global ethanol produced in 2015 [5]. Total ethanol production in the USA has increased dramatically from 175 million gallons in 1980 to 14810 million gallons in 2015 (Fig. 1b) [5].

Ethanol (C_2H_5OH) has been earmarked as a promising energy source over gasoline (C_7H_{17}) due to having several advantageous properties. Even though one liter of ethanol affords 66% of the energy provided by the same amount of gasoline, the former has a higher octane number (106–110) than the latter (91–96), which enhances the performance of gasoline when blended with ethanol [6]. The higher octane level of ethanol also allows it to be burnt at a higher compression ratio with shorter burning time, resulting in a lower engine knock. In addition, ethanol has a higher evaporation enthalpy (1177 kJ/kg at

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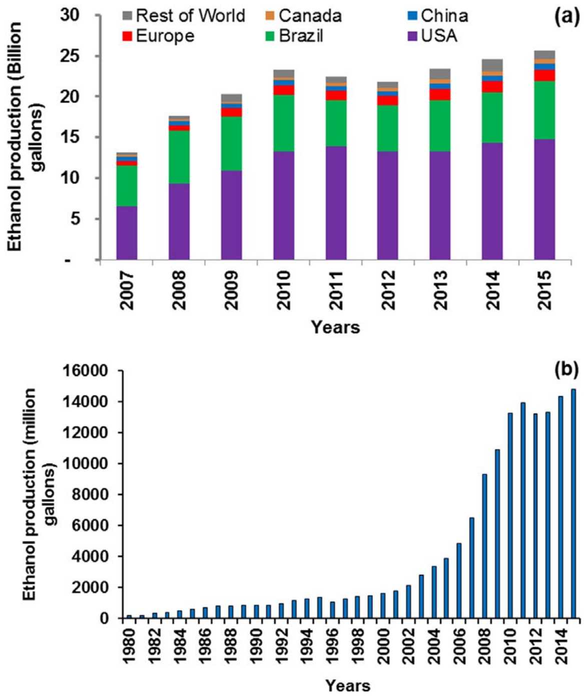

Fig. 1. (a) Global bioethanol production by country or region during last 10 years; (b) Ethanol production by the USA during 1980–2015 (Data were collected from [5]).

60 °C) than gasoline (348 kJ/kg at 60 °C) and a higher laminar flame speed (around 33 and 39 cm/s at 100 kPa and 325 K for gasoline and ethanol, respectively) [7–10]. The higher heat of vaporization of ethanol (840 kJ/kg) than that of gasoline (305 kJ/kg) ensures that the volumetric efficiency of ethanol blend is higher than the efficiency of pure gasoline, thereby improving power output [11].

Bioethanol is an eco-friendly oxygenated fuel as it contains 34.7% oxygen, whereas, oxygen is absent in gasoline. This results in about 15% higher combustion efficiency of ethanol than that of gasoline [12], thereby keeping down the emission of particulate and nitrogen oxides. Compared to gasoline, ethanol contains negligible amount of sulfur, and mixing of these two fuels helps to decrease sulfur content in the fuel as well as emission of sulfur oxide, which is a carcinogen and can contribute to acid rain [13]. Bioethanol is also a safer substitute to methyl tertiary butyl ether (MTBE), which is commonly used as an octane enhancer for gasoline and is added to the latter for its clean combustion so that production of carbon monoxide (CO) and carbon dioxide (CO_2) can be reduced [14]. MTBE has been reported to make its way into ground water that contaminates drinking water causing severe detrimental effect on health [15]. The US Energy Policy Act released an ANPR (Advance Notice of Proposed Rulemaking) in 2000 under the TSCA (Toxic Substance Control Act) to limit the use of MTBE as a gasoline extender [16].

The renewable sources used for generating bioethanol can be classified largely into sugars, starch, lignocellulosic biomass and algae. Ethanol obtained from sugars and starch is referred to as the first generation bioethanol, while lignocellulosic biomass and algae produce second and third generation bioethanol, respectively. Production of third generation bioethanol from algae is still in an immature stage and confined to the laboratory research, while other types of biomass have shown potential as bioethanol feedstocks on commercial scale. On the other hand, conversion of three major types of feedstocks (sugars, starch and lignocellulosic biomass) into bioethanol differs significantly, particularly with regard to the obtainment of sugar solutions. Sugar based raw materials require only an extraction process to get fermentable sugars, while starchy crops need to undergo hydrolysis to convert starch into glucose. Lignocellulosic biomass has to be pretreated before hydrolysis in order to alter cellulose structures for enzyme accessibility.

A comprehensive review on different raw materials, technological approaches and process parameters are expected to play significant roles on the overall research of bioethanol production. Taking into account the above facts, this review paper has been designed to discuss (1) potentials, composition and ethanol production process for different renewable sources (2) technological achievements, (3) role of microorganisms, and (4) effects of different factors on the process. The content of the paper has been confined to the 1st and 2nd generation ethanol.

2. Biomass sources for bioethanol production

2.1. Sugar sources

Sugar based raw materials include some energy crops, such as sugarcane, sugar beet and sweet sorghum; fruits like grape, dates, water melon and apple; and the sugar refinery wastes, namely cane molasses and beet molasses [17]. The major advantages of sugar crops as ethanol feedstocks are high sugar yield and low conversion costs, while the seasonal availability of these crops is the main limiting factor [1]. With regard to the ethanol production, each sugar crop or its industrial wastes have some potential as ethanol feedstock that are summarized in Table 1.

Sugarcane is a C4 plant having high capability to convert solar radiation into biomass [19], and grown in tropical and sub-tropical countries. The stalk juice of sugarcane and by-product of sugar refineries (molasses) has been used as promising feedstocks for bioethanol production over many years. Sugarcane juice is the main feedstock in Brazil that produces about 79% of its bioethanol from this feedstock, whereas molasses is the major ethanol feedstock in India [22,23]. Cane juice has sufficient organic nutrients and minerals, in addition to containing readily fermentable sugars that have made it an ideal raw material for bioethanol. However, sugar concentration in juice varies considerably depending on the variety, maturity and harvest time.

Sweet sorghum is another C4 plant and a potential energy crop for its unique characteristics, including high carbon assimilation (50 g/m^2/day), efficiency to use high water, and ability to accumulate high level of extractable sugars in the stalks [24]. Unlike sugarcane, it can be cultivated in almost all temperate and tropical climate areas and can be developed from seeds [25].

Sugar beet is a major source of sugars in Europe and North America, and used for bioethanol production in France [1]. It has also been successfully introduced in India and currently there are trials being conducted in other tropical countries such as China, Australia, Kenya, South Africa, Brazil and the USA [26]. It grows in temperate climate and require a lower rainfall than in sugarcane [1]. Sugar beet usually produces a root with average weight of 0.5–2 kg, which contains most of the sugars. The concentration of sugars in the sugar beet root varies depending to the variety and growth conditions [26].

Molasses is a dark, viscous and sugar rich by-product of sugar refinery industries. It includes two well-known by-products, namely cane molasses and beet molasses, which are produced from sugarcane and sugar beet in the respective refinery. Molasses are traditionally used as a feed ingredient and binder. Currently it is used as an attractive raw material for bioethanol production. The composition and sugar contents in molasses can vary depending on the processes used for sugar extraction as well as the composition of starting materials [19].

A number of fruits have also been investigated for bioethanol production in different parts of the world that considered mainly the waste fruits in a specific region or production area [27,28]. Usually, good amounts of fruits are discarded at harvest and during marketing due to a low quality or unacceptable physical appearance that make these fruits unfit for human consumption. Fruits are enriched with soluble sugars that can be easily fermented by yeast without any