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Fuel ethanol production from lignocellulosic biomass: An overview on feedstocks and technological approaches

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ABSTRACT

Bioethanol is one of the most promising and eco-friendly alternatives to fossil fuels, which is produced from renewable sources. Although almost all the current fuel ethanol is generated from edible sources (sugars and starch), lignocellulosic biomass (LCB) has drawn much attention in recent times. However, the conversion efficiency as well as ethanol yield of the biomass differs greatly with respect to the source and nature of LCB, primarily due to the variation in lignocellulosic content. Two major polysaccharides in LCB, namely, cellulose and hemicellulose firmly link to lignin and form a complex lignocellulosic network, which is highly robust and recalcitrant to depolymerization. For this reason, generation of ethanol from LCB requires a complicated conversion process that has made it commercially non-competitive. As attempts to exploit LCBs into commercial ethanol production, recent research efforts have been devoted to the techno-economic improvements of the overall conversion process, in addition to screen out promising feedstocks. This review paper presents an overview on the diversity of biomass, technological approaches and microbial contribution to the conversion of LCB into ethanol.

Contents

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1. Introduction

Currently the world is mostly dependent on fossil fuels for meeting its energy demand, and more than 80% of the total global energy is obtained by burning fossil fuels, of which 58% alone is consumed by the transport sector [1]. However, there are three major challenges with these conventional fuels that are being faced by each country. Firstly, rapid increase in the consumption of all kinds of fossil fuels due to the growing industrialization and motorization of the world has resulted fast depletion of these non-reneable fuels [2]. The limited reserves of the fossil fuels have been anticipated to be exhausted by the next 40–50 years [3]. Secondly, fossil fuels has the contribution to greenhouse gas emissions and global warming that cause climate change, rise in sea level, and loss of biodiversity and urban pollution [4]. Thirdly, political crisis, particularly in the Middle East countries, resulted an incidence of oil supply disruption by the major oil producer countries in the 1970 s, which has also led to a re-think of our dependence on fossil fuels, since such crises are unsettling to the energy sector of both the developed and developing nations [5]. Therefore, it is necessary to find out an alternative energy source for our industrial economies and consumer societies by using renewable, sustainable, efficient and cost–effective feedstocks with lesser emission of greenhouse gases, where bioethanol would be an attractive alternative option due to its ease of production and lack of toxicity [6].

Bioethanol is produced from biomass containing free fermentable sugars or complex carbohydrate that can be converted into soluble sugars for making it fermentable. These feedstocks can be divided into three groups, which are sugars (sugar crops and by-products of sugar refineries), starchy crops, and lignocellulosic biomass (LCB). Three groups of feedstocks differ considerably from each other with respect to the obtainment of sugar solutions [7]. Although it is relatively easier to produce ethanol from edible sources (sugars and starch) than that of LCBs, raw material costs and environmental concerns are the major barriers for sustainability of the former, in addition to the rising concern of food versus fuel debate. Furthermore, apart from the commercialization, the gross production of the first generation bioethanol is limited and has been estimated to roughly 3% of the total consumed fuels in the transport sector [8]. For these reasons, recent research efforts have been more focused on LCBs, as they are mostly waste materials, available with low and stable price, rich in carbohydrates, and non–competitive with food chain [9]. Furthermore, lignocellulosic ethanol causes lower net greenhouse gas emissions than first generation ethanol production , thereby reducing environmental pollution [10].

However, bioethanol production from LCB on commercial scale still faces certain technical barriers that make it economically non-competitive when compared to the contemporary sugar and starch based ethanol. The major bottlenecks are the necessity of energy consuming pretreatment process, requiring a number of steps for overall conversion, great diversity in the nature and composition of biomass, inability of natural microorganisms to ferment both hexose and pentose sugars, and formation of inhibitors [8,11–13]. As attempts to overcome these barriers and attain sustainability in lignocellulosic ethanol production, numerous research efforts have been devoted in recent years. These investigations can be broadly categorized into three aspects, such as screening out the promising raw materials from a wide variety of LCBs, development of effective technologies for enhanced ethanol yield and reduced production costs, and development of promising bioagents though screening of natural microorganisms or genetic engineering.

The nature of biomass and its lignocellulosic content are the primary factors affecting the conversion efficiency and ethanol yield of LCB, which further differ in response to the source of biomass [13,14]. One of the most important technological aspects for commercialization of lignocellulosic ethanol is the scale up of the process from laboratory to industrial scale. Similarly, effective improvements on the technology of pretreatment, hydrolysis and fermentation of the biomass processes also require for cost-effective ethanol production on large scale. Although many approaches have been suggested in recent years on these aspects [15–20], there are still some economic, technical and environmental challenges for implementing these efforts on the industrial scale. Microorganism is a crucial factor for the conversion of LCB into ethanol, particularly utilization of both hexoses (glucose) and pentoses (xylose) during fermentation. Since the well-known natural microorganisms are unable to utilize both types of sugars, recombinant microorganisms have been developed through introducing a heterologous metabolic pathway in the natural microorganisms, which are capable of fermenting both xylose and glucose [21–23]. However, some challenges exist with these engineered microorganisms that limit their use on commercial scale ethanol production.

Despite the techno-economic challenges, lignocellulosic ethanol is very close to industrialization. However, inadequate knowledge on the composition of LCB, conversion techniques, technological approaches and microbial roles may limit research efforts, which are being continued to overcome the bottlenecks still need to address towards a sustainable commercialization of LCB based ethanol. This paper presents an overview on the sources and composition of LCBs, technological approaches, and contribution of natural and recombinant microorganisms to the overall conversion process.

2. Source of LCB

As presented in Fig. 1, sources of LCBs can be divided into several groups, which include energy crops (perennial grasses and other dedicated energy crops), aquatic plants (water hyacinth), forest biomass and wastes (softwood and hard wood, sawdust, pruning and bark thinning residues), agricultural residues (cereal straws, stovers and bagasse), and organic fraction of municipal solid wastes (MSW) [24,25]. These biomass resources seem to be the largest, promising, abundant and are available throughout the world (Table 1). LCBs can be used as ethanol feedstocks without