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Biomass availability for lignocellulosic ethanol production

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ABSTRACT

The ethanol industry in North America uses starch derived from corn as its primary feedstock. In order to better understand the geographical distribution of advanced ethanol production, potential sources of lignocellulosic biomass for the process are considered. It is shown that the corn-producing regions of North America already support significant amounts of ethanol production, and that few unexploited sources of corn remain for the industry to utilize. Accessing other sources of sugar, including other types of biomass such as lignocellulosic materials, will become necessary for the industry as it expands, quite apart from the need to meet government mandates. The ability of bioconversion and thermochemical conversion to generate biofuels from lignocellulosic biomass is reviewed. The availability of lignocellulosic residues from agricultural and forestry operations is described, and the potential biofuel production associated with these residues is described. A residue-based process could greatly extend the potential of the ethanol industry to become a substantial contributor to the fuel and energy requirements of North America. It is estimated that ethanol production from residues could provide up to 13.7% of Canada's 2009 transportation fuel demand, and up to 5.2% of the United States' 2010 fuel demand. Utilizing lignocellulosic biomass will extend the geographic range of the biofuel industry, and increase the stability and security of this sector by reducing the impact of localized disruptions in supply. Development of a residue-based industry will help create the technologies needed to process energy crops as North America moves towards greater transportation fuel independence.

1. Introduction

Biomass-based ethanol is well-entrenched in policy as a partial substitute for petroleum-based gasoline requirements. One of the primary benefits of switching to this fuel is that biomass is renewable, and can potentially provide a sustainable fuel supply over the long term [1–3]. In addition, a reduction in net greenhouse gas emissions is generally associated with the production and use of ethanol e.g. [1,2]. The manufacture of this fuel can improve rural employment and diversify rural economies [4,5]. Finally, widespread use of this fuel may increase national security, as domestic biomass is substituted for foreign oil in fuel production [6]. The importance of biofuels and bioenergy within US national energy policy was been underscored by President George W. Bush in his 2007 State of the Union address [7]; the introduction of a renewable fuel standard within the Energy Independence and Security Act (EISA) of 2007 mandates 24 million litres of cellulosic ethanol will be available by the end of 2011, a figure that will increase to billions of litres as the policy rolls

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out towards 2022 [8]. Taken together, these policy drivers provide a strong rationale for pursuing the expansion of the ethanol fuel sector. Such a sector will be constrained by feedstock availability, which has spurred significant interest in alternative feedstocks. This has been the subject of numerable reports including the ‘Billion Ton Report’ prepared by the US Department of Agriculture and the US Department of Energy [9].

Today, the most common feedstocks for the production of ethanol are raw sugars from sugarcane or sugar beet, or starch found in the grain of cereal crops. In the US and Canada, corn is the dominant commercial feedstock used by the ethanol industry. Corn is a well-suited feedstock for ethanol production as it has a relatively high starch content of about 72% by mass of the grain kernel [10]. The yield per ha of corn is very high and increasing, with average production levels in the United States reported at 9.6 t ha^{-1} in 2008, 10.3 t ha^{-1} in 2009, and 9.6 t ha^{-1} in 2010, based on American government conversion factors and statistics for production [11,12]. Using a simplified assumption of 70% starch on a dry-weight basis, this production corresponds to between 6.8 and 7.2 t ha^{-1} of starch that can be utilized in the bioconversion process [13]. By comparison, the second-most common source of starch for industrial processing is wheat, which in the past two years across North America has had average production yields between 3.0 and 3.1 t ha^{-1} [11]. This correlates to starch yields of approximately 2.5 t ha^{-1} [14]. Other sources of starch include sorghum, barley and oats, which relative to corn are less commonly planted and are characterized by low starch yields (ranging between 1.3and 2.3 t ha^{-1}) [10,11,15]. Please note that these yields are typical for North America; in Europe, higher yields are common.

Where conditions are favourable, the ethanol industry may be able to access a larger feedstock supply by promoting increased crop production. This may be achieved by utilizing some of the approximately 400,000 km^2 of estimated excess cropland in the US [9], or by increasing plant productivity through breeding or genetic manipulation. Through the latter approach, it may be possible to produce plants and residues that better meet the industry’s specifications for bioconversion [16]. This approach, however, will take years to implement, and in the near term, it is more likely that existing crops and residues will be the primary feedstock.

Fig. 1 illustrates the relation between the supply of corn biomass and ethanol production in North America. The figure displays corn production through the relative shading of each Canadian province or US state. The darker shading indicates higher production levels. Recent ethanol production capacity figures (from 2007 to 2010) are displayed graphically as nested grey circles, which increase logarithmically in size with increased capacity. The inner circles represent the 2007 figures, while the 2010 production capacity is denoted by the outer circle. The figure confirms that most North American production is centred in areas which are primarily agricultural and produce large amounts of corn. The US states with the highest capacities for ethanol production include Iowa (annual capacity, 13.1 hm^3 a^{-1}), Nebraska (6.9 hm^3 a^{-1}), Minnesota (5.1 hm^3 a^{-1}), Illinois (4.9 hm^3 a^{-1}), and South Dakota (4.0 hm^3 a^{-1}) [17]. The relatively high corn production levels in these states have permitted the growth and expansion of the starch-based portion of the industry within these jurisdictions. Over time, we have observed that the correlation between capacity installations and corn production has risen significantly, which would seem to indicate that feedstock availability, while always a key factor in siting ethanol facilities, is now becoming the dominant factor in determining locations of new capacity.

This figure illustrates some important facts about the ethanol industry: it is well established in almost every jurisdiction that boasts large amounts of corn production, and the availability of feedstock continues to be a strong determinant in siting decisions for additional capacity. Existing and planned production capacity outside of the major corn-producing states is still relatively low, but the potential of wheat and other cereal crops to support the expanding biofuel industry is constrained by relatively low levels of productivity compared to corn, which means that area required to support new capacity may be up to three times what corn-based facilities require. Expansion opportunities for the starch-based ethanol industry are limited, which will provide an increasingly strong impetus for companies to explore other feedstock options.

Part of the difficulty with predicting the growth of the starch-based ethanol industry is that it relies completely upon biomass considered surplus to the food supply of either livestock or humans. It is well documented that crop surplus levels vary from year to year, and that these levels can be affected by localized or diffuse patterns of disturbance [e.g [22]]. Demand for food will thus act as a constraint upon expansion of the industry, an issue which is exacerbated by the ongoing food-vs.-fuel debate.

2. Bioconversion of lignocellulosic feedstocks

An option for expanding the ethanol industry is to utilize lignocellulosic residues from agricultural and forest operations as feedstocks for the process. These residues are a combination of three polymers interlinked in a dense matrix, creating challenges for the bioconversion process [23,24]. Cellulose is a straight chain polymer consisting of units of glucose connected via (1,4)-β-D linkages. Hemicellulose is a heterogeneous material made up of five sugars, including glucose, galactose, mannose, xylose, and arabinose. Lignin is composed of a number of phenolic compounds that may act as an inhibitor the hydrolysis or fermentation of sugars [25,26]. Process complexity is therefore increased compared to the sugar- and starch-based biofuel industries.

In both the US and Canada, lignocellulosic biomass will form the majority of available feedstock for the biorefinery. Implementing a bioconversion system utilizing these feedstocks requires some separation of cellulose and hemicellulose from lignin, followed by hydrolysis of five sugars (glucose, galactose, mannose, xylose, arabinose), compared to the single sugar (glucose) associated with starch [27,28]. Because of the increased complexity of the chemical structure, lignocellulosic-based bioconversion is much more difficult and more expensive. However, lignocellulosic material (while widely used in other applications) does not play an intrinsic role in the food chain and thus a fundamental aspect