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Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis

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ABSTRACT

The effects of five different biomass species and their chemical composition on the overall process efficiency and economic performance considering feedstock availability and feedstock costs to manufacture ethanol from lignocellulose were studied. First is a comparison of ethanol production and excess electricity generated between different biomass species. Results show that, at the same feedstock rate of 2000 Mg day^{-1}, aspen wood has larger ethanol production than switchgrass, hybrid poplar and corn stover, while the excess electricity generated is as follows in increasing order: aspen < corn stover < hybrid poplar/switchgrass. Second, our results show that the ethanol production is largely linear with holocellulose (cellulose plus hemicellulose) composition of the various biomass species. However, the relationship between excess electricity generated and non-holocellulose combustible component is nonlinear. Last, on environmental performance, it is found that the water losses per unit ethanol production are in the following order: aspen wood < corn stover < hybrid poplar < switchgrass. While corn stover is a potential feedstock to produce cellulosic ethanol with the lowest ethanol production cost at the present time, hybrid poplar and switchgrass are the two promising future energy crops.

The effects of plant size analysis showed that the estimated feedstock delivered costs, ethanol production, excess electricity generated and solid and gaseous waste emissions all increase with plant size for the various biomass species. The ethanol production costs decrease with the increase in plant size with optimal plant sizes for corn stover in the range from 2000 dry Mg day^{-1} to 4000 dry Mg day^{-1}.

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1. Introduction

There has been increasing interests in conversion of biomass to fuel grade ethanol for many years due to variety of reasons including alternative green energy sources, the rise in oil prices, minimizing greenhouse gas (GHG) emissions caused by the use of fossil oil [1] and others. A number of corn-to-ethanol plants have been commercially built and operating around the world for many years. Recently, a lignocellulose-based ethanol (or cellulosic ethanol) plant is operating on commercial scale [2], though there still exists technical, economical, and commercial barriers.

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Recently, the Berkeley researchers found that both corn-to-ethanol and cellulosic ethanol could produce positive net energy and thus ethanol is an effective substitute for fossil fuels for transportation [3]. However, corn ethanol would only slightly reduce GHG emissions, by about 13%, while cellulosic ethanol could greatly reduce GHG by 88% [3]. In addition, large amounts of corn required for large-scale ethanol production will occupy cropland suitable for food production competing with food and feed needs [4], whereas fast-growing cellulosic energy crops such as hybrid poplar and switchgrass can be planted and grown on different types of lands. And, there are still great opportunities for potential improvement in production of these kinds of energy crops thus lowering purchase cost of feedstocks [5]. In addition, cellulosic feedstocks have lower chemicals and energy inputs (process steam and electricity) needed for production [6,7,8]. Therefore, the future for the production of ethanol from cellulosic feedstock appears very bright [3].

There are various cellulosic biomass species that can be considered for producing ethanol: agricultural residues – corn stover, wheat straw, rice straw and bagasse, etc.; woody materials – hardwood (e.g., aspen, poplar) and softwood (e.g., pine) and their residues; herbaceous – switchgrass; wastes from pulp and paper industry, etc [9,10]. In general, different cellulosic feedstocks have different compositions, but they are primarily composed of cellulose, hemicellulose and lignin. The carbohydrate components, namely cellulose and hemicellulose can be converted into ethanol by chemical or biochemical reactions, whereas lignin is usually used for combustion/gasification in order to produce process steam and electricity or for producing biofuel oil or syngas by thermo-chemical conversion.

The process of cellulosic biomass to ethanol involves several steps including feedstock pretreatment, hydrolysis/saccharification, fermentation, product recovery, and wastewater treatment (Fig. 1). The pretreatment step is used for separating the biomass into its components of cellulose, hemicellulose and lignin. In this step, lignin can be removed and some hemicellulose can be converted by hydrolysis to soluble sugars – primarily xylose, arabinose, mannose and galactose. Then, the remaining cellulose is converted into sugars by hydrolysis or saccharification. The third step is fermentation of five-carbon sugars and six-carbon sugars into ethanol [10,11]. To date, the major problems still exist in the saccharification process where cellulose and hemicellulose need to be broken down into sugars. Besides, it is an important and yet unsolved challenge, to completely and efficiently convert the mixture of five- and six-carbon sugars into ethanol by fermentation [10].

In order to look at the potential overall benefits of the cellulosic ethanol process, it is very important to perform techno-economic modeling and analysis of the whole process. Four earlier attempts were identified in the literature [11–14]. Saddler and co-workers had set up a process model for techno-economic analysis of a wood-to-ethanol process with focus on comparing generic hardwood and softwood [13,14]. In 2000 and 2002, NREL (National Renewable Energy Laboratory) released two reports on the process models which involve using co-current dilute acid prehydrolysis of the lignocellulosic biomass with enzymatic saccharification of the remaining cellulose and co-fermentation of the resulting glucose and xylose to ethanol [11,12]. The feedstocks in NREL's two models are yellow poplar and corn stover, respectively. In this paper, we will analyze the effects of an array of cellulosic species (aspen, hybrid poplar, switchgrass and corn stover) and their compositions on the overall lignocellulose to ethanol process and its costs and benefits, and the effect of plant size on the overall process efficiency and economic performance. Environmental consideration is also taken into account. It should be noted that composition could vary considerably within species as a function of variety or clone and the geographic region where it is grown. In this article the composition data of only a single sample of a clone or variety for each species was used, as primary focus of this work is on developing a methodology of analysis.

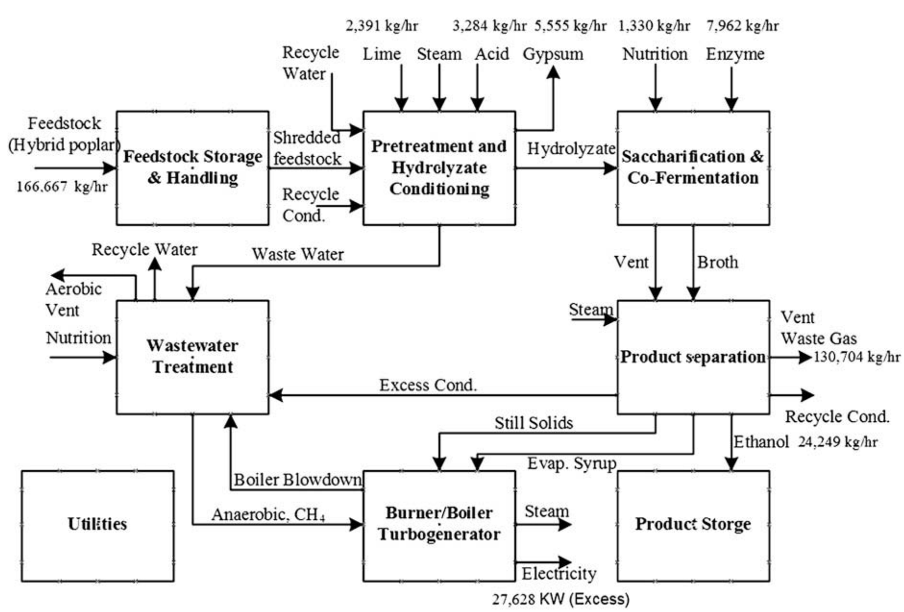

Fig. 1 – Overall process block diagram for a lignocellulose to ethanol biorefinery.

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