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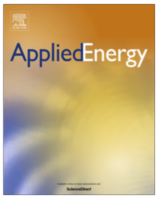

Bioethanol production from forestry residues: A comparative techno-economic analysis

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HIGHLIGHTS

- A proposed cellulosic ethanol biorefinery in Sweden was simulated with Aspen Plus.
- Forestry residues with different bark contents were evaluated as raw materials.
- The bark content negatively influenced the minimum ethanol selling price.
- Sensitivity analyses were performed to assess the influence of raw material cost.

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ABSTRACT

A techno-economic analysis was conducted to assess the feasibility of using forestry residues with different bark contents for bioethanol production. A proposed cellulosic ethanol biorefinery in Sweden was simulated with Aspen Plus. The plant was assumed to convert different forestry assortments (sawdust and shavings, fuel logs, early thinnings, tops and branches, hog fuel and pulpwood) to ethanol, pellets, biogas and electricity. The intention was not to obtain absolute ethanol production costs for future facilities, but to assess and compare the future potential of utilizing different forestry residues for bioethanol production. The same plant design and operating conditions were assumed in all cases, and the effect of including bark on the whole conversion process, especially how it influenced the ethanol production cost, was studied. While the energy efficiency (not including district heating) obtained for the whole process was between 67 and 69% regardless of the raw material used, the ethanol production cost differed considerably; the minimum ethanol selling price ranging from 0.77 to 1.52 USD/L. Under the basic assumptions, all the forestry residues apart from sawdust and shavings exhibited a negative net present value at current market prices. The profitability decreased with increasing bark content of the raw material. Sensitivity analyses showed that, at current market prices, the utilization of bark-containing forestry residues will not provide significant cost improvement compared with pulpwood unless the conversion of cellulose and hemicellulose to monomeric sugars is improved.

1. Introduction

Biomass energy, or bioenergy, is considered to be an important source of renewable energy in mitigating greenhouse gas emissions and replacing fossil fuels [1]. The use of biomass residues, such as forestry residues, is strongly advocated under European Union (EU) legislation in order to help achieve the climate and energy targets of the EU for 2020 and beyond [2,3]. Forestry residues represent a potentially large source of lignocellulosic biomass, which can be used to produce bioenergy in the form of electricity, heat and liquid transportation fuels [4,5]. For instance, bioenergy from forest and agricultural residues accounts for most of the renewable fuel in Sweden, where the bioenergy use in 2013 was around 129 TWh, corresponding to 22–23% of the total national energy consumption [6]. Furthermore, the Swedish Forest Agency estimates that the recovery of forest harvest residues can be further increased without negatively affecting the environment [7]. Consequently, considering that softwoods are one of the major

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Abbreviations: AD, anaerobic digestion; CHP, combined heat and power; COD, chemical oxygen demand; DM, dry matter; FPU, filter paper unit; HHV, higher heating value; LHV, lower heating value; MESP, minimum ethanol selling price; NPV, net present value; NREL, National Renewable Energy Laboratory; SSF, simultaneous saccharification and fermentation; WIS, water-insoluble solids.

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lignocellulosic feedstocks in the uppermost northern hemisphere, forest harvest residues constitute an abundant, sustainable supply of biomass for bioenergy production in geographical areas such as Scandinavia and the Pacific Northwest [8].

While forest bioenergy is already a feasible choice for large-scale heat and power production [9], the utilization of forestry residues for the production of liquid biofuels, such as ethanol, is hindered by economic and technical challenges [10–12]. Softwoods are generally considered to be the most recalcitrant lignocellulosic feedstock for biochemical conversion to ethanol, primarily due to their structure and high lignin content [13]. As a result, particular attention must be paid to the process steps associated with the breakdown of the biomass by pretreatment and enzymatic hydrolysis. It has been shown that more severe pretreatment conditions [14], relatively high enzyme dosage [15] and/or a delignification step [16] are needed to overcome the inherent recalcitrance of softwoods and provide a reasonable yield of monomeric sugars for the subsequent fermentation step. Furthermore, the potentially broad heterogeneity of the incoming biomass and the presence of bark make the utilization of forest harvest residues for ethanol bioconversion even more challenging.

Forestry residues include the by-products of pulp- and sawmills (sawdust and shavings; bark) and forest harvest residues from logging operations (tops and branches; nonmerchantable fuel logs), which can contain significant amounts of bark. The chemical composition and structure of bark differ significantly from those of wood [17]. Bark contains considerably less carbohydrates, but more extractives and ash [18]. These physical and chemical properties can influence the ethanol production process and its feasibility in various ways. For instance, the high content of inorganics in bark may partially neutralize the acid used for impregnation prior to pretreatment [19]. The condensation reaction of extractives during pretreatment can lead to structural changes that impair the enzymatic hydrolysis by possibly reducing the accessibility of cellulose [20], while phenolic compounds and other extractives liberated may inhibit the enzymes [21] and the fermenting microorganism [22]. In addition, the amount of ethanol that can be produced per dry metric ton of bark is lower than for wood due to the lower content of carbohydrates in bark. As a consequence, bark is generally not considered a favorable source of fermentable sugars. Although the aforementioned factors might not be as pronounced for forest harvest residues as for bark only, the theoretical ethanol potential and the overall ethanol yield are strongly influenced by the bark content of forest residues [23]. Since debarking of logging residues may be technically difficult or uneconomic, the influence of including bark must be investigated more thoroughly.

As was shown by Stephen et al. [24], the economic viability of bioenergy options, including bioethanol production, is very sensitive to changes in the type of feedstock, as the feedstock accounts for a significant part of the production cost [25,26]. Besides that the bark content of forestry residues significantly influences the softwood-to-ethanol bioconversion process, the market price of various forestry assortments also varies considerably based on their typical end use. For instance, hog fuel from debarking operations, composed mostly of bark, might be competitive with debarked whole roundwood due to its lower price [27]. In previous techno-economic evaluations of bioethanol production from softwood, processes consisting of SO_2-catalyzed steam pretreatment followed by enzymatic hydrolysis and fermentation, performed either simultaneously or separately, have been studied from several aspects [28–31]. However, the effect of including bark in the feedstock on the ethanol production cost to our knowledge has not been investigated.

This study was therefore carried out to evaluate the feasibility of utilizing forestry residues with different bark contents for bioethanol production and focused on determining the effect of bark content on the production process and the ethanol production costs. The intention was not to calculate absolute ethanol production costs for future facilities, but to assess and compare the future potential of utilizing different forestry residues for ethanol production in terms of economic performance within the context of the wood-to-ethanol bioconversion process. Overall, the attained results will help understand how the bark content of the raw materials influences the economic viability of bioethanol production from different forestry assortments.

2. Methods

The feasibility of utilizing forestry residues with different bark contents for bioethanol production was assessed by comparing the cost of production through a techno-economic analysis based on process simulation and economic evaluation of ethanol production from 6 different forestry assortments. Flowsheets were implemented and simulated in the commercial software Aspen Plus version 8.2 (Aspen Technology Inc., Massachusetts, USA) to perform rigorous thermodynamic calculations for mass and energy balances. The capital and operation costs were estimated using Aspen Process Economic Analyzer and vendors' quotations. These data were then imported and used in an Excel spreadsheet to calculate the overall investment cost and ethanol production cost, expressed as the minimum ethanol selling price (MESP), for each forestry residue.

2.1. Process simulations

The model used in this study is an updated and modified version of the model developed and previously described by Sassner et al. [31], Wingren et al. [28] and Joelsson et al. [32]. NRTL-HOC was selected in Aspen Plus as the standard method for all simulations. It was complemented with the STEAMNBS model that was used in the steam cycle in the heat and power production stage. The physical properties of the lignocellulosic biomass components, such as cellulose and lignin, and other complex components, such as yeast and enzymes, were taken from the National Renewable Energy Laboratory (NREL) database for biofuel components [33].

The energy recovery, based on the lower heating values (LHVs) calculated in Aspen Plus, was defined as the energy output in the products (ethanol, pellets, biogas, electricity and carbon dioxide) divided by the energy input, comprising the raw material, molasses and enzymes.

2.2. Conceptual design

An overview of the assumed design of the ethanol production process, which was the same in all cases regardless of the forestry residue utilized, is shown in Fig. 1, while more detailed flow diagrams of the main parts of the process have also been added to the Supplementary materials. As each process step has been described in detail previously [28,31,32,34], only a brief summary will be provided here, focusing mainly on the slight modifications made.

The proposed bioethanol plant was assumed to be located in Sweden, with the capacity to process 200,000 dry metric ton of raw material annually, being operated for 8000 h per year. It was assumed that the forestry residues are transported to the plant by truck and stored in a stack before being fed to the pretreatment area. The biomass was first impregnated with sulfur dioxide (0.015 kg SO_2/kg dry material) and then preheated to 95 °C by direct injection of low-pressure secondary steam prior to steam pretreatment. Steam pretreatment was modeled as a continuous

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