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Life cycle assessment of ethanol derived from sawdust

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HIGHLIGHTS

- The life cycle of ethanol derived from sawdust is evaluated considering two scenarios.
- The net energy consumption, CO_2 emission and production cost are estimated.
- Competitiveness of production cost remains doubtful unless Feed-in Tariff (FiT) is considered.

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ABSTRACT

The life cycle of ethanol derived from sawdust by enzymatic hydrolysis process is evaluated to determine if environmentally preferable and economically viable ethanol can be produced. Two scenarios are considered to estimate net energy consumption, greenhouse gas (GHG) emission and production costs. The estimated net energy consumption, GHG emission and production costs are 12.29–13.37 MJ/L, 0.75–0.92 kg CO_2 e/L and about $0.98–$1.04/L, respectively depending on the scenarios of this study. The result confirmed that environmental benefit can be gained with present technologies; however, economic viability remains doubtful unless Feed-in Tariff (FiT) is considered. The production cost of ethanol reduces to $0.5/L, if FiT is considered to be $0.025/MJ. This study indicates that the implementation of FiT program for ethanol industry not only helps Ontario mitigate GHG emissions, but may also attract more investment and create rural employment opportunities.

1. Introduction

The growing concerns about climate change, rising costs of fossil fuels and the geo-political uncertainty associated with possible interruption of current fossil fuel-based energy supplies have motivated nations to seek clean and renewable substitutes to reduce their greenhouse gas (GHG) emission. Renewable energy reduces the reliance on foreign oil, improves energy security, provides significant environmental benefits and enlarges rural economies. Lignocellulosic ethanol is a widely recognized alternative to fossil gasoline, and its production and use have been emphasized because it is highly reproducible and does not compete with food. According to the Renewable Energy Regulation (SOR/2010-189), Canadian fuel producers and importers of gasoline require to have renewable fuel content of at least 5% of distillates (by volume) that they produce and import yearly (Environment Canada, 2010), which creates huge demand, especially on lignocellulosic ethanol.

The potential sources of renewable biomass in Canada include waste products from forestry and agricultural residues, municipal solid waste, and energy crops. In Canada, the amount of lignocellulosic biomass production is reported to be approximately 9.4×10^6 t/year. Residual lignocellulosic feedstock could provide up to 50% of Canada's 2006 transportation fuel demand (Mabee and Saddler, 2010). Forestry products, particularly sawdust, forest thinning and trimming are potential feedstock for ethanol production (Kadam et al., 2000; Mu et al., 2010). The life cycle GHG emissions from biofuels and their ability to reduce GHG emission are dependent on choice of feedstock, agricultural practices, and conversion technologies with differing socioeconomic and environmental impacts (Luo et al., 2009; Kaufman et al., 2010). Although many researchers have evaluated the life cycle of lignocellulosic ethanol produced by enzymatic hydrolysis process, ethanol from sawdust received only limited attention (Slade et al., 2009; Sandilands et al., 2009), their research deals with thermochemical conversion (gasification-synthesis). This study evaluated the life cycle of ethanol produced by enzymatic hydrolysis and considered two scenarios to determine if environmentally preferable and economically viable ethanol can be produced from sawdust in Ontario, Canada.

2. Methodology

Life cycle assessment (LCA) is a tool that evaluates the environmental impacts of each stage of a product, process or activity's life. LCA is widely used to evaluate environmental performance of

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renewable energy technologies including ethanol. Accordingly, the LCA methodologies (ISO, 2006) are used to determine the net energy consumption, gressenhouse gas (GHG) emission and production cost of ethanol produced from sawdust. This study is conducted based on the estimated and literature data.

2.1. Goal definition and scoping

The goal of this study is to evaluate the life cycle of ethanol from sawdust through enzymatic hydrolysis process considering two scenarios. The functional unit (FU) is defined as 1 L of anhydrous ethanol produced from sawdust.

2.2. System boundary and assumptions

The forest products industry produces woody biomass as a byproduct, including bark, sawdust and shavings. In Canada, sawmill residue production rate is estimated to be approximately 2.3×10^6 dry-tons/year (Ackom et al., 2010). The forest area in Ontario is reported to be 71,067,769 ha in 2008 (MNR, 2011), which produces a considerable amount of residues. Sawdust is reported to be high in cellulose content, thus a suitable raw material for ethanol production. Cellulose, hemicellulose and lignin contents are reported to be 55%, 14% and 21%, respectively (Olsson and Hahn-Hägerdal, 1996). Ethanol yield is assumed to be 0.305 L/kg of dry sawdust (Olsson and Hahn-Hägerdal, 1996). Two scenarios are considered to evaluate the life cycle of ethanol from sawdust (Table 1). Sawdust from sawmills (base case: scenario-1) and sawdust produced from forest residues (thinning, pruning, shaving etc., scenario-2) are considered as carbon neutral, because these are byproducts of timber industry (sawmill) and forest, respectively. However, any marginal inputs (energy consumption in collection and transportation of sawdust, and preparation of sawdust from forest residues) and emissions are allocated to sawdust from sawmills or sawdust produced from forest residues (thinning, pruning, shaving etc.). GHG emission has been calculated interms of CO_2 e (i.e., GWP for a time span of 100 year; IPCC, 2001).

An ethanol processing plant is assumed to be established nearby the forest/sawmill area for efficient utilization of forest and sawmill residues. The ethanol processing plant capacity is considered to be 20,000 kL/year. Lignocellulosic biomass is noted to have a low bulk density and higher moisture content ranging from 10% to 70%. The moisture content in raw material (sawdust/forest residues) is considered to be 40% (wb). The transportation distance is assumed to be 15 km (base case: sawdust transportation distance is estimated based on feedstock demands and the transportation distance reported by Mani et al., 2006). The bagged sawdust assumed to be transported by 6 m (20 feet) trailer truck. The transportation capacity is calculated based on the density of sawdust (417 kg/m^3) and volume of the trailers. The loading capacity is assumed to be 75% of the volume of the trailer. Cradle to gate scenario [system boundary of life cycle of ethanol from sawdust: sawdust either from sawmills (transportation) or sawdust prepared from forest residues (collection and transportation) followed by pre-treatment, saccharification and fermentation, distillation and purification, and waste management] has been adopted for this study. The environmental impacts related to the construction of the ethanol processing plant, storage facilities and the production of transportation and other machines, building and roads are not considered. It is also worthy to note that energy input in the form of labor and energy content in the feedstock are not taken into account. Net energy consumption is defined as the difference between the sum of the energy consumption in each process and the amount of energy recovered from the lignin byproduct (hereafter referred to byproduct).

2.3. Pretreatment

Lime pretreatment (calcium capturing by carbonation, i.e., CaCCO process at 120 °C for 1 h; lime 10%) is considered for this study (Park et al., 2010; Shiroma et al., 2011). The solid concentration during pretreatment is considered to be 30% (w/w).

2.4. Fermentation and distillation

The pretreated sawdust slurry (solid content 10% wt) is then allowed for simultaneous saccharification and fermentation (SSF) at 33° for 72 h. The enzyme loading is considered to be 14 FPU (filter paper unit)/g-cellulose (McMillan et al., 1999). Vacuum extractive fermentation and distillation, and purification (using glycerol) processes are adopted (Dias et al., 2009; Junqueira et al., 2009). The ethanol concentration in the vacuum extractive fermentation is assumed to be more than 7.5% wt.

2.5. Enzyme (cellulase) and yeast production

Energy consumption in enzyme production process is calculated based on the enzyme production cost (enzyme loading: 15 FPU/g-cellulose i.e. 19,263 FPU/L) and retail electricity price in the USA in 1997 (Wooley et al., 1999; EIA, 2010). Then, enzyme cost of this study is worked out (based on the 2012 electricity price in Ontario). The cost of yeast ($0.01/gallon) is collected from the literature (Dutta et al., 2010).

2.6. Waste management

The waste stream is assumed to be separated into centrifuged solids (lignin) and liquid streams (waste water). The lignin is assumed to be dried by utilizing the wasted heat from the boiler. Anaerobic digestion of the wastewater produces biogas (Cardona and Sánchez, 2006). It is assumed that energy consumption and cost incurred in waste management processes would be offset by biogas, and the byproduct recovered in the waste management processes can be used for process heat generation. Based on the heating value of lignin and the boiler efficiency (80%; Mani et al., 2009) heat generation from the byproductis estimated and used to offset some of the heat supplied by LNG (liquid natural gas). The emission and cost that credited to lignin is determined with the emission factor and cost of LNG.

Table 1
Scenarios of this study.

Scenario	Feedstock source	Transport distance, km	Cost, $/t[b]
Scenario-1 (base case)	Sawdust (sawmill byproduct)	15[a]	80
Scenario-2	Sawdust (produced from forest residues: thinning, pruning, and the logging residues)	20	60

[a] Distance estimated based on the Mani et al., 2006; 6 m (20 feet) tailor truck is used for transportation.
[b] Plant gate price.