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Greenhouse gas emissions and production cost of ethanol produced from biosyngas fermentation process

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HIGHLIGHTS

- Life cycle of ethanol from biosyngas fermentation process has been evaluated.
- Treated (torrefied) and untreated (raw) feedstock (miscanthus) were used.
- ASPEN Plus simulation was used for biosyngas with/without CLG process.
- CLG and untreated feedstock were nominally advantageous to abate GHG emissions.

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ABSTRACT

Life cycle (LC) of ethanol has been evaluated to determine the environmental and economical viability of ethanol that was derived from biosyngas fermentation process (gasification-biosynthesis). Four scenarios [S_1: untreated (raw), S_2: treated (torrefied); S_3: untreated-chemical looping gasification (CLG), S_4: treated-CLG] were considered. The simulated biosyngas composition was used in this evaluation process. The GHG emissions and production cost varied from 1.19 to 1.32 kg-CO_2 e/L and 0.78 to 0.90 $/L, respectively, which were found to be dependent on the scenarios. The environmental and economical viability was found be improved when untreated feedstock was used instead of treated feedstock. Although the GHG emissions slightly reduced in the case of CLG process, production cost was nominally increased because of the cost incurred by the use of CaO. This study revealed that miscanthus is a promising feedstock for the ethanol industry, even if it is grown on marginal land, which can help abate GHG emissions.

1. Introduction

The global energy consumption is increasing remarkably at a rate of 2.3% since 2000 (Enerdata, 2014). The global energy consumption was 13583×10^6 tOe in 2013 and emitted about 31097×10^6 tCO_2, contributing to global warming, which is one of the serious problems human kind faces nowadays (Enerdata, 2014). Liquid biofuels are identified as an alternative to fossil fuel to reduce the dependence on fossil fuel and abate greenhouse gas (GHG) emissions. The world ethanol production or consumption was 113853.8×10^6 L in 2013 and predicted to be 162664.6×10^6 L by 2021 (OECD-FAO, 2013). Till date, corn based ethanol is the main contributor to total ethanol production in Canada. Therefore, emphasis has been placed on the lignocellulosic ethanol because it does not compete with food.

The major sources of lignocellulosic biomass (here after referred to biomass) in Canada are agricultural residues, forest residues, municipal solid waste and energy crops. The supply of these feedstocks to the ethanol industry is limited by the technical, economic and sustainability constraints (Kludze et al., 2010). Conversely, low quality or marginal land can be used to grow miscanthus (Kludze et al., 2013), meeting/surpassing numerous viable uses of biomass without significantly affecting the supply of food crops in Canada (Kludze et al., 2010). Fuel producers and importers in Canada are required to have renewable fuel content of at least 5% in the distillates that they produce or import. The Government of Canada also offers an incentive of $0.10/L to the ethanol industry for up to seven consecutive years (Biofuelnet, 2013), which has created a substantial market for ethanol.

Ethanol has been produced from biomass by either biochemical (hydrolysis) or thermochemical conversion processes. Biomass contains a large amount of non-carbohydrate materials (lignin), which cannot be converted into ethanol in the biochemical conversion process (Henstra et al., 2007). Conversely, the thermochemical

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process converts all the components of biomass to biosyngas (Pereira et al., 2012) irrespective of biomass quality, which can then be fermented into ethanol, therefore eliminates complex pretreatment steps required in the conventional lignocellulosic ethanol production process (Munasinghe and Khanal, 2010). In the thermochemical conversion process, biosyngas can be converted into ethanol by catalytic synthesis or biosynthesis process. The catalytic synthesis process requires high pressure, high temperature, expensive metallic catalyst and complex gas cleaning steps (Subramani and Gangwal, 2008); however, the biosynthesis process can be operated at ambient conditions with no inorganic catalyst poisoning (Munasinghe and Khanal, 2010).

The biosynthesis process consists of biomass gasification and biosyngas cleaning followed by microbial fermentation of biosyngas into ethanol. Syngas quality is also dependent on the on the feedstock and gasification conditions (Kuo et al., 2014; Daystar et al., 2013; He and Zhang, 2011). The chemical looping gasification (CLG) process improves the syngas quality (Acharya et al., 2009) and eases the syngas cleaning process. The pretreated biomass also improves the gasification process and syngas quality (Chen et al., 2013; Kuo et al., 2014; Roy, 2014). LCA is a methodology widely used to determine environmental viability and the life cycle cost analysis (LCCA) was used to determine economical viability of biofuels. Although the life cycle (LC) of ethanol (derived either by biochemical or thermochemical) has been extensively evaluated, the biochemical dominates over thermochemical processes (Subramani and Gangwal, 2008). Several researchers have studied the LC of ethanol produced by the thermochemical conversion process and deals with agricultural- and forest residues (Foust et al., 2009; Tan and Dutta, 2013). However, ethanol produced from syngas that was derived from treated (torrefied) feedstock and CLG process is yet to be evaluated. In this study, we have evaluated the LC of ethanol derived from treated (torrefied feedstock) and untreated (non-torrefied) energy crops (miscanthus) with or without CLG by biosynthesis process to determine GHG emissions and production cost of ethanol.

2. Methods

The life cycle assessment (LCA) methodologies (ISO 14040) were adopted to evaluate the life cycle (LC) of ethanol derived from biosyngas fermentation process.

2.1. System boundary and assumptions

Lignocellulosic biofuels were noted to be environmentally sustainable products (González-García et al., 2012; He and Zhang, 2011; Hsu et al., 2010); however, the production cost and emissions are dependent on the feedstock, processing conditions, plant capacity, and byproduct utilization, etc. (Spath and Dayton, 2003; van Kasteren et al., 2005; Piccolo and Bezzo, 2009; Martín and Grossmann, 2011; Roy, 2014). Miscanthus was reported to be a promising feedstock for the ethanol industry in Canada (Kludze et al., 2013; Roy, 2014). Consequently, this study evaluates the LC of ethanol derived by fermenting the biosyngas produced from treated and untreated miscanthus with or without CLG process to determine if that is environmentally and economically viable in Ontario, Canada. The cradle to gate scenario approach was adopted to define the system boundary of this study (SI-1, SI: Supporting information). The raw biomass was assumed to be transported to an integrated processing plant (pretreatment–gasification–fermentation–distillation) in Ontario, Canada. The feedstock transportation distance was estimated to be from 45 to 47 km depending on the yearly feedstock demand. Although the processing plant cost may vary depending on the type of processing, it was assumed to be the same for all scenarios of this study. In this study, the literature and estimated data have been used. The energy content in the feedstock, energy required in machineries production, and construction of the ethanol plant, and energy input as labor were not considered. The net emission has been estimated in terms of CO_2 e (i.e., global warming potential for a time span of 100 year). The functional unit of this study was assumed to be 1 L of anhydrous ethanol.

2.2. Pretreatment

The mild heat treatment that is given to biomass (typically from 200 to 300 °C in an inert atmosphere) to improve thermochemical properties of biomass is defined as torrefaction. The torrefaction process produces a more stable, dense, and hydrophobic material, with higher energy values, thus reduces the biomass handling cost (Bessou et al., 2011). A Quartz Wool Matrix (QWM) reactor was used to produce treated feedstock and the energy consumption was estimated because the QWM reactor is yet to be optimized. The torrefied biomass yield was assumed to be 85% in this study (260 °C for 30 min).

2.3. Gasification and biosyngas cleaning

The heat released by the exothermic carbonization reactions in the chemical looping gasification (CLG) system supplies most of the heat required by the endothermic reactions (Acharya et al., 2009). The CLG concept consists of two fluidized bed reactors (operate parallely), which were functioning as a calciner and gasifier. In the calciner, limestone was calcined. Lime was then circulated to the reactor (gasifier), where the lime sorbent was carbonated in parallel with the gasification reactions, tying up most of the CO_2 as $CaCO_3$. The $CaCO_3$ was then recirculated to the calciner, acting as a regenerator. The calcium oxide was noted to be a cheaper and effective sorbent for capturing CO_2 at very high temperatures results in a cleaner (a small fraction of CO_2 in the flue gas) product gas and minimize auxiliary power consumption (Acharya et al., 2009). Consequently, CaO was selected as an absorbent in this study. The syngas composition and quality are dependent on the feedstock and gasification conditions (Acharya et al., 2009; He and Zhang, 2011; Kuo et al., 2014). Lesser efforts were required in the syngas cleaning process in the case of treated biomass and CLG processes. The thermal degradation experiments conducted at the laboratory in a micro gasifier (TGA-FTIR; TGA: SDT-Q600, TA Instruments-Waters LLC, USA; FT-IR: Thermo Scientific Nicolet 6700, TA Instruments-Waters LLC, USA) at 900 °C have also confirmed that gas composition and quality are not only dependent on the feedstock but also on the gasification conditions (Roy, 2014).

Although thermal degradation experiments have been conducted, the simulated (with Aspen Plus V7.3) data (gas composition) have been used to estimate the cold gas efficiency (CGE) and the ethanol yield. The simulation parameters are reported in the Supporting information (SI-2 information). The simulated biosyngas composition also confirmed that gas quality is dependent on the feedstock and gasification conditions. The CGE calculation methods were reported in the Supporting information (SI-3). Table 1 represents the simulated biosyngas composition, heating value and estimated cold gas efficiency. The cyclone was assumed to be used to separate the solid particles in the product gas, if any (van Kasteren et al., 2005; Acharya et al., 2009; Martín and Grossmann, 2011) and then, the product gas was cleaned with a water scrubber or water wash process (Spath and Dayton, 2003; van Kasteren et al., 2005). The benefit achieved in the syngas cleaning process of treated biomass and CLG was assumed to be offset