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Environmental life cycle assessment of bio-fuel production via fast pyrolysis of corn stover and hydroprocessing

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HIGHLIGHTS

- Three cases of corn stover fast pyrolysis bio-oil production and hydroprocessing were investigated on a life cycle basis.
- Bio-oil upgrading process was the key unit in the overall pathway.
- All three cases showed obvious advantages over conventional gasoline and diesel in net non-renewable energy and GWP.
- The environmental benefits increased from Case 1 to Case 3 while the biofuel yields were reduced in corresponding case.

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ABSTRACT

A comparative life cycle assessment (LCA) of biofuel production from corn stover fast pyrolysis and subsequent hydrotreating and hydrocracking was conducted based on the Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) model. Three different cases were investigated as a result of different hydrogen treatment in bio-oil upgrading process. Environmental impacts such as non-renewable energy demand and Global Warming Potential (GWP) were primarily evaluated for 1 MJ biofuel produced. All the results showed obvious environmental benefits compared with conventional gasoline and diesel based on the year of 2010. The results of Case 1 in which hydrogen was provided by external natural gas reforming displayed a reduction of 67.5% in net non-renewable energy demand and a reduction of 69.1% in net GWP in contrast to conventional gasoline and diesel. Net non-renewable energy demand was lowered by 76.6% and net GWP was reduced by 73.0% in Case 2 where 35% of bio-oil aqueous phase was consumed by steam reforming for hydrogen production. Case 3 gained an obvious advantage on both environmental aspects over the others, in which surplus hydrogen from steam reforming of whole aqueous phase of bio-oil was obtained as a coproduct. The results displayed a significant net non-renewable energy reduction of 147.5% and a net GWP reduction of 119.4%. However, the outcomes indicated decreasing biofuel yields from Case 1 to Case 3 compared with increasing environmental benefits. The biofuel yields of three cases were 31.2%, 23.7% and 11.5% respectively in this work.

1. Introduction

In order to reduce net greenhouse gas emissions and slow down fossil fuel depletion, there has been a long and urgent desire to find an alternative fuel which can replace increasing fossil energy consumption. Biomass has gained attention as a promising renewable fuel due to significant environmental benefits [1–3]. Liquid biofuels can be produced through various biomass conversion pathways and they can be used as a promising substitute for petroleum fuel in transport sector [4–6]. The US Environmental Protection Agency (EPA) has released Renewable Fuel Standard (RFS2) to mandate the annual use of 36 billion gallons of biofuels in 2022. At least 16 billion gallons of them are required from cellulosic biofuel while no more than 15 billion gallons from corn ethanol [7]. RFS2 also mandates that each category of renewable fuel should emit fewer greenhouse gas than the petroleum fuel it replaces in order to achieve the life cycle greenhouse gas threshold standards [7]. Among various conversion methods, fast pyrolysis has been investigated widely and has been demonstrated as a feasible and economic method to convert different biomass feedstocks to liquid biofuel [8–12]. Since bio-oil derived directly from fast pyrolysis presents severe disadvantages such as high oxygen and water content, it needs to be upgraded so that it can

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be consumed as a share of transportation fuel like gasoline and diesel. Bio-oil through hydrotreating and hydrocraking are reported to be a feasible way for gasoline and diesel production in literature [13,14].

Life cycle assessment (LCA) is widely used to evaluate environmental impacts of a product system including all the stages of product life cycle [15,16]. A lot of LCA papers have been published on biofuel production such as ethanol, green diesel [17–22]. The Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) model developed by US Argonne National Lab with the support from US Department of Energy provides a free platform and strong database for LCA work [23]. This work is based on LCA model constructed on GREET platform.

As far as the authors know, only a few papers have been published on biofuels through fast pyrolysis with different feedstocks [24–30]. Corn stover as a typical kind of agriculture residue, it shows great interest in biofuel production and is selected as biomass feedstock in this work. With the calculation of the available properties data from literature, a design case of fast pyrolysis is simulated by Aspen Plus 7.1. Hydroprocessing upgrading process accompanied by bio-oil production is also investigated in Aspen Plus in order to get basic mass and energy balance data for this LCA work.

The present study applies LCA method to liquid biofuel production from corn stover fast pyrolysis and subsequent upgrading using GREET model. As a result of various hydrogen treatments in upgrading process, three different cases are comparatively analyzed in detail. All these three scenarios might be promising conversion pathways in industrial application in future. Based on the inventory data from the calculation, our Aspen Plus simulation results, GREET database based on the year of 2010 and a few assumptions as indicated in this paper, non-renewable energy demand and its associated Global Warming Potential (GWP) on different scenarios are investigated and compared with conventional gasoline and diesel as well as similar work done by other researchers.

2. LCA goal and scope definition

This current study focuses on the environmental impacts of liquid biofuel production from corn stover fast pyrolysis and subsequent hydrotreating and hydrocraking upgrading process. Non-renewable energy demand and its associated GWP are primarily evaluated in this LCA work. Due to different hydrogen treatment in bio-oil upgrading process, three different scenarios are investigated. Hydrogen produced from natural gas is consumed in Case 1 and all the bio-oil produced from fast pyrolysis is upgraded to gasoline and diesel. It was worth noting that the bio-oil in our study was composed of 62.1% of aqueous phase and 37.9% of leftover bio-oil designated as pyrolytic lignin. In Case 2, hydrogen for hydroprocessing is provided by steam reforming of 35% of aqueous phase while the leftover bio-oil is hydrogenated to gasoline and diesel. In Case 3, steam reforming of all 62.1% of aqueous phase of bio-oil is conducted to produce hydrogen while pyrolytic lignin is hydroprocessed for liquid bio-fuel production. Part of hydrogen produced by steam reforming is consumed by hydroprocessing in bio-oil upgrading process while the remaining hydrogen is treated as coproduct in this case. Since the coproducts have great value in the market, the credits of coproducts are addressed and displacement method is employed in this work. The displacement method indicates that 100% of energy and emission flows into the primary product and a conventional product is assumed to be replaced by coproduct obtained along with the production of primary product [23].

It should be noted that different refinery opportunities for pyrolysis bio-oil has been reported by UOP report [13]. Hydrotreating/hydrocraking of pyrolytic lignin has been tested successfully by UOP and Pacific Northwest National Laboratory (PNNL). Hydrogen production from organic compounds in the aqueous phase through steam reforming is considered to be the primary technology for hydrogen generation and integrating pyrolysis bio-oil into refineries. The outlines and specific methods of hydroprocessing pyrolytic lignin to produce gasoline and aqueous phase reforming of water-soluble components to produce hydrogen have been presented to demonstrate that pyrolysis bio-oil is a potential feedstock for transportation fuel production [13]. Bio-oil is composed of various light and heavy compounds and it may be suitable for hydroprocessing at a refinery especially with the advancing of new technology [14].

This LCA study consists of six steps: biomass production, biomass transportation, biomass pretreatment, bio-oil production, bio-oil upgrading, and upgraded bio-oil transportation and distribution. The detailed information of different unit processes was provided in inventory analysis in Section 3 of this paper. The system boundaries for Case 1, Case 2 and Case 3 are showed in Fig. 1A–C individually.

Gasoline and diesel are produced from illustrated three pathways. The properties of gasoline and diesel such as lower heating value (LHV) and the ratio of hydrogen to carbon are assumed to be exactly the same. The LHVs of gasoline and diesel are 43 MJ/kg and the ratio of hydrogen to carbon is 2. The functional unit employed in this study is 1 MJ biofuel produced, which is a mixture of equal amount of gasoline and diesel in this work. Materials and energy inventories are obtained from calculation, our own Aspen Plus simulation results and GREET database. GREET 2013 version is employed to investigate environmental impacts of biofuel production pathways. This paper primarily examines the potential of reducing non-renewable energy demand and its associated GWP on biofuel production from agriculture residue. It is assumed that all the weights in LCA inventories are on dry basis, otherwise they are stated. LHVs are reported in this work. It is worth noting that the materials and energy associated with the infrastructures are beyond the scope of this LCA work.

3. Inventory analysis

3.1. Biomass production

This inventory module involved energy use and emissions associated with collecting corn stover. The yield of corn stover was assumed to be 4214 kg/ha with a collection rate of 50% according to GREET database. The LHV of corn stover was considered to be 15.6 MJ/kg by calculation from ultimate analysis [14]. We assumed the replacement of nitrogen fertilizer, P_2O_5 and K_2O at the rates of 8.49 g, 2.21 g and 13.23 g for 1 kg corn stover removed according to GREET database. Diesel fuel was consumed in corn stover collection production process such as farming tractor. See Table 1 for further information.

3.2. Biomass transportation

We assumed that corn stover was transported by diesel truck with a distance of 61 km one way from stacks to pyrolysis plant. The truck returned back empty without any loading. Fuel economy was considered to be 2.1 km/L. These assumptions were made based on GREET database. The detailed information was listed in Table 1.

3.3. Biomass pretreatment

In order to prevent increasing the cost and reducing product yield in pyrolysis facility, corn stover needed to be pretreated such as grinding and drying before being fed to fast pyrolysis reactor.