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Life cycle assessment of energy consumption and environmental emissions for cornstalk-based ethyl levulinate

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HIGHLIGHTS

- The first LCA of cornstalk-based ethyl levulinate.
- Life cycle energy consumption and environmental emissions were evaluated.
- Detailed foreground data from a demonstration project in China was used.
- Criteria emissions in the combustion stage were based on engine tests.
- Sensitivity analysis was performed based on different cornstalk prices.

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ABSTRACT

This study analysed the sustainability of fuel-ethyl levulinate (EL) production along with furfural, as a by-product, from cornstalk in China. A life cycle assessment (LCA) was conducted using the SimaPro software to evaluate the energy consumption (EC), greenhouse gas (GHG) and criteria emissions, from cornstalk growth to EL utilisation. The total life cycle EC was found to be 4.54 MJ/MJ EL, of which 94.7% was biomass energy. EC in the EL production stage was the highest, accounting for 96.8% of total EC. Fossil EC in this stage was estimated to be 0.095 MJ/MJ, which also represents the highest fossil EC throughout the life cycle (39.5% of the total). The ratio of biomass to fossil EC over the life cycle was 17.9, indicating good utilisation of renewable energy in cornstalk-based EL production. The net life cycle GHG emissions were 96.6 g CO_2-eq/MJ. The EL production stage demonstrated the highest GHG emissions, representing 53.4% of the total positive amount. Criteria emissions of carbon monoxide (CO) and particulates $\leqslant$10 μm (PM10) showed negative values, of −3.15 and −0.72 g/MJ, respectively. Nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions showed positive values of 0.33 and 0.28 g/MJ, respectively, mainly arising from the EL production stage. According to the sensitivity analysis, increasing or removing the cornstalk revenue in the LCA leads to an increase or decrease in the EC and environmental emissions while burning cornstalk directly in the field results in large increases in emissions of NMVOC, CO, NO_x and PM10 but decreases in fossil EC, and SO_2 and GHG emissions.

1. Introduction

Fossil fuels have played an important role in rapid societal development; however, global warming, energy supply security, fossil fuel depletion and environmental impacts have stimulated interest in more sustainable energy sources. Bioenergy is the only form of renewable energy that can be collected, stored and transported, and is the form most similar to "conventional" fossil fuel energy sources; it is also the only carbon-neutral energy resource that can be converted into any form of fuel, including solid, liquid or gas, all of which play important roles in renewable energy utilisation [1,2]. Development of biomass-based liquid fuel is the main focus of research into biomass utilisation. Bioenergy resources, such as lignocellulosic biomass, can be converted into liquid fuels [3] and then used as internal combustion engine alternative fuels [4,5], which represents an important direction for development.

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Lignocellulosic biomass is one of the most abundant biomass resource on earth. China is a major agricultural country, producing 600–800 million tonnes of crop straw every year [6]; the main type of crop straw is cornstalk, accounting for one third of the total with a production amount of 250 million tonnes per year [7]. Although China has abundant crop straw, there is significant wastage of this potential energy resource due to discarding or direct burning in the field, with associated adverse environmental impacts. The use of these lignocellulosic biomass resources for the production of liquid fuels could therefore be highly beneficial for enhancing oil security, alleviating pressures arising from the demand for fossil energy and resources, reducing environmental pollution and developing rural economies [8,9].

Levulinic acid (LA), derived from acid catalysis of lignocellulosic biomass, is one of the top-12 building blocks, and a potentially versatile building block for the synthesis of several chemicals for practical applications [10]. Levulinates can be produced through esterification of LA [11,12]; they are used in the flavouring and fragrance industries [13], and as a blending component or oxygenated additive for biodiesel and diesel used in unmodified diesel engines [8]. Ethyl levulinate (EL) is a levulinate ester with an oxygen content of 33%, obtained by esterifying LA with ethanol, and can be used as an oxygenate additive in fuels. It has been reported that a blend of 20% EL and 79% petroleum diesel, with 1% co-additive, had a 6.9% oxygen content, and burned significantly cleaner than diesel [14]. Previous studies have analysed the distillation curves of EL-diesel blends and fatty acid-levulinate ester biodiesel blends, and investigated the cloud points, pour points and cold filter plugging points (CFPPs) of blends of biodiesel produced from cottonseed oil and poultry fat with EL contents of 2.5, 5, 10, and 20 vol.% [15,16]. A diesel engine functions normally when fuelled with EL-diesel blends containing up to 10% EL without any other latent solvent or co-additive [17]. Various biomass feed stocks, including starch, sugar crops and cellulosic biomass, have been used to produce LA and ethanol [18,19]. Crop straw can also be used as a potential raw material for the production of EL by direct conversion in an ethanol medium [20].

These reports on the production and utilisation of EL from biomass resources have focused on technical aspects. It is essential to use life cycle assessment (LCA) to analyse the sustainability of EL production from biomass (cornstalk) and utilisation in diesel engines. LCA is an evaluation tool for assessing the potential effects of a product or service on the environment over the complete period of its life, is a widely accepted approach [21]. Quantification of the potential environmental impacts of a product system over an entire life cycle, identification of opportunities for improvement, and an indication of the most sustainable alternatives, can be derived from the results of an LCA study [4,22]. Life cycle management has rapidly become a well-known and widely used approach in environmental management. The LCA approach involves a cradle-to-grave assessment, where the product is followed from the primary production stage from raw materials, through to its end use [23].

The LCA of greenhouse gas (GHG), energy consumption (EC) and environmental impacts of biomass based liquid fuels have been attracting much attention in recent years. Life cycle EC and GHG emission of fuel ethanol produced from corn stover [4], sugarcane [21], cassava [24] and agave [25] were investigated using LCA. The potential of vetiver leaves as a lignocellulosic biomass feedstock for biorefinery concept to produce ethanol and furfural were conducted through LCA to estimate the GHG emissions and fossil energy demand [26]. Biodiesel produced from different feedstocks such as soybean [27], rapeseed [28] and microalgae [29] have also been extensively studied. In addition, there have been many studies on biofuels specific to China such as ethanol produced from wheat, corn and cassava in different areas of China [30], biodiesel produced from soybean [31], biojet fuel from microalgae [32] and ethylene produced from corn and cassava [33].

EL produced from biomass can be also taken as fuel additives in engine to reduce environmental pollution, it is essential to use LCA to evaluate its energy consumption and environmental impact. However, to the best of our knowledge there is no detailed LCA study on biomass-based EL production to date. This study therefore aims to fill this gap. Here we present the first LCA of cornstalk-based EL based on a demonstration project in China. An LCA model for EC, greenhouse gases (GHG) and criteria emissions was built using the SimaPro software and the key life cycle stages, including cornstalk growth, collection and chopping, and EL production, transportation and utilisation as an additive in diesel, were investigated. The main purpose of the analysis was to determine the EC of EL across its life cycle, and to evaluate the potential for reducing criteria emissions in a 5% blend of EL with diesel (E5) used as a vehicle fuel. The foreground input data is mainly from the demonstration project in China while background process data is mainly from inventory databases in SimaPro. The LCA results can assist policy makers in evaluating the environmental performance of biomass-based EL production in relation to other biofuels. In addition, it will offer the potential to enhance the utilisation efficiency of biomass resources and reduce air pollution.

2. System boundary and LCA methodology

2.1. System boundary

Biomass energy is a form of renewable energy arising from solar energy. Theoretically, carbon dioxide (CO_2) released from burning biomass has been captured previously from the atmosphere during biomass growth. However, GHG emissions during production processes, as well as criteria emissions, need to be taken into account. The key stages in the system boundary for the present analysis are found in the field-to-fuel (FTF) stages, including (1) cornstalk growth, (2) cornstalk collection, (3) cornstalk chopping, (4) EL production, (5) EL transportation and (6) EL utilisation as an additive in diesel vehicle. As can be seen from Fig. 1, the life cycle progresses from cornstalk growth to EL production, and ends in EL consumption. The system boundaries of the cornstalk to EL section can also be divided into three subsystems: "feedstock collection" (S1), "EL production" (S2) and "EL utilisation" (S3).

Energy is consumed across every stage of the life cycle, and several kinds of EC, including diesel, electricity and biofuel, are present. Some key assumptions and explanations for the LCI analysis are as follows: (1) The EC relating to the manufacturing and maintenance of transportation vehicles, machinery and buildings used in EL production and utilisation is not included as these were usually found to be negligible over the whole life cycle (e.g., less than 0.3% of the total in [34]); (2) Cornstalk was selected as the EL production material. In this part of the study, cornstalk is assumed to be a waste product or by-product of the corn production process. However, cornstalk has a market value, as it can be used as a feedstock for some other industries. Thus, the EC of cornstalk growth is considered on the basis of the ratio of corn to cornstalk prices on the Chinese market; and (3) The CO_2 absorption during the biomass growth and quantities of CO_2 emission at each step of the life cycle are considered and calculated. This will help show the CO_2 sources and sinks along the cornstalk to EL supply chain and highlight future potentials for CO_2 capture and storage.

2.2. LCA methodology

LCA EC and environmental emissions results were calculated according to the FTF stages, based on the ISO14040 [35] and