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

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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 4.54MJ/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 ≤ 10 um (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.

Keywords: Cornstalk; ethyl levulinate; life cycle assessment; energy consumption; environmental 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.

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).

Fig. 1 System boundaries for LCA of cornstalk-based EL from cornstalk growth to EL utilisation (EL5).

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 ISO14044 [36] guidelines. In the FTF stages, EC can be calculated in terms of primary energy sources, such as coal, oil and biomass. GHG emissions are calculated as CO_2 equivalents (CO_2-eq), with methane (CH_4) having a global warming potential (GWP) 23 times greater than that of CO_2 [37]. Nitrous oxide (N_2O) emissions are included in background datasets within SimaPro. Criteria emissions include no-methane volatile organic compounds (NMVOC), carbon monoxide (CO), nitrogen oxides (NO_x), particulates ≤ 10 um (PM10) and sulphur dioxide (SO_2); these were calculated based on the EC process, material depletion, solid and liquid waste discharge, land use changes and EL utilisation in vehicles. Data were mainly obtained from the ecoinvent life cycle inventory (LCI) dataset. Some data were taken directly from the SimaPro

8.0.5.13 database, such as water, steel and chemical material consumption, using the ReCiPe Midpoint method (H). The functional unit was the production and utilisation of 1 t of EL. EC and environment emissions were calculated based on the aforementioned functional unit.

3. Cornstalk-based EL Production

3.1 Project description

An EL plant (land occupation, 20,000 m^2) with 3,000 t/a cornstalk (feedstock) consumption was used as a baseline case; EL fuel is produced along with furfural – the main by-product – in the plant, which is located in Henan Province, China. Cornstalk growth around the plant is abundant. When the cornstalk moisture content is 15%, about 3,530 t will be consumed in the plant annually. Henan is the biggest agricultural province in China and is rich in biomass energy resources. More than 50 million tonnes of grain were produced in the past year, and almost one-third of that was corn [38]. A photographic view of the plant is shown in Fig. 2. Data for the study were mainly gathered from the plant.

Fig. 2 A photographic view of the biomass to EL plant with 3,000 t/a cornstalk (feedstock) consumption.

3.2 Life Cycle Inventory (LCI) analysis of key stages

3.2.1 Cornstalk growth

If corn mass underproduction and planted area reduction are not considered, the CO_2 cycle can last indefinitely, and cornstalk can be used as a circulation pattern biomass [39]. CO_2 is produced during cornstalk utilisation but is reabsorbed as the cornstalk grows. Absorption of CO_2 by cornstalk can be described simply by the following reaction:

$$CO_2 + H_2O \xrightarrow[\text{Chlorophyl}]{\text{Photosynthesis}} (CH_2O) + O_2 \quad (1)$$

Three possible hypotheses have been suggested for assessing material use, EC and emissions in cornstalk growth: (a) EC and emissions are all allocated to corn because cornstalk is agricultural waste, (b) half of the EC and emissions can be allocated to food production and half to cornstalk growth, and (c) EC and emissions are allocated to different components of the system according to food and corn stalk revenues.

A large amount of cornstalk is unused and burned in fields, mainly due to the low price of cornstalk and increasingly high labour prices in China. Cornstalk is usually considered a waste product or by-product of the corn production process; however a growing amount of cornstalk is recycled and reused in China, commensurate with the development of technologies that aid its use in energy production, fertiliser production, feed production and biochemical processes. Hence, the basic calculations in this study are based on hypothesis (c). The residue to crop ratio for corn is about 1.2, and the price of corn is about 10 times that of cornstalk. Thus, corn generates about 90% of the total revenue, with cornstalk generating about 10%. Accordingly, the allocation percentages of the EC and environmental emissions for these agricultural stages were set to be 90% for corn and 10% for cornstalk. Data on relative consumption in corn production were obtained from the SimaPro database.

A sketch map of the main material, energy, CO_2 absorbance, and GHG and criteria emissions is shown in Fig. 3. In cornstalk growth, GHG emissions can be divided into inputs and outputs.

Fig. 3 Energy and emissions allocation for corn and cornstalk growth based on their revenue.

3.2.2 Cornstalk collection

Biomass resource analysis is the basis of biomass to EL production; it is important that abundant feedstock is available for production before establishing a plant. Henan province is the biggest agricultural province in China, and therefore the biggest producer of agricultural residues. Cornstalk and wheat straw are the main residues in the province. Crop fields can yield two crops a year; wheat represents about 95% of the total summer crop-cultivated land and is harvested in summer, while corn represents about 80% of the total autumn crop-cultivated land and is harvested in autumn [40]. The amount of crop straw can be calculated from the crop yield, crop-cultivated area and crop residue. When crop straw is used to produce energy, the reduction coefficient of the cornstalk should be considered:

$$J = \sum_{i=1}^{n} S_i Y_i \theta_i \eta_i \quad (2)$$

where J is the total amount of crop straw that can be collected for energy utilisation, in theory, in t/a; S_i is the cultivated area of the i_{th} crop in km^2/a; Y_i is the crop yield of the i_{th} crop in t/(km²·a); θ_i is the residue-to-crop ratio for the i_{th} crop in kg/kg; and η_i is the reduction coefficient of the i_{th} crop straw in %.

The plant located in Xinxiang, Henan province has a total cultivated area of corn of more than 200 thousand ha, and an average corn yield of about 7.50 t/ha, which is equal to 750 t/km^2. The residue-to-crop ratio for the corn in Xinxiang is 1.2. The reduction coefficient of cornstalk is about 0.6. According to Eq. (2), the total amount of cornstalk that can be used for energy production is about 1.2 Mt [38]. This is sufficient cornstalk for the EL plant.

The collection radius of the cornstalk can be calculated using the following expression:

$$Z = \pi R^2 = P_y / \left[Y\theta(1-\eta)\xi\lambda \right] \tag{3}$$

where Z is the cornstalk collection area in km^2; R is the collection radius of the cornstalk in km; P_y is the annual cornstalk consumption in t/a; Y is the corn yield in t/(km^2·a); θ is the cornstalk to corn ratio in kg/kg; η is the reduction coefficient of the cornstalk (reducing the utilisation for fertilisers, foraging, industrial material and edible fungi feedstock); ξ is the cultivated land coefficient (where the cultivated land area accounts for the local area ratio between the biomass and EL plant); and λ is the corn cultivated land coefficient (where the corn cultivated land area accounts for the total crop cultivated land area).

Data relating to the cornstalk collected for the EL plant are listed in Table 1.

Table 1 Cornstalk collection data for a 3,000 t cornstalk to EL plant.

Scale (t/a)	P_y (t/a)	Y (t/(km^2·a))	θ	η	ξ	λ	R (km)
3000	3530	750	1.2	0.60	0.67	0.80	2.41

There is a distance of about 3 km from the EL plant to the core of the corn planting area, so the collection radius of the cornstalk is R' = 2.41+3 = 5.41 km for the plant.

The hypothetical transportation distance at no load and full load is 1:1; a mathematical model of the oil consumption that considers vehicle and transportation parameters can be calculated using the following expression [41,42]:

$$\left[g_1 (L/2v_1) + g_0 (L/2v_0) \right] N_{en} / \left[m(L/2) \right] = (g_1/v_1 + g_0/v_0)(N_{en}/m) = q \tag{4}$$

where g_1 is the unit fuel consumption at full load in kg/kWh; g_0 is the unit fuel consumption at no load in kg/kWh; v_1 is the average vehicle speed at full load in km/h; v_0 is the average vehicle speed at no load in km/h; N_{en} is the vehicle rated power in kW; m is rated load mass of the vehicle in 10^3 kg; L is the average transport distance of a single vehicle in km; and q is the oil consumption per km and per kg of the vehicle in kg/(kg·km). The average transport distance is equal to twice the actual collection radius of the cornstalk, $L = 2R'$.

There is a relationship between the vehicle mass and vehicle rated power: the larger the value of m, the larger N_{en} is, and the ratio of the vehicle rated power to the vehicle mass is expressed as $k_n = N_{en}/m$. The heat quantity of the diesel oil consumption for an average vehicle can be calculated using the following expression:

$$Q_o = qLm'E_o \tag{5}$$

where Q_o is the heat quantity of diesel oil consumption in an average vehicle in MJ; m' is the average vehicle load in kg; and E_o is the low heating value of diesel oil in MJ/kg (where the average low heating value is 42.50 MJ/kg).

An agricultural diesel vehicle was chosen to transport the cornstalk from the farm to the EL production plant. Because of the low density of cornstalk, only approximately 500 kg of cornstalk can be transported on each occasion. Half of that is the average vehicle load. Under rural road conditions, the base parameters for the cornstalk transport vehicle are listed in Table 2.

Table 2 Base parameters for a cornstalk transportation vehicle.

Speed at full load (km/h)	Speed at no load (km/h)	Oil consumption at full load (kg/kWh)	Oil consumption at no load (kg/kWh)	Ratio of vehicle rated power to rated load mass of vehicle (kW/kg)
25	35	0.382	0.310	0.0072

The oil consumption for collection of 3,530 t cornstalk can be calculated using Eqs. (4), (5) and Table 2. Vehicles used for transportation were not taken into account in the LCA because they will be used outside this study. On the basis of oil consumption and direct environmental emission factors for the vehicle [39] (see Table 3), EC, GHG emissions and criteria emissions were calculated.

Table 3 Direct environmental emissions factors from transportation tools (g/MJ).

GHG emissions		Criteria emissions				
CH_4	CO_2	NMVOC	CO	NO_x	PM	SO_2

0.0042	74.0371	0.0853	0.4739	0.2843	0.0413	0.0160

EC, GHG emissions and criteria emissions for diesel production were calculated using SimaPro 8.0 software. The same method will be used in the EL transportation stage.

3.2.3 Cornstalk chopping

The particle size of the feedstock is an important physical and chemical characteristic, which indirectly affects the economy of biomass to EL plants, especially in the hydrolysation stage. In this study, it was assumed that the cornstalk needed to be chopped to a particle size ranging from 5 to 15 mm, with electricity consumption not more than 20 kWh/t. About 70,600 kWh is therefore consumed for chopping 3,530 t of cornstalk, and because the chopping machine is used only for cornstalk chopping and EL production, about 2 t of steel consumption should also be accounted for. The EC, GHG emissions and criteria emissions from electricity and steel consumption were calculated using the SimaPro 8.0 software. The same method will be used for steel consumption in the EL production stage.

The electricity consumption can be stated as a heat quantity of coal, and can be calculated using the following expression:

$$Q_c = 3.6E_e / \eta_e \eta_{grid} \tag{6}$$

where η_e is the average power generation efficiency in %; η_{grid} is the electricity transmission and distribution efficiency in %; E_e is the electricity consumption in kWh (with 1 kWh equal to 3.6 MJ); and Q_c is the heat quantity of the electricity equivalent to coal in MJ. In China, the average power generation efficiency is 37%, and the electricity transmission and distribution efficiency is 93% [43].

3.2.4 EL production

In the process of hydrolysation, cornstalk moisture should be a maximum of 15%, with a particle size between 5 and 15 mm. Hydrolysis residues are dried by solar energy so that the moisture content is 15% or less. The EC for solar drying of hydrolysis residues is not considered in the LCA. Data on the proximate analysis (as-received basis) and chemical analysis (air-dried basis) of the cornstalk used in the plant are shown in Table 4.

Table 4 Proximate analysis and chemical analysis of cornstalk and hydrolysis residues (wt%).

	Proximate analysis				Chemical analysis			
	V	FC	A	M	Ch1	Ch2	Ch3	Ch4
Cornstalk	64.69	15.23	5.15	14.93	33.85	27.46	16.42	22.27
Hydrolysis residues	67.13	11.56	6.41	14.90	11.18	3.63	36.16	49.04

V: volatile; FC: fixed carbon; A: ash; M: moisture; Ch1: Cellulose; Ch2: Hemicellulose; Ch3: Lignin; Ch4: Others

The LHV of cornstalk is about 14.38 MJ/kg (air-dried basis), and that of the hydrolysis residue is about 18.52 MJ/kg (air-dried basis).

Hydrolysation is a two-stage process with high- and low-pressure components. Several hydrolysis reactors are used to maintain continuous hydrolysis, and the hydrolysis products are separated by intermittent refinery. The hydrolysis temperature is about 210 ^{o}C with a high steam pressure. Hydrolysis products mixed with levulinate acid and furfural enter the heating exchange at 180 ^{o}C. After distillation of the hydrolysis products, levulinate acid and furfural are obtained for esterification and extraction. Esterification of levulinate acid and ethanol is conducted at 100 ^{o}C, and EL is finally obtained by dehydration. The process of EL production is shown in Fig. 4.

Fig. 4 A schematic layout on the main production process of cornstalk to EL and furfural.

The material balance in the process of EL production is shown in Table 5. To protect intellectual property rights, most data are stated as averages.

Table 5 Material balance in the process of ethyl levulinate (EL) production

Input system		Output system	
Items	Unit: t/a	Items	Unit: t/a
Cornstalk (about 15% moisture)	3530	EL	372
Sulphuric acid	75	Furfural [by-product]	360
Sodium carbonate	30	Sodium formate [by-product]	25

Ethanol	120	Hydrolysis residues	1315
Catalyst	15	Circulating water, catalyst, extractant	34241
Water	35470	Waste water	2160
		Evaporation losses	767
Total	39240	Total	39240

In the process of EL production, water is mainly used for hydrolysation, distillation, separation and purification, heating steam, condensing steam, and circulating cooling water. The steel consumption is about 20 tonnes in this stage. The assumed lifetime of the industry is 12 years.

Electricity is consumed across several pumps, fans and lamps in the EL production process, with a total electric power of about 80 kW. The system operates for about 300 days per year, and about 12 h per day, giving a total electricity consumption of about 288,000 kWh. The consumption of 1,000 tonnes of cornstalk as fuel should also be added. The primary EC, and GHG and criteria emissions from electricity in EL production, can be calculated by the same method as used in the cornstalk chopping stage.

In the process of EL production, steam heat is supplied by a biomass boiler burning with fuel blends of 1,000 t cornstalk and 1,315 t hydrolysis residues. The thermal efficiency of the biomass boiler is about 90%. About 127 t biomass ash are discharged from biomass combustion per year. Cornstalk is chopped and hydrolysis residues are dried using solar energy. The LCA of the 1,000 t cornstalk used for boiler burning is mainly divided into the four stages of cornstalk processing (growth, collection, chopping and combustion). The primary EC and GHG emissions and criteria emissions of the burned cornstalk in the cornstalk growth, collection and chopping stages are analysed using the same methods as described in the stages above. The emission components during the combustion stage were measured using an exhaust gas analyser (Testo360; Testo Instruments Inc., Lenzkirch, Germany) and gas chromatography (7890A; Agilent, Wilmington, DE, USA). The direct environmental emissions from the biomass combustion boiler are listed in Table 6.

Table 6 Direct environmental emissions factors for the biomass combustion boiler (g/MJ).

GHG emissions		Criteria emissions				
CH_4	CO_2	NMVOC	CO	NO_x	PM	SO_2
0.0036	82.5027	0.0021	0.019	0.0208	0.0189	0.0033

By-products are produced in the EL production stage, and the LCA for EC and environmental emissions from furfural and sodium formate should be reduced. There is no detailed life cycle data for furfural in China; however, the EC was around 600 kWh/t in reference [44]. The LCA for furfural in this study used 600 kWh for 1 t furfural. The LCA of sodium formate was calculated using SimaPro 8.0 software.

3.2.5 EL transportation

Assuming EL can be purchased and sold by gas stations, the average distance between an EL plant and a gas station is 20 km. Middle oil transportation vehicles are used to transport EL, and approximately 4 t of EL can be transported during each journey. The LCA for EL transportation was calculated using the SimaPro 8.0 software.

3.2.6 EL utilisation in vehicles

According to the investigation of diesel and EL blended fuels, EL5 fuel blends (5% vol. EL and 95% vol. diesel) are in line with China's national standard for biodiesel fuel blends (B5). Engine powers and torques obtained using EL5 fuel blends are in general similar to those of diesel. Direct environmental emissions from our engine tests using diesel and EL5 are listed in Table 7. In the engine test, we were not able to measure N_2O emissions in the tests but these were expected to be very small in comparison to CO_2 emissions in terms of global warming potential [45].

Table 7 Direct environmental emissions factors from engine tests (g/MJ)[46].

	GHG emissions		Criteria emissions				
	CH_4	CO_2	NMVOC	CO	NO_x	PM	SO_2
Diesel	0.0051	75.6090	0.0543	0.6468	0.2218	0.0602	0.0162
EL5	0.0048	82.0234	0.0520	0.5077	0.2163	0.0285	0.0154
EL	-0.0034	258.0465	-0.0111	-3.3095	0.0654	-0.8414	-0.0066

As can be seen from Table 7, some EL5 emissions were significantly lower than those obtained using neat diesel, such as CO and PM10. The LHVs of diesel, EL5 and EL, were 35.53 MJ/L (42.50 MJ/kg), 34.98 MJ/L (41.42 MJ/kg) and 24.60 MJ/L (24.21 MJ/kg), respectively. Thus, 1.23 MJ of EL and 33.75 MJ of diesel comprise 34.98 MJ EL5, which represents 3.52% and 96.48% of the LHV of EL5. Hence, we can calculate the emissions factors (EF) for EL5, using EF for EL5 = EF of EL × 3.52%

+ EF of diesel × 96.48%. The EF values for EL are listed in Table 7.

Although EL5 can be used in unmodified diesel engines, and environmental emissions for this scenario could be obtained, further research should be conducted to assess environmental emissions from driving passenger vehicles fuelled with EL5.

3.2.7 LCI analysis

Considering all stages from cornstalk growth to EL transportation, the LCI for energy and material consumption is shown in Table 8. For the EL utilisation stage, only emissions are compared, and this parameter is calculated last and not included in Table 8.

Table 8 Life cycle inventory. Values are presented per functional unit (i.e. 1 t of EL).

	Amount	Unit
1. Cornstalk growth		
1.1 Diesel	10.49	kg
1.2 Electricity	19.82	kWh
1.3 Nitrogen fertiliser	13.61	kg
1.4 Phosphate fertiliser	4.72	kg
1.5 Potash fertiliser	5.80	kg
1.6 Pesticide	0.05	kg
1.7 Arable land occupation	1075.27	m^2
2. Cornstalk collection		
2.1 Diesel	17.84	kg
3. Cornstalk chopping		
3.1 Electricity	189.78	kWh
3.2 Steel (in life span)	0.45	kg
4. EL production		
4.1 Electricity	774.19	kWh
4.2 Biomass fuel (43.20% cornstalk)	6.22	ton
4.3 Steel (in life span)	4.48	kg
4.4 Water (waste)	5.81	ton
4.5 Ethanol	322.58	kg
4.6 Sulphuric acid	201.61	kg
4.7 Sodium carbonate	80.65	kg
4.8 Iron(III) chloride	40.32	kg
4.9 Biomass ash (waste)	341.40	kg
4.10 Industry land occupation	53.76	m^2
4.11 Furfural (production)	-967.74	kg
4.12 Sodium formate (production)	-67.20	kg
5. EL transportation		
Diesel	3.05	kg

4. Results and Discussion

Fig. 5 shows the LCA EC results. The total EC was 109.9 GJ for 1 functional unit (1 t EL); 104.1 GJ of that was from biomass energy, which represents 94.7% of the total EC. The LHV of EL is 24.2 GJ/t, so the total EC is equal to 4.54 MJ/MJ, and 4.30 MJ/MJ of that was biomass energy. The EC was highest in the EL production stage, representing 96.8% of the total EC, and 97.8% of that in this stage was biomass energy. In general, with the exception of biomass EC, fossil fuel EC in the EL production stage was also highest, accounting for 2.1% of the total EC. EC in the cornstalk growth stage was similar to that in the cornstalk collection stage. EC in the EL transportation was the lowest. In addition, without considering biomass energy, EC in the EL production stage was still the highest, representing 39.5% of the total fossil fuel EC. The EC ratio of biomass energy to fossil energy was 17.9 in the LCA, indicating good utilisation of renewable energy in the cornstalk EL production process.

Fig. 5 LCA of energy consumption distribution from cornstalk growth to EL transportation (i.e. 1 t of EL).

The LCA of GHG emissions is shown in Fig. 6. A large quantity of CO_2 is fixed during cornstalk growth – much higher than the allocation – such that the value of GHG emissions was negative. GHG emissions were positive in the cornstalk collection, cornstalk chopping, EL production, EL transportation and EL utilisation stages. Negative GHG emissions were 83.3% of positive GHG emissions, indicating that cornstalk-based EL has a large capacity for reduction of GHG emissions. The EL production and utilisation stages were the main positive GHG emissions stages in the LCA, representing 53.4% and 44.5% of the total positive GHG emissions, respectively. There were only small positive GHG emissions in other stages. In addition, if 1 t EL is burned completely in oxygen, only 2.14 t CO_2 will be emitted based on the equation $2C_7H_{12}O_3 + 17O_2 = 14CO_2 + 12H_2O$; however, about 6.25 t CO_2 were emitted in the utilisation stage, mainly due to complete combustion efficiency with diesel and a reduction in CO and smoke emissions. Net GHG emissions in the LCA were about 2.34 t $CO_{2,eq}$/t (96.6 g/MJ).

Fig. 6 LCA of GHG emissions from cornstalk growth to EL utilisation (i.e. 1 t of EL).

The LCA for criteria emissions is shown in Fig. 7. Criteria emissions of NMVOC, CO, PM10 and SO_2 show a negative value in the EL utilisation stage, so it makes sense that these criteria emissions will decrease when using EL as an additive fuel. Moreover, criteria emissions of CO and PM10 show a negative value across the whole LCA, because the reductions in emissions in the utilisation stage are 20.5 times and 7.0 times the total for other stages, for CO and PM10, respectively. Total NMVOC, CO, NO_x, PM10 and SO_2 in the LCA were 0.30, -76.22, 8.03, -17.47 and 6.83 kg/t (equivalent to 0.01, -3.15, 0.33, -0.72 and 0.28 g/MJ), respectively. There is a small amount of positive VOC emissions in the LCA, because the reduction in VOC emissions in the utilisation stage represents 46.9% of total positive NMVOC emissions in the LCA. However, emissions of NO_x show a positive value in all stages of the LCA, especially in the EL production stage, which represents 62.4% of total NO_x emissions. Although there was a small reduction in SO_2 emissions in the utilisation stage, SO_2 emissions show a positive value in the LCA due to large emissions in the EL production stage, representing 67.8% of total positive SO_2 emissions.

Fig. 7 LCA of criteria emissions from cornstalk growth to EL utilisation (i.e. 1 t of EL).

5. Sensitivity and Uncertainty Analysis

5.1 Sensitivity analysis

In the cornstalk growth stage, EC and environmental emissions were allocated into different parts according to corn and cornstalk revenues; however, these revenues may be variable. Taking the basic LCA of cornstalk-based EL as Baseline case, a sensitivity analysis was conducted using scenarios including different allocations between cornstalk and corn. The hypotheses presented here were as follows: (1) EC and emissions are all allocated to corn, and cornstalk is treated as agricultural waste, denoted as Scenario 1; and (2) assuming the price of cornstalk increases significantly, the allocation percentages of EC and environmental emissions are allocated 50% to cornstalk, denoted as Scenario 2. Baseline case was taken as a baseline, and all coefficients were set to be 1 or -1 for positive and negative values, respectively. Emissions and EC can therefore be standardised and transformed into values to make a concise comparison. Standardisation is performed using the following equation:

$$c_{j,i}=x_{j,i} / |x_{0,i}| \tag{7}$$

where, $c_{j,i}$ is the coefficient of other scenarios relative to Baseline case on the i_{th} emissions and EC values; $x_{0,i}$ is the value of the i_{th} emissions and EC values of Baseline case; and $x_{j,i}$ is the value of i_{th} emissions and EC values of other scenarios, j = 1, 2.

The LCA comparison of Baseline case, Scenarios 1 and 2 can be seen in Fig. 8.

Fig. 8 LCA sensitivity analysis of environmental emissions and EC based on variations between allocations of cornstalk and corn.

As shown in Fig. 8, compared to Baseline case, all emissions and the EC in Scenario 1 decreased, whereas those of Scenario 2 increased. The maximum decrease was observed in the NMVOC emissions in Scenario 1, with a 20% reduction; the maximum increase was observed in the NMVOC emissions in Scenario 2, with an 80% increase. Compared to Baseline case, larger decreases were found in Scenario 1 for emissions of CH_4, NO_x and SO_2, which were reduced by between 8 and 13%; other emissions, and the EC for Scenario 1, did not show significant changes. Larger increases were found in Scenario 2 for emissions of CH_4, NO_x and SO_2, which increased between 29 and 48%. Other emissions for Scenario 2 did not change much. In general, changes in Scenario 1 were smaller than those in Scenario 2, because only a 10% emissions and EC allocation was provided to cornstalk in Baseline case.

Cereal fields can yield two crops per year or three crops every 2 years in Northern China. The time interval between harvesting and planting is short: fields must therefore be cleared, or straw must be used in time, or some cornstalk may be burned directly in the field. This will result in air pollution or other social problems, so recovery and reuse of agricultural wastes are effective pathways for eliminating emissions [47]. It is therefore important to compare a scenario where cornstalk is burned directly, denoted Scenario 3. The EC in Scenario 3 was calculated using the same allocation to cornstalk growth ratio as employed for Baseline case. There is no public research on emissions from directly burned cornstalk; hence, data from SimaPro 8.0.5.13 were used. The emissions from stalk burning have been calculated based on standard emission factors for stalk combustion in a 6 kW capacity heater; however, the LCA of the heater is not included in the study. The cornstalk growth stage should be considered, including allocation and carbon absorbance, which is the same as for Baseline case. Following the analysis in the stages described above, it was found that 10.75 tonnes of cornstalk for feedstock and fuel are consumed to produce 1 functional unit of EL. An LCA comparison between cornstalk burned directly and cornstalk used to produce EL is shown in Table 9.

Table 9 LCA comparison of cornstalk burned directly and cornstalk used to produce EL

	GHG emissions (kg)		Criteria emissions (kg)					EC (MJ)
	CH_4	CO_2	NMVOC	CO	NOx	PM10	SO_2	Fossil energy
Baseline case	4.47	2236.28	0.30	-76.22	8.03	-17.47	6.83	5826.45
Scenario 3	3.25	-1140.05	1.47	528.01	24.00	17.40	0.82	40.41

As can be seen from Table 9, compared to Baseline case, emissions of NMVOC, CO, NO_x and PM10 increased in Scenario 3 by 383.5%, 792.7%, 198.8% and 199.6%, respectively. SO_2 emissions decreased by 88.1%.

This increase in criteria emissions may be attributed to low efficiency combustion during direct burning; it is therefore essential to deal with agricultural residues with a high conversion and utilisation efficiency. The higher SO_2 emissions in Baseline case are due to coal-based electricity consumption.

However, compared to Baseline case, CH_4 and CO_2 emissions were lower by 27.4% and 151.0%, respectively, for Scenario 3. Emissions including NMVOC, CO and PM10 can increase unburned carbon, resulting in reduced CO_2 emissions.

The EC of Scenario 3 was calculated from cornstalk growth under fossil fuel energy. Here, stalks are burned directly without being used as an energy fuel, so it is appropriate to subtract the biomass EC from Baseline case. Compared to Baseline case, the fossil EC in Scenario 3 decreased by 99.3%.

5.2 Uncertainty analysis

To date this demonstration project is the only biomass based EL production plant in China. According to the operation of this plant, there are still many uncertainties in the process of EL production regarding the economic and even technological feasibility of EL with many assumptions required at each step of the process to get an optimum result considering energy consumption and environmental emissions. Because of intellectual property rights, most data available from the plant are in the form of average values, which means uncertainty analysis is not possible at this stage. In addition, there is conflict between economic benefit and environmental benefit of EL production, which need to be keeping balance to make a decision on EL production with considering both environment and economy. Sometimes, the economic viability of EL production may be a very big limitation to that of environmental sustainability. With development of biomass-based EL industry, the related technologies will be transparent and environment-friendly will be more strictly in production process. Uncertainty analysis will be conducted with careful investigation in the EL production plant or similar biomass-based EL plants in the future. There is also uncertainty in the energy efficiency and emissions results for EL from the engine tests due to the limitations of our experimental set up. This will be further explored in future work.

6. Conclusions

In this paper, the first LCA of energy consumption and environmental emissions of cornstalk-based EL were performed with detailed foreground data from a demonstration project in China. Life cycle EC was found to be 109.9 GJ/t (or 4.54 MJ/MJ), of which 94.7% was biomass energy. The EC in the EL production stage were the highest, representing 96.8% of the total EC, 100% of total biomass energy and 39.5% of the total fossil fuel EC. The EC ratio of biomass energy to fossil energy was 17.9 in the LCA, which showed good utilisation of renewable energy in the cornstalk-based EL production. The net life cycle GHG emissions were 2.34 t $CO_{2,eq}$/t (or 96.61 g/MJ). Cornstalk-based EL has a large capacity for GHG emission reduction, because the negative GHG emissions were equal to 83.3% of the positive. The EL production and utilisation stages were the main positive GHG emissions stages, representing 53.4% and 44.5% of the total positive, respectively. Life cycle criteria emissions of NMVOC, CO, NO_x, PM10 and SO_2 were 0.30, -76.22, 8.03, -17.47 and 6.83 kg/t (or 0.01, -3.15, 0.33, -0.72 and 0.28 g/MJ), respectively. NMVOC, CO, PM10 and SO_2 emissions showed negative values in the EL utilisation stage because of reductions in these emissions when using EL as an additive fuel for more complete combustion of diesel.

The important processes in the LCA were the use of biomass energy in the EL production stage, and improvement of the combustion efficiency of EL-diesel blended fuel in the EL utilisation stage. These steps will offer the potential to enhance the utilisation efficiency of biomass resources and reduce air pollution. Further research will be conducted to assess other environmental impacts such as human toxicity, water footprint and natural land transformation of cornstalk-based EL to offer a more comprehensive view of its sustainability.

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Figure Captions

Fig. 1 System boundaries for LCA of cornstalk-based EL from cornstalk growth to EL utilisation (EL5).

Fig. 2 A photographic view of the biomass to EL plant with 3,000 t/a cornstalk (feedstock) consumption.

Fig. 3 Energy and emissions allocation for corn and cornstalk growth based on their revenue.

Fig. 4 A schematic layout on the main production process of cornstalk to EL and furfural.

Fig. 5 LCA of energy consumption distribution from cornstalk growth to EL transportation (i.e. 1 t of EL).

Fig. 6 LCA of GHG emissions from cornstalk growth to EL utilisation (i.e. 1 t of EL).

Fig. 7 LCA of criteria emissions from cornstalk growth to EL utilisation (i.e. 1 t of EL).

Fig. 8 LCA sensitivity analysis of environmental emissions and EC based on variations between allocations of cornstalk and corn.