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ORIGINAL ARTICLE

Life cycle assessment and life cycle cost analysis of Jatropha biodiesel production in China

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Abstract

In this study, a Life Cycle Cost (LCC) is integrated within a life cycle assessment (LCA) model to comprehensively evaluate the energy, environment, and economic impacts of the Jatropha biodiesel production in China. The total energy consumption of producing 1 ton of Jatropha biodiesel is 17566.16 MJ, in which fertilizer utilization and methanol production consume 78.14% and 18.65% of the overall energy consumption, respectively. The production of 1 ton of Jatropha biodiesel emits a number of pollutants, including 1184.52 kg of CO_2, 5.86 kg of dust, 5.59 kg of NO_x, 2.67 kg of SO_2, 2.38 kg of CH_4, and 1.05 kg of CO. By calculating and comparing their environmental impacts potentials, it was discovered that NO_x and dust emissions during the fertilizer application, combustion of Jatropha shells, and methanol production urgently require improvement, as they contribute to serious global warming and particulate matter formation issues. LCC study shows that the cost of Jatropha biodiesel is 796.32 USD/ton, which is mostly contributed by Jatropha oil cost (44.37% of the total cost) and human input (26.70% of the total cost). Additional profits are generated by the combustion of Jatropha shells and glycerol by-product, which can compensate 16.76% of the cost of Jatropha biodiesel.

Keywords Life cycle assessment · Life cycle cost · Jatropha biodiesel · Heterogeneous catalyst · Sensitivity analysis · China

1 Introduction

The world energy consumption is rapidly growing with the continuous growth of the global population and economy [1, 2]. The utilization of conventional fossil fuels has been considered a major contributor to irreversible environmental deterioration, which imposed negative impacts on human health. Therefore, the development of renewable energy is not only necessary but also an urgent need to sustain the future energy demand [3, 4]. In recent years, biodiesel is gaining paramount interest as a promising alternative to replace current diesel, owing to its facile production process and superior fuel properties [5]. Compared to petroleum fuels, the combustion of biodiesel leads to over 90% reduction of total unburned hydrocarbons (HC) and a 75–90% decrease in polycyclic aromatic hydrocarbon (PAHs) [6]. Importantly, using biodiesel in transportation vehicles resulted in 78, 46.7, and 66.7% reductions in the net carbon dioxide emission, carbon monoxide, and particulate matters [7], respectively, which can effectively mitigate the global warming effect [8]. Besides, there are several other advantages that biodiesel can offer, including its higher energy return, engine compatibility, higher combustion efficiency, higher cetane number, lower sulfur, renewability, and biodegradability [9].

In the last decades, the biofuel production and consumption rapidly grew in China, according to the Medium and Long-term Development Plan for Renewable Energy issued by the National Development and Reform Commission on August 31, 2007 [10]. The information about the biodiesel industry in China in recent years is given in Table 1 [11]. The production of biodiesel in China is far smaller than that of Indonesia and the USA (7900 and 6500 million liters) in 2019 [12]. One of the most

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Highlights
- LCA was integrated with LCC to assess environmental and economic impacts of Jatropha biodiesel.
- Fertilizer, Jatropha shell combustion, and methanol production are the main sources of pollution.
- 1 ton of Jatropha biodiesel needs 17566.16 MJ of total energy input.
- The cost of Jatropha biodiesel in China is 796.32 USD/ton.
- 44.37% of biodiesel cost is caused by the cost of feedstock oil.

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significant limitations for the further expansion of biodiesel in China is the availability of feedstock in China. Unlike bioethanol plants, the Chinese biodiesel production plants are often small-scaled and private owned [13], whose feedstocks are primarily relying on waste cooking oil or animal fat. Nevertheless, the prices for such feedstocks are not economic for biodiesel production, as they are also demanded for feed industry and other chemical processing [13]. In addition, the lack of recognized subsidies to promote biodiesel production and usage results in undermining the full capacity for biodiesel production. According to the US Energy Information Administration, the Chinese biodiesel refinery capacity use was only 30% [14]. To avoid food competition, inedible oil resources are gaining growing attention, including *Jatropha curcas* (Jatropha), *Aza-rdirachta indica* (neem), *Hevea brasiliensis* (rubber seed tree), *P. pinnata* (karanja or honge), *Calophyllum inophyllum* nagchampa, *M. indica* and *Madhuca longifolia* (mahua), *Simmondsia chinensis* (jojoba), and *Ceiba pentandra* (silk cotton tree) [15].

Among inedible oil resources, Jatropha is identified as one of the most suitable feedstock due to its high oil content, strong resistance to drought and pests, and good adaptability to the soil condition [16, 17]. The seed production is up to 0.8 kg/m^2 annually, and the oil content of the seeds is about 38–41 wt.% and the oil content of kernel is between 49 and 62 wt.% [18]. Jatropha is especially abundant in the southern part of China, especially in Guangxi, Yunnan, Sichuan, and Guizhou, with a total forest area of 20×10^4 ha [19]. In the natural environment in China, seed yield per hectare is about 0.75 ton annually and the oil yield is about 0.225 ton annually, which results in 150,000 ton of seed production and 45,000 ton of oil [19]. Jatropha was introduced from the Caribbean region to Asia and China by Portuguese in the fourteenth to fifteenth century [20]. Jatropha oil was directly burned for lighting in the earlier time. In the 1930s, Jatropha was firstly applied as the water and soil conservation plant. In the late 1970s, the research and development of Jatropha oil as a raw material for biodiesel production started to emerge [19]. In 2005, the National Forestry Administration of China initiated a national Jatropha biodiesel program, in order to fully develop Jatropha biodiesel industry [19]. The cultivation of Jatropha also promotes the development of rural area and stimulate the local economy, which results in an economically profitable, ecologically viable, and socially acceptable agroforestry system. Industrial stakeholders, such as Sinopec, Petro, China, China National Offshore Oil Corporation, and China Oil and Foodstuffs Corporation, have been investing in Jatropha forest cultivation and biodiesel processing innovation and technology.

It has been widely proved that Jatropha is a highly promising oil feedstock to produce biodiesel. In addition to the selection of more suitable feedstock oils, the dominant trend in biodiesel research continues to be the synthesis of innovative and efficient catalysts [21–23]. There are also a few studies that used software modeling to design, optimize, and monitor biodiesel production processes [24, 25]. However, the energy consumption, emissions, and economics of the process need to be fully investigated and understood upon selecting an uncommon feedstock oil for biodiesel production. Therefore, to promote the production and utilization of Jatropha biodiesel, it is necessary to evaluate its entire up-production process. A life cycle assessment (LCA) is a systematic tool that assesses the environmental influence of a process, product, or activity from “cradle to grave” [26]. From the early 1970s to today, LCA is fully developed and applied in various scenarios and cases [27–31]. LCA boundary is set up to include six stages: (1) extraction and processing of feedstock; (2) manufacture; (3) transportation and distribution; (4) utilization, reuse, and maintenance; (5) recycling; and (6) disposal [32]. Therefore, LCA helps to identify the most important impacts and activities in the lifecycle that require improvement. According to the International Organisation for Standardisation (ISO, 14,040:2006), an LCA study is composed of four phases, including goal definition and scoping, inventory analysis, impact assessment, and interpretation [33, 34].

There are several LCA studies on the preparation of biodiesel from Jatropha seed, especially from India [27], Malaysia [35], Thailand [36], Mexico [30], Zimbabwe [37], and Indonesia [38], but few studies have been reported from China. Most of the studies chose waste cooking oil (WCO) or palm oil as the feedstock oil, and the evaluation method was only using LCA or Life Cycle Cost (LCC). More importantly, most of the currently reported LCA studies of biodiesel are based on a homogeneous base catalyst system, using NaOH [27, 30, 39], KOH [40], and $NaOCH_3$ [41] as catalysts to promote transesterification reactions of oil feedstock. Such a homogeneous system is suffered from the drawbacks of generating a large amount of waste water and complicated catalyst separation [42, 43]. Consequently, the heterogeneous catalytic system is gaining inevitable interests in various chemical reactions, which has presented great environmental and economic potentials in chemical industries, since it is easily separable and reusable [44, 45]. As a heterogeneous base catalyst, $Ca(OCH_3)_2$ has been extensively studied and applied in the transesterification reactions to produce biodiesel and it showed excellent catalytic activity [46–49], while its LCA study has not yet been reported. Although the application of heterogeneous catalysts is still at laboratory stage and has not been expanded to industrial scale, its LCA study has instructive significance and can provide insightful guidance for industrial development of biodiesel.

It is highlighted that $Ca(OCH_3)_2$ was chosen as a novel heterogeneous catalyst for transesterification of Jatropha

Table 1 Information about biodiesel industry in China [11]

Unit: million liters	2015	2016	2017	2018	2019	2020
Production	787	909	1043	834	939	1455
Consumption	793	841	867	1330	1140	800
Imports	33	8	18	853	953	60
Exports	27	76	194	357	752	715
Number of plants	53	48	46	44	40	42

oil to produce biodiesel in this study, to evaluate its real industrial potential in biodiesel production and utilization. In addition, a LCC is integrated within the LCA boundary model to assess economic feasibility of the process. Both methods have been used to study biodiesel production from different feedstock oils (soybean oil, microalgae oil WCO, etc.) and most of the processes used homogeneous catalytic systems (Table 2). However, LCA and LCC study of Jatropha biodiesel production using heterogeneous catalytic system is not yet reported. In this work, the energy, environmental, and economic impacts of the Jatropha biodiesel that are produced from heterogeneous catalytic system are comprehensively investigated, to provide a holistic overview of its sustainability and help with decision-making of biodiesel industry development.

2 Materials and methods

Jatropha oil is applied as the oil feedstock for transesterification to produce biodiesel. Its general physicochemical properties are presented in Table 3. Due to its relatively high acid value, a homogeneous base catalyst (e.g., NaOH, KOH) is not suitable for its direct transesterification. Meanwhile, Jatropha oil can be directly converted to biodiesel with the heterogeneous base catalyst under relatively moderate reaction conditions [57]. The physical and chemical properties of Jatropha biodiesel are presented in Table 4. The properties of Jatropha biodiesel [58–60] are similar to that of diesel [61], with the advantages of low viscosity, high flash point, and high cetane number. Biodiesel produced from Jatropha oil meets American Society of Testing Materials (ASTM) [59] biodiesel standard and can be used directly in the engine to replace petroleum diesel [62, 63].

2.1 Objective and scope

The main objective of the LCA and LCC in this study is to evaluate the energy consumption and environmental emissions during the life cycle of Jatropha biodiesel under the China condition from cradle to wheel, quantify the impacts on the environment, compare the cost of each stage in the life cycle and analyze the common benefits of environment and economy.

In this study, the LCA method was used to evaluate the life cycle of Jatropha biodiesel under the China condition. The system boundary includes Jatropha planting, extracting Jatropha oil from the seeds to produce biodiesel, and using this biodiesel in vehicles. The energy consumption and environmental emissions at different stages were investigated, to quantitatively evaluate the environmental impact and types of the whole process. On the basis of the LCA boundary framework, LCC is incorporated to evaluate the economic feasibility of Jatropha biodiesel production.

2.2 Functional unit and assumptions

The functional unit is the preparation and utilization of one ton of Jatropha biodiesel by an average car on an average road, so that it is easier to be compared with diesel and other types of biodiesel. In the LCA of Jatropha biodiesel production, the following assumptions are made:

- Jatropha trees have been grown for 3–4 years and the seeds yields are relatively stable [64]. The age of Jatropha trees is assumed, because only when the trees are 3 years old, they will give stable fruits production [65].
- In order to reduce transportation costs, the oil extraction equipment is nearby (within 2 km) the biodiesel production plant. This distance is assumed on the basis of average distance from previously published work [53, 66].
- The capacity of the biodiesel plant is 100, 000 t/year and the lifetime of the biodiesel plant is 30 years [53].
- The separation efficiency of biodiesel and glycerol is 100% for the maximizing of resource utilization.
- Economic benefits generated from by-product seed cake, shell combustion for power generation, and glycerol are considered in the Jatropha biodiesel production process.
- Biodiesel is used at full load condition in diesel engines, so that the biodiesel is combusted in the same working condition, reducing the error of energy consumption and pollutant emission [64].
- The Chinese government strongly supports renewable energy production, and allocated corresponding land for

Jatropha cultivation, so land cost is not taken into account when calculating the life cycle cost [67].

2.3 System boundary

The system boundary defines the basic components and elements that are composed in the LCA study. The geographic boundary selected for the current study is China. Figure 1 shows the life cycle system boundary of Jatropha biodiesel production in the current study, including Jatropha plantation, seed harvest and separation, oil extraction, biodiesel production and by-production application, biodiesel transportation, and biodiesel utilization in a vehicle. The system boundary also presents the main

Table 2 LCA and LCC studies on biodiesel production

Feedstock	Catalyst	Method	Location	Results	Ref
Soybean oil and WCO	NaOH and lipase	LCA	Brazil	Compared to alkali-catalyzed transesterification, enzyme-catalyzed methods have a significantly reduced environmental impact. The enzyme-catalyzed process with WCO as feedstock shows better LCA results	[50]
WCO	H_2SO_4 and CaO	LCC	China	The cost of producing 1 ton of WCO biodiesel is 990.8 USD (6291.56 RMB), which is 65.28% higher than that of diesel. WCO requires pre-treatment and creates additional processing costs, which account for 15.6% of the total cost	[51]
Crude palm oil (CPO) and WCO	Pyrolysis	LCA	Thailand	The global warming potential (GWP) makes the largest contribution to the overall environmental impact and the pyrolysis process makes the largest contribution to all environmental impacts. The WCO and CPO biodiesel production processes contribute 70.45 g CO_2 eq./MJ and 61.5 g CO_2 eq./MJ, respectively	[52]
WCO	H_2SO_4 and NaOH	LCA and LCC	China	WCO biodiesel has better environmental performance than fossil diesel, but has a greater environmental impact on certain categories such as climate change (CC), particulate matter formation (PMF), and human toxicity (HT). The cost of WCO biodiesel is 31% higher than that of fossil diesel, and WCO collection accounts for the largest proportion of LCC, followed by the methanol cost	[53]
WCO, palm oil	Alkali catalyzed and acid catalyzed	LCA and LCC	Portugal	The production of biodiesel using WCO as feedstock has a lower environmental impact than palm oil. Although the WCO biodiesel production process is more expensive in terms of initial investment, it is more profitable in the long-term	[54]
Palm oil	NaOH	LCA	Brazil	The biodiesel production process reduced fossil energy consumption by 9.6 kJ $MJ_{FAME}{}^{-1}$, and greenhouse gases (GHG) of 2.6 g CO_{2eq} $MJ_{FAEE}{}^{-1}$	[55]
Soapberry oil	N.A	LCA	China	The analysis was mainly focused on Soapberry cultivation under Chinese conditions. Soapberry plantations have good environmental performance, but low yield. From an environmental point of view, further improvements are needed in artificial fertilization	[56]
Jatropha oil	$Ca(OCH_3)_2$	LCA and LCC	China	Fertilizers, Jatropha shell combustion, and methanol production are the main sources of pollutant emissions. 1 ton of Jatropha biodiesel needs 17,566.16 MJ of total energy input. The cost of Jatropha biodiesel in China is 796.32 USD/ton, which is significantly influenced by the cost of feedstock oil	This work

$^*kJ\ MJ_{FAME}{}^{-1}$, energy consumption from 1 MJ of biodiesel production; $CO_{2eq}\ MJ_{FAEE}{}^{-1}$, CO_2 emissions from 1 MJ of biodiesel production inputs and outputs for the processes. The seed cake produced from the process can be used as fertilizer during Jatropha growth and Jatropha shells are used for direct combustion to generate electricity. The by-product, glycerol, is a value-added chemical, which can be sold as additives for fuels [68–70]. It is worth to mention that the preparation of $Ca(OCH_3)_2$ catalyst was considered a part of transesterification in our study. The outputs of the system include waste gas emission, waste water, biodiesel product, glycerol by-product, and heat.

2.4 Assessment indexes

The assessment indexes of biodiesel life cycle include the life cycle energy consumption and life cycle emissions. The life cycle emission inventories mainly study the emissions of CO_2, SO_2, NO_x, CH_4, CO, and dust pollutants. The pollutant data generated at different stages are collected from previous studies. Life cycle energy consumptions including electricity, coal, and fuel are calculated in units of MJ. The production of electricity will emit corresponding pollutants. Leng et al. [71] showed that 1 kW • h of electricity in China contributed to 413.452 g of CO_2, 1.268 g of SO_2, 0.532 g of NO_x, 0.004 g of CH_4, 0.041 g of CO, and 0.053 g of dust (PM_{10}).

The quantitative analysis of pollutant emissions during the life cycle of Jatropha biodiesel includes GWP (global warming potential), AP (acidification potential), EP (eutrophication potential), and PMF. GWP is used to characterize the ability of various greenhouse gases (e.g. CO_2, N_2O, CF_4, CH_4, NO_x) that cause global warming [72]. In this paper, CO_2, CH_4, and NO_x are considered the greenhouse gases and kg CO_2-eq is used as the reference unit for calculation. AP refers to the formation capacity of acid rain caused by SO_2 and NO_x, which is quantified using the reference unit of kg SO_2-eq. EP refers to the ability of pollutant discharge to deteriorate water quality (freshwater and marine), which is calculated using kg PO_4-eq as the reference units. PMF refers to the ability of pollutant emissions that increase particulate matter in the air. Particulate matter is a mixture of very small particles, and it is calculated using kg dust as the reference unit [40].

The life cycle cost (unit: USD) is a method to assess the total cost of a subject during its life cycle, which is composed of raw material cost, capital cost, operational cost, fuel cost, and land cost [73]. In this study, since the biodiesel industry is strongly supported by the government, it is assumed that the land is allocated by the government, so the calculation of land cost is neglected [67]. The economic feasibility of Jatropha biodiesel was investigated by calculating its LCC, in order to provide informative guidance for the government and companies

Table 3 Physicochemical properties of Jatropha oil produced in China [19]

Density (g/ml)	Refractive index (n_D)	Acid value (mg/mL)	Saponification value (mg/mL)	Molecular weight (g/mol)	Typical chemical composition (carbon chain number, %)						
					C16: 0	C18: 0	C18: 1	C18:2	C18: 3	C20: 0	C22:1
0.911–0.913	1.47	12.8–27.8	188.2–196.4	870.2–887.6	13.9	7.8	55.9	19.6	1.4	1.2	0.2

Table 4 Physiochemical properties of biodiesel and diesel [58–61]

Category	Calorific value (MJ/kg)	Viscosity (mm^2/s)	Density (g/mL)	Flash point (℃)	Cetane number	Saponification value	Acid value
Jatropha biodiesel	35.14	3.96	0.88	133	57	312.76	2.53
Diesel	37.50	4.27	0.83	57	49.50	-	-
Biodiesel standard ASTM	-	1.90–6.00	0.87–0.90	> 100	> 47	-	< 0.8

to develop biodiesel industries. The price of electricity in China is regulated by China Power Grid. The price of methanol is from East China Port of Methanol Market and calcium oxide price is from Changshu Sanhe Calcification Company. Other cost data are from references or market surveys.

2.5 Life cycle inventory (LCI) analysis

The LCI data were collected from various sources to model the environmental performance of Jatropha biodiesel. The target of LCI is to establish a data list on the basis of the functional unit and present the energy and mass flows during the Jatropha biodiesel production system. The production and utilization of Jatropha biodiesel comprise five stages, namely Jatropha plantation, the extraction of seed oil, transesterification of Jatropha oil, transportation at different stages, and utilization of Jatropha biodiesel (Fig. 1).

2.5.1 Jatropha plantation

Jatropha starts to produce fruits from the second year since its plantation and the yield stabilizes from the fourth or fifth year. Its average lifetime with effective fruit yield is up to 50 years [64]. Wild Jatropha can grow well under natural conditions, but the appropriate application of chemical fertilizers can enhance the yields of Jatropha seeds in large-scale artificial planting environments. In the process of following Jatropha oil extraction, a large amounts of by-product seed cakes will be produced. Seed cake yields vary according to the oil content of the Jatropha seeds, ranging between 30 and 37.5% of the total Jatropha seed weight [74]; thus, it is assumed to be 30% in this study. Unlike seed cake from rapeseed and palm tree seed, Jatropha seed cake cannot be used as animal feed, because it contains a certain amount of curcin and therefore is not suit for animal feeding [35]. However, it contains a high amount of protein (50–65%), which can be used as a suitable organic source of nutrients [35]. One ton of seed cakes are equivalent to 44 kg of nitrogen fertilizer, 19 kg of P_2O_5, and 13 kg of

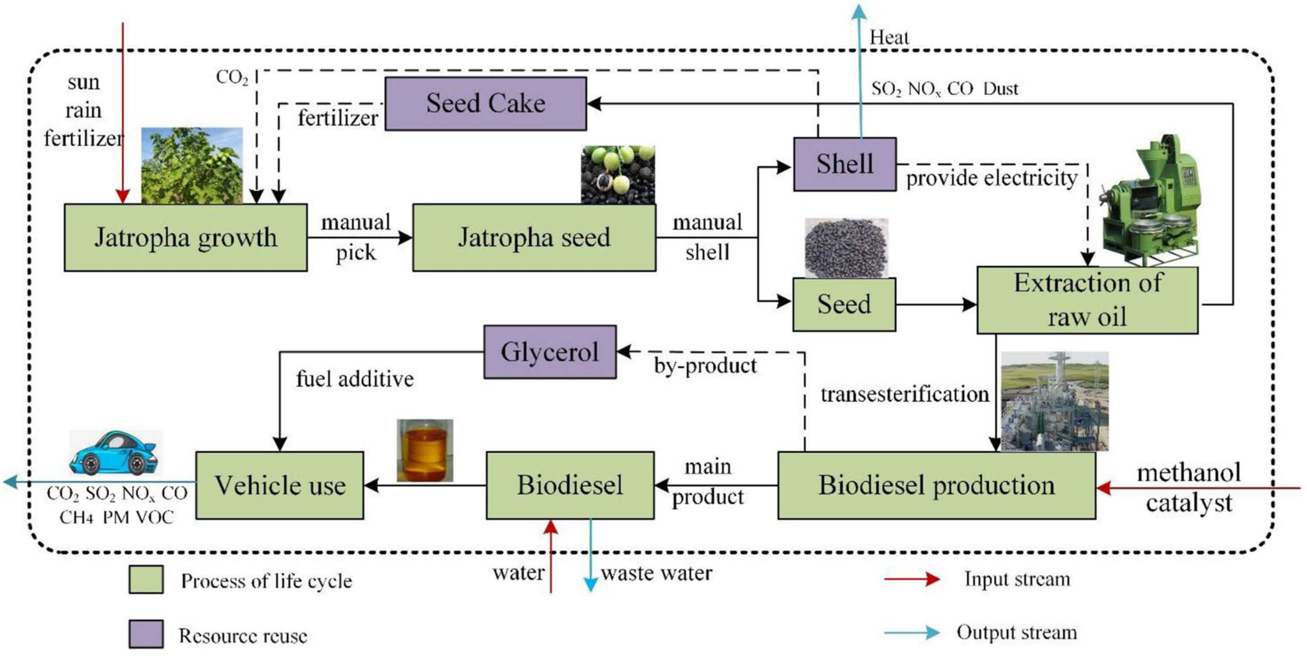

Fig. 1 The LCA boundary of biodiesel prepared from Jatropha oil

K_2O [75]. Therefore, it is common to apply seed cake as an organic fertilizer [19], which not only reuses the by-products but also reduces the application of chemical fertilizers. In order to increase the yield of Jatropha seed, the seed cake and fertilizer are mixed and applied in the fields.

According to Portugal-Pereira et al. [29], planting 2.68 ton of Jatropha seeds needs 51.99 kg of nitrogen fertilizer, 14.47 kg of P_2O_5, and 9.65 kg of K_2O. Table 5 presents the inventoried data during the process of Jatropha plantation, oil extraction, biodiesel production, and biodiesel utilization. Table 6 summarizes the overall pollutant emissions during each stage of biodiesel production from Jatropha (the detailed calculations at each stage are presented in Appendix A). During the growth period of Jatropha, the control of disease is not considered, as Jatropha is disease resistant and the damage from insects is not significant [76]. In order to reduce the impact of weeds and protect the environment, the farmland is manually mowed twice a year. Although Jatropha has strong drought tolerance, it is very water-consuming during the growth period [77]. In the first 3 years of Jatropha sprouting and growth, irrigation demand was relatively large [75], but this article has assumed that the Jatropha plants are already in a stable growth period, considering the 50-year life expectancy of Jatropha, the annual irrigation demand is about 210 m^3/ha [29].

The seed yield of Jatropha is one of the most important factors determining its economic feasibility, it varies between 0.3 and 5.25 t/ha in China, depending on the climatic and soil condition and the breed type [19, 78]. The oil content of Jatropha seeds varies greatly between 32.2% to 40.2% [18]. The oil content of Jatropha seeds can be stabilized at 40% by improving the quality of Jatropha seeds breed and soil management [76]. Therefore, this study assumes that the oil content of Jatropha seeds is 40%, and the production of 1 ton biodiesel requires 2.68 ton of Jatropha seeds. When the Jatropha seeds are mature, the Jatropha seeds are harvested by manual picking. They were sun-dried and manually shelled, which reduces the consumption of fossil energy but increases labor force cost.

2.5.2 Oil extraction

Mechanical extraction was applied to obtain Jatropha oil from Jatropha seed. The energy consumption in this process is mainly electric energy. The processing capacity of 1 ton of Jatropha oil requires 7.41 kW • h of electrical energy [76]; thus, the energy consumption during the oil extraction process is 7.93 kW • h, which is 28.55 MJ of energy. It was suggested that 0.4 ton of shells are produced as residue from 1 ton of Jatropha seeds processing [29]; thus, 2.68 ton of Jatropha seeds produces 1.07 ton of shells. These shells can be used to generate electricity through direct combustion and provide electricity for the system. The calorific value of the Jatropha shell is 17.22 MJ/kg [79] and the generated CO_2 during the combustion process can be offset by the CO_2 absorption during the photosynthesis process. Maiti et al. [79] showed that the power generation efficiency of Jatropha shell was 24.50%; thus, 1.07 ton of Jatropha shells can generate 1256.29 kW • h of electricity, which is 4522.64 MJ of energy. The data of pollutant emissions during the combustion of Jatropha shells are collected from literature (Table 6, see Appendix A for detailed calculations) [81].

2.5.3 Transesterification of Jatropha oil

The transesterification (Eq. 1) is commonly used to produce biodiesel, which converts oil feedstock and alcohol into methyl (or ethyl) esters and glycerol with the assistance of catalysts. Biodiesel is the major product and glycerol is the by-product [87]. An excessive amount of alcohol is required in the transesterification process, in order to maximize the biodiesel yield. Methanol is preferred, due to its relatively cheaper price [88, 89]. Although CaO catalyst has strong alkalinity, the transesterification reaction rate using pure CaO catalyst is very slow, due to its poor reactivity and stability [90]. On the other hand, the activity of alkali metal alkoxide is higher than that of CaO and $Ca(OH)_2$; thus, $Ca(OCH_3)_2$ catalyst shows promising potential in transesterification reactions [57]. Teo et al. [57] synthesized $Ca(OCH_3)_2$ catalyst and applied it to the transesterification of Jatropha oil. It was easy to prepare, non-toxic, and cost-effective, presenting excellent catalytic ability, stability, and easy separation property. Table 7 shows the structural properties of $Ca(OCH_3)_2$ and biodiesel yield at the optimized reaction conditions. Therefore, under their optimized condition, the production of 1 ton of biodiesel requires 1.07 ton of Jatropha oil, 502.17 kg of methanol, and 21.43 kg of $Ca(OCH_3)_2$ catalyst, while producing 105.50 kg of glycerol as by-products.

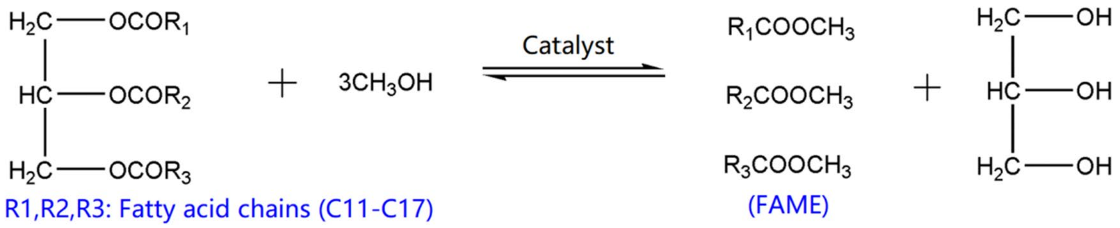

Table 5 Life cycle inventory analysis

Stage	Input	Output
Jatropha plantation [19, 35, 74, 75]	Rain, irrigation water, sun and CO_2	Jatropha seeds (2.68 t)
	Fertilizer (51.99 kg of N, 14.47 kg of P_2O_5, 9.65 kg of K_2O)	
	Labor	
	Diesel	
Oil extraction [29, 76, 79]	Jatropha seeds	Jatropha oil (1.07 t) Seed cake (0.804 t) as fertilizer Shell (1.072 t) to generate electricity
	Electricity	
	Labor	
	Diesel	
Biodiesel production [59, 74, 80]	Jatropha oil, methanol, and catalyst	Jatropha biodiesel (1 t) Glycerol (105.50 kg) as fuel additives
	Electricity	
	Water	
	Labor	
	Diesel	
Biodiesel utilization	Biodiesel	/

Table 6 The energy consumptions and pollutant emission data of each stage in the process of producing biodiesel from Jatropha oil

Category	CO_2 (kg)	SO_2	NO_x	CH_4	CO	Dust	Energy (MJ)	Ref
Fertilizer	1116.92	1.26	1.28	2.34	0.61	0.11	17,260.92	[71]
Oil extraction	3.28	0.01	< 0.01	< 0.01	< 0.01	< 0.01	28.55	[76]
Combustion of Jatropha shell	-	0.06	0.92	-	0.25	0.55	−4522.64	[79, 81]
Production of $Ca(OCH_3)_2$	10.33	0.03	> 0.01	< 0.01	< 0.01	< 0.01	90.00	[57]
Methanol production	2.04	1.25	3.15	0.04	0.09	5.19	4120.30	[82, 83]
Biodiesel production	14.14	0.04	> 0.01	< 0.01	< 0.01	< 0.01	123.12	[74]
Total transport	37.81	> 0.01	0.20	< 0.01	0.08	< 0.01	465.91	[84–86]
Total	1184.52	2.67	5.59	2.38	1.05	5.86	17,566.16	-

* < 0.01: the actual data is smaller than 0.01; > 0.01: the actual data is between 0.01 and 0.02. All actual data are given in Table A.3 of Appendix

Equation 1 Transesterification reaction.

The preparation of $Ca(OCH_3)_2$ catalyst mainly consumes electric energy. According to our calculation based on the catalyst preparation procedure, the preparation of 21.43 kg of catalyst consumes about 25 kW • h of electricity, which is 90.00 MJ of energy [57]. Methanol is produced using the Chinese coal method. The production of 1 kg of methanol requires 8.205 MJ of energy while emitting 0.1936 g of CO_2, 0.119 g of SO_2, 0.299 g of NO_x, 0.0036 g of CH_4, 0.009 g of CO, and 0.492 g of dust into the environment [82, 83]. Therefore, producing 502.17 kg of methanol consumes 4120.30 MJ of energy and emitting 2.04 kg of CO_2, 1.25 kg of SO_2, 3.15 kg of NO_x, 0.04 kg of CH_4, 0.09 kg of CO, and 5.19 kg of dust (Table 6, see Appendix A for detailed calculation).

In the process of transesterification under the aforementioned optimized reaction condition, the electrical energy consumption is calculated. The production of 1 ton of biodiesel requires 34.2 kW • h of electricity, which is 123.12 MJ of energy. Meanwhile, it releases 14.14 kg of CO_2, 0.04 kg of SO_2, 0.018 kg of NO_x, 0.0001 kg of CH_4, 0.0014 kg of CO, and 0.0018 kg of dust (Table 6, see Appendix A for detailed calculation) [74]. To ensure the quality of biodiesel, crude biodiesel needs to be washed with water to remove the impurities, such as excessive methanol, by-product glycerol, soap, and trace catalysts [59, 80, 91]. After calculation, the water resource consumption for producing 1 ton of biodiesel conversion is 0.37 m^3 [92].

While producing 1 ton of biodiesel, 105.50 kg of by-product glycerol is produced. Crude glycerol is a good fuel additive, which can improve fuel performance, increase flow performance, and reduce hazardous substances in the combustion exhaust gas. Therefore, by-product glycerol is applied to diesel as a high value-added glycerol fuel additive in this study [11].

2.5.4 Transport process

The transportation process includes the transportation of Jatropha seeds, the transportation of seed cake and fertilizer, the transportation of biodiesel and glycerol. Assuming that the distance of each transportation stage is 50 km [29, 93], and a medium-sized truck was used as a transportation vehicle that is fueled by diesel. Transportation energy consumption and emission data are shown in Table 4 and detailed calculation can be found in Appendix A [84–86].

2.5.5 Inventory analysis of LCC

The life cycle cost (C_t) is composed of variable cost (C_v) and fixed cost (C_f), in which variable cost includes the raw material cost (C_r), operation cost (C_o), fixed cost includes human cost (C_h), land cost (C_l), and equipment asset depreciation (C_e). China's land is under a socialist public ownership system, with a part of it being allocated to farmers, and the rest are state-owned land that are managed by the State Council on behalf of the country. The Chinese government vigorously supports the renewable energy production and allocates the corresponding land for Jatropha planting; thus, the cost of land is no longer considered. Therefore, the LCC is calculated as follows:

$$C_t = C_v + C_f = C_r + C_o + C_h + C_e$$

2.5.6 Variable cost

During the life cycle of biodiesel production, raw materials include Jatropha oil [94], methanol, $Ca(OCH_3)_2$ catalyst [57] (produced from calcium oxide and methanol) and water. The prices of methanol and calcium oxide refer to the commercial market price from East China Port of Methanol Market and Changshu Sanhe Calcification Company. Industrial water consumption is also taken into account. Wang's [95] research showed that an appropriate increase of industrial water price was beneficial for saving water resources and improving water resource utilization efficiency. The price of water in this study refers to shadow price of industrial water in Jiangsu Province, which is 7.53 USD/m^3 (47.84 RMB/m^3).

Operational costs include the electricity consumption during the life cycle of biodiesel production and diesel consumption during transportation. According to the China Power Grid, the average electricity price in China is 0.094 USD/kW • h (0.6 RMB/kW • h). During the entire life cycle, the process stages consuming electrical energy include the biodiesel production, the catalyst preparation, and methanol production.

2.5.7 Fixed cost

In the research of this study, the fixed cost calculation includes equipment asset investment and its depreciation and labor cost. Labor cost includes the staff, management, and the drivers of the transportation cargo. Assuming that the staff works 8 h a day, the average wage is 23.62 USD (150 RMB) per person a day by surveying the local labor market in Jiangsu Province. The overall cost calculations can be found in Appendix B.

3 Results and discussion

3.1 LCA results and interpretation

The corresponding proportion of each emission in different stages of the Jatropha seeds biodiesel life cycle was shown in Fig. 2. It can be seen from Table 6 and Fig. 2, the CO_2 emission is the most significant pollutant, with a value of 1184.52 kg. The use of fertilizers in the planting stage of Jatropha is the main cause of CO_2 emission, which accounts for 94% of the total CO_2 emissions. The emissions of dust and NO_x are 5.86 and 5.59 kg, respectively, which are much smaller than CO_2 emissions. Methanol production and Jatropha shell combustion are the major causes of dust emission, accounting for 89% and 9% of the total dust emission, respectively, and the sum of the two is as high as 98%. Similarly, methanol production, fertilizer, and Jatropha shell combustion are the main contributors for the NO_x emission, accounting for 56, 23, and 16% of the total NO_x emission, respectively. The emissions of SO_2, CH_4, and CO are both within 3 kg; thus, they have relatively little impacts on the environment.

Table 7 Structural properties of $Ca(OCH_3)_2$ and its catalytic performance at optimized reaction condition [57]

Catalyst	S_s (m^2/g)	Pore diameter (nm)	Methanol/oil (molar ratio)	Catalyst amount (wt.%)	Reaction time (min)	Reaction temperature (°C)	Yield (%)
$Ca(OCH_3)_2$	30.5	31.97	15	2	90	65	95
			12				85
			9				68

During the life cycle of 1 ton of biodiesel from Jatropha oil, the energy consumption is 17566.16 MJ. Table 4 shows the calorific value of Jatropha biodiesel is 35.136 MJ/kg, which means the energy of 1 ton of Jatropha biodiesel is 35136 MJ. The net energy ratio (NER, NER = renewable energy output / full energy input) was estimated according to the input and output energy of 1 ton of Jatropha biodiesel, and it is used as an indicator of energy efficiency [96–98]. In this study, the NER for Jatropha biodiesel is 2.00. According to Mohammadshirazi et al. [99], NER of waste cooking oil biodiesel was 0.67. Passell et al. [100] reported that NER of algae biodiesel production was 0.64. The results of Morales et al. [96] showed that the NER of soybean biodiesel is about 0.85. The large NER value is favored, since it means more renewable energy is produced by consuming less energy input. Therefore, in comparison with aforementioned waste cooking oil and algae biodiesel, Jatropha biodiesel production is more energy efficient. Further analyzing the energy consumption of each production stage, it can be seen from Fig. 3 that the energy consumption of chemical fertilizers is the most significant stage, which is 17260.92 MJ, accounting for 78.14% of the total energy consumption. The energy consumption of methanol production is also considerably high, which is 4120.30 MJ, accounting for 18.65% of the total energy consumption. The transportation, biodiesel production, catalyst production, and Jatropha oil extraction processes consume much less energy, which account for 2.11, 0.56, 0.41, and 0.13% of the total energy consumption, respectively. It is noted that 4522.64 MJ of energy is generated during the Jatropha shell combustion process to generate electricity, which can compensate 20.48% of the total energy consumption during the entire life cycle of Jatropha biodiesel production.

3.2 LCA comparison and improvements

The choice of feedstock is crucial to the development of biodiesel. In China, soybean oil [101], waste oil [102], microalgae oil [67], and Jatropha oil [103] are the most widely used. Yang et al. [104] compared the energy consumption and pollutant emissions in the production of biodiesel from soybean oil and waste oil using LCA method. The total energy consumption of 1 ton of soybean oil biodiesel in the life cycle was 15,990.75 MJ, and the CO_2 emission was 2411.29 kg. The total energy consumption of the waste oil biodiesel in the life cycle was 6033.23 MJ, and the CO_2 emission was 411.93 kg. Luo et al. [105] designed an integrated refinery process with a daily output of 8.8 ton of microalgae biodiesel, and carried out life cycle analysis accordingly. Their results show that the total energy consumption for producing 1 ton of microalgae biodiesel was 10,592.41 MJ, and the CO_2 emission was 2208.21 kg. The results of our study show that the total energy consumption of 1 ton of Jatropha biodiesel in the life cycle is 17566.16 MJ, which is slightly higher than the aforementioned studies, but the CO_2 emissions are relatively smaller, only 1184.52 kg. Compared to previous studies [104, 105], the low CO_2 emissions could be attributed to the process of fertilizer use and catalyst preparation. Jatropha tree can grow in poor soil condition and requires less fertilizer than other plants (soybean, palm, rapeseed, etc.) for growth. Moreover, the by-product seed cake was used as a fertilizer, which further reduced the use of fertilizer. In addition, $Ca(OCH_3)_2$ is a green, environmentally friendly catalyst that released a small amount of CO_2 during the preparation process [57].

By analyzing of the energy consumption and pollutant emissions of each production stage, the application of fertilizers during the Jatropha plantation, the production process of methanol and combustion of Jatropha shell need to be further improved. One possible solution is to reduce the amount of fertilizer applied in farmland, which can be achieved by modifying the application techniques (e.g. buried deeply in the soil to maximize the effects of fertilizer and use liquid fertilizer like ammonium urea [106]). For methanol production, Wang et al. [107] optimized the coal-to-methanol production process. Their results showed that the energy consumption of coal-to-methanol was reduced by 16% and waste water, residue, and gases were also reduced after process optimization. Shi et al. [108] adopted the water electrolysis and tri-reforming production process for producing methanol in a more sustainable manner. Compared with the traditional methanol production process, their method substantially reduced the net CO_2 emissions, which was 570,000 ton per year less for producing 1 ton of methanol.

Although a lot of CO_2 is generated during the shell combustion process to generates electricity, the generated CO_2 is absorbed back to Jatropha plants during its growth [29]. Due to the simple technology and low cost of combustion power generation, biomass combustion for power generation has become the most common practice in China. With higher requirements for environmental protection and sustainable development, novel technologies to minimize biomass (straw, leaves, and fruit shells, etc.) combustion pollutants have been reported. Lu et al. [109] proposed the use of biomass reburning denitrification technology, which effectively improved the denitrification efficiency and reduced NO_x emissions by changing the biomass particle size, reburning temperature, and reburning ratio. Wang et al. [110] studied the mechanism of desulfurization and denitrification using TiO_2 catalyst during biomass combustion. The results showed that TiO_2 catalyst not only effectively improved combustion efficiency, but also catalyzed the desulfurization and denitrification reaction of CaO, reducing SO_2 and NO_x emissions. Therefore, appropriate strategies can be employed to improve methanol and combustion of Jatropha shell processes and reduce their pollutant emissions and energy consumption.

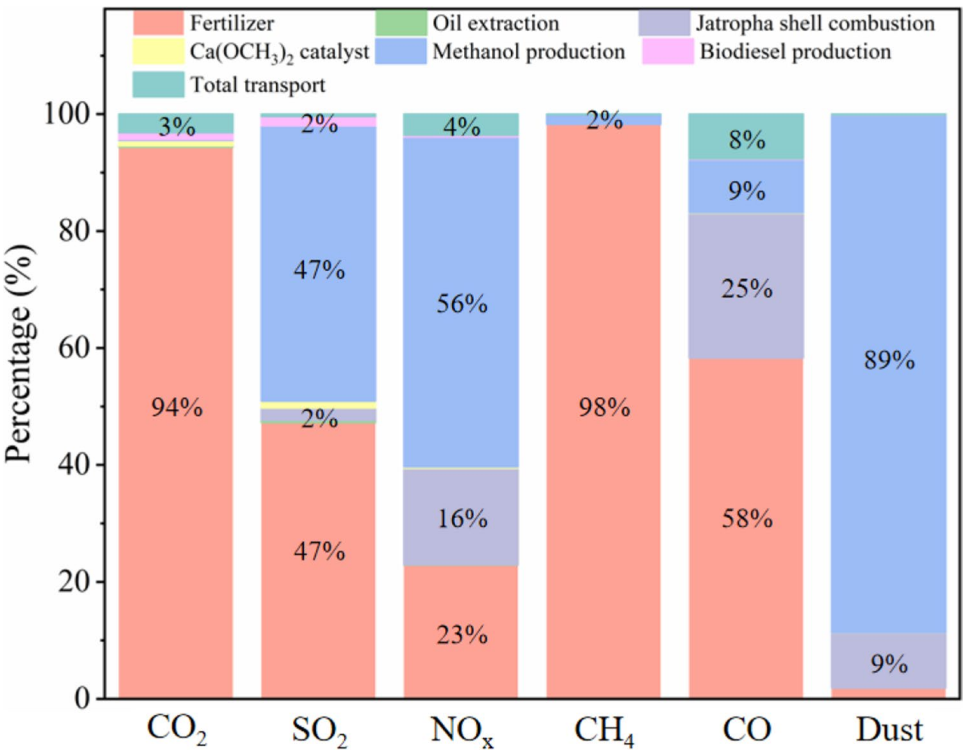

Fig. 2 Proportion of pollutant emissions in each life cycle process

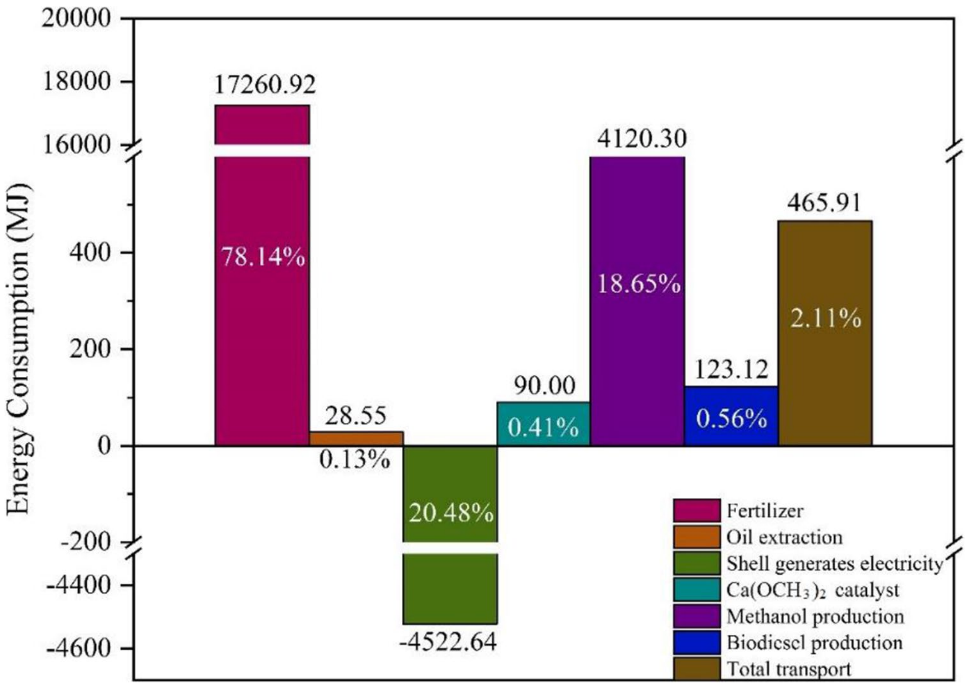

Fig. 3 Proportion of energy consumption in each life cycle process

3.3 Environmental impacts evaluation of Jatropha biodiesel production

Four quantitative indicators of environmental impacts are analyzed in the current study, including GWP, AP, EP, and PMF. The above data are standardized and weighted respectively to obtain four types of environmental impact potential values, and further to analyze the overall environmental impact potentials of Jatropha biodiesel production throughout its life cycle. The results are presented in Tables 8 and 9 (see Appendix C for the detailed calculation).

For the global warming impact, CO_2 has a smaller impact on GWP than NO_x, since its impact potential is lower. On the other hand, although NO_x emission quantity is about

212 times lower than CO_2 emission quantity, it has a rather higher equivalent factor. As a result, the NO_x emission has a greater impact potential of GWP, which is about 1.5 times larger than CO_2 emission (Table 8). A large amount of NO_x emission is produced during the methanol production, fertilizer application, and Jatropha shell combustion (Fig. 2). Similarly, the NO_x emission is also the major reason for AP and EP. PMF pollution is caused by dust emission that is mainly from the methanol production and Jatropha shell combustion power generation stages (Fig. 2). During the life cycle of producing 1 ton of Jatropha biodiesel, the total weighted environmental impact potential was 0.70 mPE_{China} (Table 9). Among the four assessed environmental impact indicators, GWP is the most significant factor, accounting for 40.00% of the total weighted environmental impact potential, followed by PMF that accounts for 28.57% of the total weighted environmental impact potential. The environmental impacts of AP and EP are relatively small, accounting for 18.57 and 12.86% of the total weighted environmental impact potential respectively. Although CO_2 emission has a significant amount, NO_x emission has a more outstanding negative influence on the overall environmental impact during biodiesel production than CO_2 emission. In summary, controlling the NO_x emission during the combustion of Jatropha shells for power generation and improving the current methanol production technology for CO_2 reduction are urgently required for resolving the environmental issues related to biodiesel production.

3.4 Comparison of pollutant emissions from biodiesel and diesel utilization

In comparison with diesel combustion, Jatropha biodiesel combustion is a rather clean process, as the pollutant emissions are significantly reduced (Table 10). It is highlighted that Jatropha biodiesel does not contain any sulfur; thus, the SO_2 emissions are zero. In addition, CO_2 and CO emissions of Jatropha biodiesel combustion is reduced significantly, both showing 48% reductions. Fine particulate matter (PM 2.5) and volatile organic compounds (VOC) emissions also decreased using Jatropha biodiesel. However, it was noted that the NO_x emissions increased slightly using all types of biodiesel products presented here [64]. For Jatropha biodiesel, the NO_x emission increased by 10%, which is comparable to that of other biodiesel products. Compared to diesel, biodiesel has a higher oxygen content. As the engine load increases, the temperature in the cylinder increases, which is beneficial to NO_x formation [113–115]. In comparison with other popular biodiesel products, such as rapeseed biodiesel (R-BD) [116], waste cooking oil biodiesel (W-BD) [117] and microalgae biodiesel (M-BD) [118], Jatropha biodiesel (J-BD) is evidently advantageous, due to its effective reduction of pollutant emissions and minimized environmental impacts (Table 9). Overall, the application of biodiesel can significantly alleviate the environmental burdens caused by traditional diesel utilization and Jatropha biodiesel shows a particularly promising prospect.

3.5 LCC result and interpretation

The life cycle costs of producing 1 ton of Jatropha biodiesel are given in Table 11 (see Appendix B for the detailed calculation). As can be seen, the cost of Jatropha biodiesel is 796.32 USD/ton. According to the research of Liu et al. [51], the production cost of diesel accounts for 63% of its retail price, which is about 3806.72 RMB/t (599.48 USD/ton). Compared to the cost of diesel, the cost of Jatropha biodiesel is 32.84% higher. The cost of Jatropha biodiesel is dominantly influenced by the price of Jatropha oil that accounts for 44.37% of the total cost. Human cost and methanol cost are also significantly high, accounting for 26.70 and 16.88% of the total cost of Jatropha biodiesel, followed by catalyst cost, accounting for 9.09%. The costs of water, electricity, diesel, and capital investment are relatively small. It is noted that in comparison with other popular oil feedstocks, Jatropha oil is much lower, which is only higher than that of waste cooking oil (Table 12). Therefore, Jatropha biodiesel has been considered a promising biofuel that has true economic viability in different countries. Sampattagul et al. [119] showed that the cost of Jatropha biodiesel in Thailand was 0.6 Euro/L, which was 773.09 USD/ton (1 Euro = 1.13 USD), which is 2.92% lower than our results. Wang et al. [76] analyzed the economic feasibility of biodiesel production from Jatropha oil, and the results showed that the cost of Jatropha biodiesel was 9 RMB/L (1616.10 USD/ton) that is 72.41% higher than the price of diesel (0.822 USD/L). The results of this paper show that the cost of Jatropha biodiesel is 50.73% lower than that of Wang's research.

By comparison, it is found that the cost of Jatropha biodiesel is greatly affected by the Jatropha seeds yield. The cost of Jatropha biodiesel decreases with increasing seeds yield. Baral et al. [125] showed that the cost of Jatropha biodiesel in Nepal was 1.2–1.5 USD/L; thus, the lowest cost was 1368.30 USD/ton. Yusuf et al. [94] in Malaysia showed that the cost of Jatropha biodiesel was 0.78 USD/kg, which was 780 USD/ton. Quintero et al. [126] in Peru reported that the cost of Jatropha biodiesel was between 0.84 and 0.87 USD/L, and its lowest cost was equivalent to 957.81 USD/ton. The result in our study is either close or lower than these reported ones. By comparison, it was discovered that the cost of Jatropha oil is playing a key role in determining the overall cost of Jatropha biodiesel, and an improved yield of Jatropha seeds can significantly reduce the cost of Jatropha biodiesel. Overall, our results show that the production of biodiesel from Jatropha oil has great economic advantages in China.

In order to further explore the factors affecting the price of Jatropha oil, a detailed cost analysis of Jatropha oil is performed based on LCA (Table 13, see Appendix D for detailed calculation). It is found that the gross cost of producing 1.07 ton of Jatropha oil is 366.83 USD, which is close to the selling price of Jatropha oil (330.21 USD) given in the references, considering the profit margin for oil company [94]. For the gross cost of Jatropha oil, the labor cost of two stages is the dominant factor, accounting for 83.71% of the total cost of Jatropha oil production. Except the inevitable labor input, such as picking Jatropha seeds, transportation, and management, other manual processes can be improved by using agricultural machinery equipment to reduce the gross cost of Jatropha oil production. For instance, a lawnmower can be used to weed the Jatropha fields that have a large gap (2 m × 3 m) between trees [76], which not only improves the efficiency of removing weed but also reduces labor costs. A fruit shelling machine can be used to perform Jatropha seeds and shells separation process [127], but incomplete separation and the presence of impurities in the nuts still exist using the current technology platform. Therefore, innovative modern agricultural machinery technology needs further improvement for the large-scale treatment of Jatropha seeds to reduce labor costs and time in the long run.

It is worth to mention that additional economic profit can be gained from the whole process of biodiesel production from Jatropha oil. Combustion of Jatropha shells to generate electricity and selling glycerol as a fuel additive can bring extra economic benefits. The combustion of 1.072 ton of Jatropha shells can produce 1256.29 kW·h of electricity, which is 118.70 USD. The market price of crude glycerol is 0.08–0.2 USD/kg [128, 129]. In this study, we take the median value of 0.14 USD/kg; thus, the price of 105.50 kg by-product glycerol is 14.77 USD. In the life cycle

Table 8 Different environmental impact potentials of Jatropha biodiesel production

Environmental impact indicator	Pollutant	Emission (kg)	Effect equivalent factor ($g \cdot g^{-1}$) [84, 111]	Impact potential ($kg \cdot a^{-1}$)
GWP	CO_2	1184.52	1 (CO_2-eq)	1184.52
	NO_x	5.59	310 (CO_2-eq)	1732.90
	CH_4	2.38	21 (CO_2-eq)	49.98
	Total GWP			2967.40
AP	SO_2	2.67	1 (SO_2-eq)	2.67
	NO_x	5.59	0.7(SO_2-eq)	3.91
	Total AP			6.58
EP	NO_x	5.59	1.35 (PO_4-eq)	7.55
PMF	Dust	5.86	1 (PM_{10}-eq)	5.86

Table 9 Standardized and weighted environmental impact potentials

Environmental impact indicator	Standardized benchmark [104, 112] ($kg \cdot person^{-1} \cdot a^{-1}$)	Standardized impact potential (mPE_{China})	Weight factor [104, 112]	Weighted impact potential (mPE_{China})
GWP	8700	0.34	0.83	0.28
AP	36	0.18	0.73	0.13
EP	61	0.12	0.73	0.09
PMF	18	0.33	0.61	0.20
Total				0.70

Table 10 Pollutant emission of 1 ton of different biodiesel products during their combustions (benchmarked against the combustion of 1 ton of diesel)

Pollutants	CO_2	SO_2	CO	CH_4	PM2.5	VOC	NO_x
J-BD [64]	− 48%	− 100%	− 48%	0%	− 47%	− 27.87%	+ 10%
R-BD [116]	− 48%	− 95%	− 25%	0%	− 33.32%	− 27.87%	+ 12.01%
W-BD [117]	2.94%	− 83.02%	− 20.36%	− 0.52%	− 94.80%	− 52.93%	+ 3.02%
M-BD [118]	− 12.31%	− 100%	− 25.32%	− 75%	− 9.52%	− 38.82%	+ 92.37%

*J-BD, Jatropha biodiesel; R-BD, rapeseed biodiesel; W-BD, waste cooking oil biodiesel; M-BD, microalgae biodiesel process of biodiesel production from Jatropha oil, the total economic benefits brought by by-products are 133.47 USD, which can compensate 16.76% of the life cycle cost, making biodiesel production from Jatropha oil more economically competitive.

3.6 Sensitivity analysis of the LCC study

A sensitivity analysis is necessary when different variables influence the results and it can evaluate the influence of variables on the economy [130, 131]. In biodiesel production processes, in addition to raw materials and equipment, operating conditions also affect biodiesel yields and hence the cost of biodiesel [132]. With reference to the operating conditions and results from the experiments of Teo et al. [57], sensitivity analysis of the cost of biodiesel was carried out by varying alcohol/oil molar ratio (15, 12, and 9). Using the same calculation method, when the alcohol/oil molar ratio is 12, the biodiesel yield is approximately 85%, requiring 1195.92 kg of Jatropha oil and 449.01 kg of methanol. The total cost of 1 ton of Jatropha biodiesel is 822.87 USD, of which 48.15% is contributed by the feedstock oil and 14.61% is caused by the methanol cost. With an alcohol/oil molar ratio of 9, the biodiesel yield was approximately 68%, requiring 1195.92 kg of Jatropha oil and 449.01 kg of methanol. 1 ton of Jatropha biodiesel costs 907.58 USD, of which 54.58% is attributed to feedstock and 12.42% is caused by methanol. The costs of Jatropha biodiesel produced using different alcohol/oil molar ratios are compared in Fig. 4. In comparison to the cost of biodiesel production with an alcohol/oil molar ratio of 15, the cost of biodiesel production using alcohol/oil molar ratios of 12 and 9 increased by 3.33 and 13.97%, respectively. Although the cost of methanol was reduced using a lower alcohol/oil molar ratio, the cost of Jatropha oil increased significantly, resulting in an increase in the total cost of biodiesel. Therefore, the feedstock oil has a significant influence on the cost of biodiesel and the selection of suitable and cheap oil is beneficial to reduce the cost of biodiesel production [133–135].

3.7 Limitations of Jatropha biodiesel development

From the LCA and LCC results, the production of biodiesel from Jatropha oil has a great potential, but there are still some limitations. Many Jatropha projects have been implemented in many countries over the past decades, but there are different constraints to Jatropha cultivation and biodiesel production in different regions (Table 14) [136, 137]. It is clear from Table 14 that there are still major problems related to the cultivation of Jatropha in most countries. Many companies that invested in Jatropha cultivation and biodiesel production have stopped or suspended their investments after a few years of operation [138]. In addition, studies have shown that lower than expected seed yields are responsible for the termination of Jatropha projects established in many areas [139, 140]. Low water availability, bad soil quality, and poor agronomic skills of the farmers have led to a significant decrease in Jatropha seed yields. In contrast, areas with suitable soil types and moderate rainfall (900–1200 ml) can produce more than 5 t/ha of seed in 1 year [141]. However, there is no commonly agreed criteria for assessing the effect of soil type and quality on the yield and quality of Jatropha seeds and their oil content [142].

We also note that although various techniques have been used for the production of biodiesel from Jatropha oil, most of them have been carried out in bench or pilot scale and may have limitations for industrial biodiesel production processes [136]. Studies have shown that 24% of the various factors affecting Jatropha cultivation are

Table 11 Life cycle cost of producing 1 ton of Jatropha biodiesel

	Jatropha oil [94]	Methanol	Catalyst	Water [95]	Electricity [76]	Diesel [29, 93]	Human	Capital investment [53]	Total
Cost (USD)	353.32	134.44	72.41	2.54	6.34	4.27	212.60	10.40	796.32
Proportion (%)	44.37	16.88	9.09	0.32	0.80	0.54	26.70	1.30	100

*Jatropha oil, water, and capital investment and costs are referenced from published literature; methanol, catalyst, electricity, diesel, and human cost are calculated based on our assumptions and local market survey (see Appendix B for detailed calculation).

Table 12 The prices of different popular oil feedstocks

Feedstock	Sunflower seed	Cotton seed	Rapeseed	Soybean	Palm	Jatropha oil	WCO
Cost (USD/ton)	1382	857	852	683	636	330.21	224
References	[120, 121]	[122]	[120, 121]	[120, 121]	[120, 121]	[94]	[123, 124]

*1 USD = 6.35 RMB (February 15, 2022, exchange rate)

Table 13 Life cycle cost of production Jatropha oil (1.07 t)

Cost categories	Description	Cost (USD)
Jatropha plant stage		
Fertilizing	Fertilizer cost: N, P_2O_5, K_2O	43.15
Diesel	Transportation of fertilizer and Jatropha seeds	5.41
Labor	Manual weeding, fertilizer application, picking Jatropha seeds and driver	165.35
Water	Agricultural water	8.86
Oil extraction		
Electricity	Electricity consumed by oil pressing equipment	0.75
Labor	Staff, separation of Jatropha seeds and driver	141.73
Diesel	Transport seed cake back to the field	1.58
Total		366.83

*Agricultural irrigation water 16.54 USD/ha (105 RMB/ha) (Jiangsu Provincial Price Bureau).

related to economic issues [160, 161]. It appears that seed collection and processing is still done manually, increasing the total cost of Jatropha biodiesel. In addition, the by-products generated in the process from Jatropha cultivation to biodiesel production have limited market [152, 162]. Therefore, the development of Jatropha biodiesel requires even more technology and engineering advancement, as well as national policy support to urge local implementation of biofuels as a strategy for rural development [156].

In order to evaluate more objectively the indicators of the Jatropha biodiesel production process, other evaluation methods, such as those based on concepts of emergy, energy, and exergy use, should be used in addition to the LCA and LCC methods [163, 164]. The concept of emergy, which integrates ecology, thermodynamics, and general systems theory, has been developed to assess the long-term sustainability of systems [165]. But the method has shortcomings such as lack of accuracy, consistency, reproducibility, and completeness. Traditional energy analysis is based on the first law of thermodynamics, and cannot provide reliable insights on the efficiency, productivity, and sustainability of production systems [163] Exergy is a rigorous engineering accounting technique that reveals the degree of sustainability of an energy system, also taking into account economic and environmental aspects [166]. Overall, all of these methods have some limitations and may lead to misleading conclusions. Combining two or more methods seems to be a promising tool to analyze biofuel production systems and contribute to the advancement of the biodiesel industry [167–169].

4 Conclusions and outlook

In the current study, the LCA and LCC analyses of the entire process of Jatropha biodiesel production were performed to evaluate its energy, environment, and economic impacts under Chinese conditions, and obtained the following results:

- The LCA results show that the total energy consumption for producing 1 ton of Jatropha biodiesel is 17566.16 MJ. The largest energy consumption is attributed to the use of fertilizers, accounting for 78.14% of the overall energy consumption.
- The production of 1 ton of Jatropha biodiesel emits a large number of pollutants, including 1184.52 kg of CO_2, 5.86 kg of dust, 5.59 kg of NO_x, 2.67 kg of SO_2, 2.38 kg of CH_4, and 1.05 kg of CO.
- The total environmental impact load of Jatropha biodiesel preparation process is 0.70 mPE_{China} and its impact on the environment is mainly manifested in global warming due to CO_2 and NO_x emission and particulate matter formation due to dust emission.
- The LCC results show that the cost of Jatropha biodiesel is 796.32 USD/ton, of which the cost of Jatropha oil and human are the major factors, contributing to 44.37 and 26.70% of the total cost.
- A sensitivity analysis of the cost of biodiesel by varying the alcohol/oil molar ratio showed that the price of feedstock oil has a significant impact on the total cost compared to the price of methanol.

From the above conclusions, choosing cheap feedstock oil for biodiesel production can effectively reduce the cost of biodiesel. Overall, the use of Jatropha biodiesel has promising competitive advantages under southern China condition, considering its total energy consumption, environmental benefits, and economic feasibility. In order to fully realize a more sustainable and economical Jatropha biodiesel industry in China, several improvements have to be implemented:

- Minimize or optimize fertilizer use by improving the application techniques or using novel liquid fertilizers.

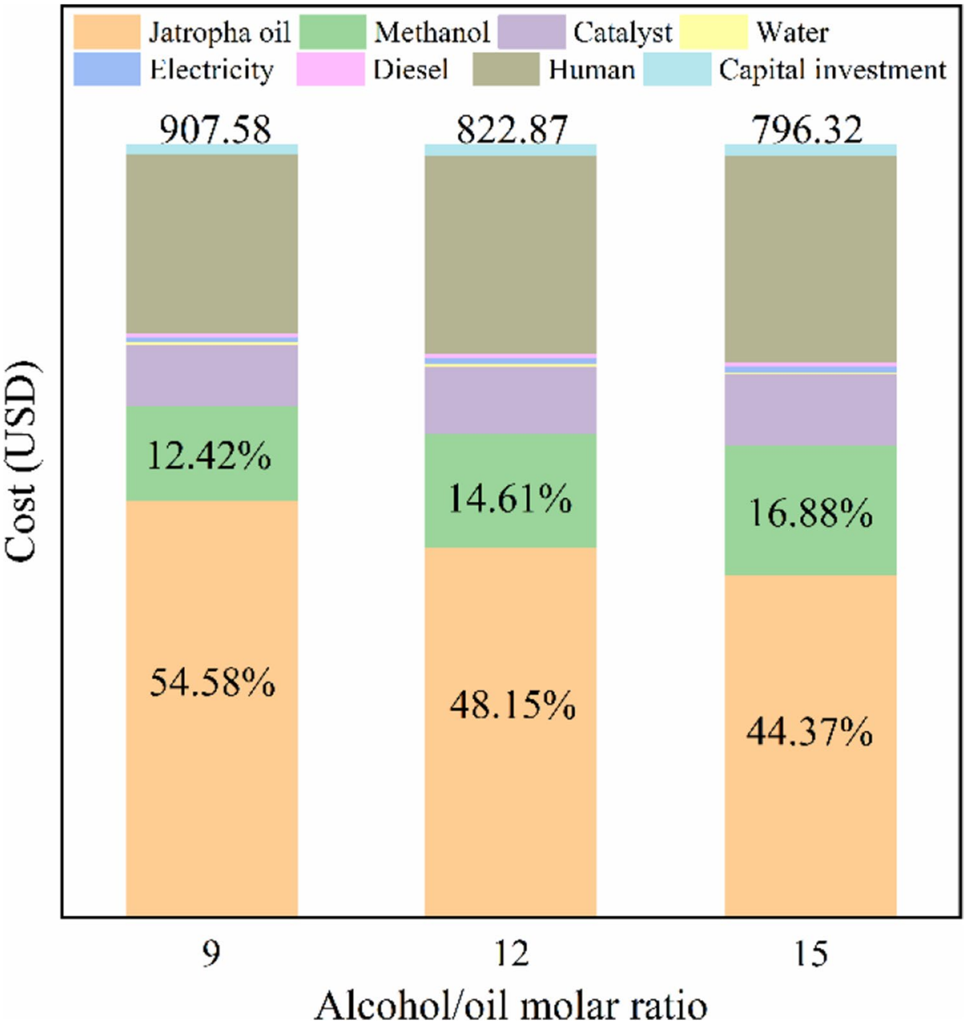

Fig. 4 Costs of Jatropha biodiesel using different alcohol/oil molar ratios and the relative percentages of each cost factor

Table 14 Major constraints to Jatropha biodiesel production in different regions [136, 137]

Country	Major barriers to Jatropha cultivation and biodiesel production	Ref
China	High demand for seeds, high market risk, limited level of learning, weak public support, and development	[103, 143]
Brazil	Poor seedling management techniques, inadequate biodiesel production technologies	[144, 145]
Nicaragua	Lack of farmers' interest, insufficient project promotion, lack of good technical advisers and lack of markets for by-product sales	[146, 147]
India	Farmers' expectations are not meet, with issues of land holding and limited access to water for irrigation	[148, 149]
Rwanda	Lack of improved seeds, shortage of land, poor soil quality, low seed yields, and lack of reliable markets	[150, 151]
Mexico	Jatropha profitability, payment of expected subsidies, and pest damage play significant roles in the abandonment of Jatropha cultivation	[152, 153]
South Africa	Intensive harvesting labor (therefore unprofitable Jatropha cultivation), rainfall as the main determinant of Jatropha seed yield, lack of knowledge, and awareness of Jatropha among investors	[154, 155]
Ghana	Limited nurturing and management experience, poor business planning, limited community involvement, inequitable pay practices, barriers created by civil society, and unconstructive involvement of local officials	[156, 157]
Tanzania	Lack of government advocacy, structural, infrastructure and logistics issues, poor technical skills and knowledge, limited local research	[158, 159]

- The current coal-to-methanol production process has to be improved to reduce its pollutant emissions, which can be achieved using process optimization or a more environmentally benign process.
- Although the Jatropha shell direct combustion process can be used to generate electricity and provide energy for the whole system, appropriate pollution control tech-

technology and strategies should be employed to effectively reduce the NO_x and dust emissions.

- Jatropha trees with high oil content should be bred to reduce the oil feedstock cost and modern agricultural machinery equipment should be used to continuously improve the biodiesel process, increase production efficiency, and reduce production costs.

Overall, the entire production process of Jatropha biodiesel was evaluated using LCA and LCC methods, and satisfactory results were obtained. Meanwhile, the issues were also objectively analyzed and corresponding improvement measures were proposed. The industrial development of biodiesel requires the evaluation of various indicators, and it is believed that this work can provide a theoretical basis for guiding Jatropha biodiesel industry from the environmental and economic perspectives. Biodiesel industry has been promoted with strong governmental support, such as allocation of land and financial subsidies. Based on this work, the government still need to further improve and refine related policies, such as lowering taxes, developing a complete industrial chain and promoting clean production of raw materials. In addition, the green chemistry concept and advanced machinery technology have to be employed, and cross-disciplinary collaborations are required to establish a circular economy for the sustainable development of Jatropha biodiesel industries in China.

Appendix A Pollutant emissions and energy consumption calculations

Pollutant emissions and energy consumption calculations at different stages in the life cycle assessment of Jatropha biodiesel are presented in the following subsections.

1. Fertilizer use: the emissions of pollutants during the use of fertilizers were referenced from Ref [71], which are listed in the following table.

Table 15

In the research of this article, 2.68 t of Jatropha seeds need 51.99 kg of nitrogen fertilizer, 14.47 kg of P_2O_5, and 9.648 kg of K_2O. Take CO_2 emission and energy consumption as examples for calculation:

$$CO_2 : 13623.40 \times 51.99 + 26298.07 \times 14.47 + 2913.33 \times 9.648 = 1116921\text{g} = 1116.92\text{ kg}$$

$$\text{Energy} : 222.67 \times 51.99 + 365.77 \times 14.47 + 40.74 \times 9.648 = 17260.92\text{ MJ}$$

2. Oil extraction

In the process of oil extraction, it consumes 7.93 kW·h of electricity. Ref [71] showed that 1 kW • h of electricity consumption contributed to 413.452 g of CO_2, 1.268 g of SO_2, 0.532 g of NO_x, 0.004 g of CH_4, 0.041 g of CO, and 0.053 g of dust (PM_{10}). When calculating energy consumption, 1 kW·h = 3600 kJ.

For example:

$$CO_2 : 413.452 \times 7.93 = 3278.67\text{g} = 3.278\text{kg}$$

$$\text{Energy} : 7.93 \times 3600 = 28548\text{KJ} = 28.55\text{MJ}$$

3. Combustion of Jatropha shell

In this article, 2.68 t of Jatropha seeds produce 1.072 t of shells. According to Ref [79], the calorific value of Jatropha shell is 17.22 MJ/kg, so the energy produced from the combustion of 1.072 t of shells is: 17.22 × 1072 = 18459.84 MJ. Because 1 kW·h = 3600 kJ, 18459.84 MJ = 5127.733 kW·h. The electric energy conversion efficiency is 24.5% [79], thus the electric energy generated from Jatropha shell combustion is: 5127.733 kW·h × 24.5% = 1256.29 kW·h.

$$\text{Energy} : 1256.29 \times 3600 = 4522644\text{KJ} = 4522.64\text{MJ}$$

According to Ref [81], 0.476 t of biomass combustion emit 25 g of SO_2 (SO_x), 409 g of NO_x, 115 g of CO, and 246 g of dust. Therefore 1.072 t of Jatropha shells emit 0.056 kg of SO_2 (SO_x), 0.921 kg of NO_x, 0.259 kg of CO, and 0.554 kg of dust. Take SO_2 emission as an example for calculation:

$$SO_2 : 1.072 \div 0.476 \times 25 = 56.3025\text{g} = 0.056\text{kg}$$

4. Production of $Ca(OCH_3)_2$ catalyst

In the process of catalyst production, it consumes 25 kW·h of electricity. Ref [71] showed that 1 kW • h of electricity consumption contributed to 413.452 g of CO_2,

Table 15 Pollutant emissions and energy consumption during fertilizers use

	CO2 (g)	SO2 (g)	NOx (g)	CH4 (g)	CO(g)	Dust (g)	Energy (MJ)
N (kg)	13623.40	9.88	11.70	33.28	8.32	1.04	222.67
P2O5 (kg)	26298.07	48.36	43.16	39.52	11.44	3.64	365.77
K2O (kg)	2913.33	4.94	4.94	4.40	1.30	0.53	40.74
	CO2 (kg)	SO2 (kg)	NOx (kg)	CH4 (kg)	CO (kg)	Dust (kg)	Energy (MJ)
Values in the article	1116.92	1.26	1.28	2.34	0.61	0.11	17260.92

1.268 g of SO_2, 0.532 g of NO_x, 0.004 g of CH_4, 0.041 g of CO, and 0.053 g of dust (PM_{10}). When calculating energy consumption, 1 kW·h = 3600 kJ.

For example:

$$CO_2: 413.452 \times 25 = 10336.3\text{g} = 10.336\text{kg}$$

$$\text{Energy}: 25 \times 3600 = 90000\text{KJ} = 90.00\text{MJ}$$

5. Methanol production

Ref [82] indicated that the production of 1 kg of methanol requires 8.205 MJ of energy; thus, 502.17 kg of methanol consumes 4120.30 MJ of energy.

The production of 1 MJ methanol emits 0.1936 g of CO_2, 0.119 g of SO_2, 0.299 g of NO_x, 0.0036 g of CH_4, 0.009 g of CO, and 0.492 g of dust into the environment [83].

Take CO_2 emission as an example for calculation: 0.1936 × 10545.57 = 2041.62 g = 2.0416 kg.

6. Biodiesel production

In the process of biodiesel production, it consumes 34.2 kW·h of electricity. Ref [71] showed that 1 kW • h of electricity consumption contributed to 413.452 g of CO_2, 1.268 g of SO_2, 0.532 g of NO_x, 0.004 g of CH_4, 0.041 g of CO, and 0.053 g of dust (PM_{10}). When calculating energy consumption, 1 kW·h = 3600 kJ.

For example:

$$CO_2: 413.452 \times 34.2 = 14140.058\text{g} = 14.1401\text{kg}$$

$$\text{Energy}: 34.2 \times 3600 = 123120\text{KJ} = 123.12\text{MJ}$$

7. Total transport

The transportation process includes the transportations of Jatropha seeds, seed cake, biodiesel and glycerol in which each transportation distance is 50 km. The reference value and the article value are listed in the table below:

Table 16

The transportations include 2.68 t of Jatropha, 0.804 t of seed cake, 0.076 t of fertilizer, 1 t of biodiesel, 0.1055 t of glycerol, and the total mass is 4.6655 t.

CO_2 emission: 1620.6 kg/10^4 t·km × 4.6655 t × 50 km = 37.81 kg (other pollutant emissions calculations are the same).

Diesel consumption: 0.0482 L/(t·km) × 4.6655 t × 50 km = 11.24 L.

Energy: the quality of diesel consumption = 11.24 L × 0.9 kg/L = 10.12 kg, thus the transportation energy = 46.04 MJ/kg × 10.12 kg = 465.91 MJ.

Appendix B Life cycle cost calculations

Cost calculations include Jatropha oil, capital investments, chemical reagents, water resource, energy cost, and human cost are presented in the following subsections.

1. The price of 1.07 t of Jatropha oil refers to the value given in Ref [94], which is 353.32 USD (C_{oil}).
2. In the transesterification stage, 502.17 kg of methanol is consumed, and the price of methanol is 1.7 RMB/kg (East China Port of Methanol Market, China). Therefore, the calculation results of this article are:

$$C_{methanol} = 1.7 \times 502.17\text{kg} = 853.69\text{RMB} = 134.44\text{USD}$$

3. The method of preparing $Ca(OCH_3)_2$ catalyst is referenced from Ref [57]. According to the chemical equation of “$2CH_3OH + CaO = Ca(OCH_3)_2 + H_2O$,” 13.45 kg of methanol and 11.83 kg of CaO are required for producing 21.43 kg of Ca $(OCH_3)_2$ catalyst. Since excess methanol is needed to react with calcium oxide, the amount of methanol is increased to 26.9 kg. The price of calcium oxide is 35 RMB/kg (Changshu Sanhe Calcification Company, Jiangsu, China). Therefore, the catalyst cost calculation of this article is:

$$C_{catalyst} = 35 \times 11.83 + 1.7 \times 26.9 = 459.78\text{RMB} = 72.41\text{USD}$$

Table 16 Pollutant emissions during transportation and basic physicochemical properties of diesel

Values in Ref [84–86]	CO_2 (kg/10^4t·km)	SO_2	NO_x	CH_4	CO	Dust	Density (kg/L)	Calorific value (MJ/kg)	Consumption (L/(t·km))
	1620.6	0.51	8.71	0.045	3.4	0.23	0.9	46.04	0.0482
Article value	CO_2 kg	SO_2	NO_x	CH_4	CO	Dust	Energy MJ		Consumption L
	37.81	0.01	0.20	< 0.01	0.08	0.01	465.91		11.24

* < 0.01: the actual data is smaller than 0.01

Therefore, $C_r = C_{oil} + C_{methanol} + C_{catalyst} = 353.32 + 134.44 + 72.41 = 560.17$ USD.

4. The biodiesel is washed by water after transesterification. A total volume of 0.37 m^3 of water resources is required for 1 t of crude Jatropha biodiesel product, and the industrial water price is 6.86 USD/per cubic meter, according to Ref [95]. Therefore, the cost calculation of water resource after transesterification in this paper is:

$$C_{water} = 6.86 \times 0.37 = 2.54\text{USD}$$

5. Electricity consumptions include Jatropha oil extraction, catalysts preparation, and biodiesel production. The electricity consumption is 7.93 kW·h, 25 kW·h, and 34.2 kW·h, respectively. The electricity cost in China Power Grid is 0.6 RMB/kW·h. Therefore, the electricity energy cost calculation in this paper is:

$$C_{electricity} = 0.6 \times (7.93 + 25 + 34.2) = 40.28\text{RMB} = 6.34\text{USD}$$

6. Diesel consumptions include the transportations of jatropha oil, biodiesel, and glycerin. A total volume of 5.2430 L of diesel is consumed [84–86]. The price of diesel is 5.17 RMB/L; therefore, the calculation results in this paper are:

$$C_{diesel} = 5.17 \times 5.2430 = 27.11\text{RMB} = 4.27\text{USD}$$

Therefore, $C_o = C_{water} + \text{Celectricity} + C_{diesel} = 2.54 + 6.34 + 4.27 = 13.15$ USD.

7. The labor input consists of biodiesel production staff, sales and management staff, and biodiesel transportation and glycerin drivers. Biodiesel production requires two people for 2 days, while sales and management also require two people for 2 days and transportation needs one driver for one day. Therefore, the human cost calculation in this paper is:

$$C_h = 150 \times (2 \times 2 + 2 \times 2 + 1 \times 1) = 1350\text{RMB} = 212.60\text{USD}$$

8. The capital investment cost is calculated according to the value given in Ref [53]. Therefore, the calculation results of this article are:

$$C_e = 10.40\text{USD}$$

Therefore, total cost $C_t = C_v + C_f = C_r + C_o + C_h + C_e = 560.17 + 13.15 + 212.60 + 10.40 = 796.32$ USD. Table 17

Table 17 Life cycle cost of producing 1 t of Jatropha biodiesel (Table 11 in the article)

	Jatropha oil [94]	Methanol	Catalyst	Water [95]	Electricity [76]	Diesel [29, 93]	Human	Capital investment [53]	Total
Cost (USD)	353.32	134.44	72.41	2.54	6.34	4.27	212.60	10.40	796.32
Proportion (%)	44.37	16.88	9.09	0.32	0.80	0.54	26.70	1.30	100

Appendix C Environmental impact load

1. Impact potential = Emission × Effect equivalent factor

Take PMF as an example to calculate: Dust Emissions are 5.86 kg, and the Effect equivalent factor is 1 (PM_{10}eq.), so the Impact potential value calculation:

$$5.86 \times 1 = 5.86\text{kg} \cdot a - 1$$

2. Standardized impact potential = Impact potential ÷ Standardized benchmark

Take PMF as an example to calculate: Impact potential value is 5.86 kg·a^{-1}, and the Standardized benchmark is 18 kg·person^{-1}·a^{-1}, so the Standardized impact potential value calculation:

$$5.86 \div 18 = 0.33\text{mPE}_{China}$$

3. Weighted impact potential = Standardized impact potential × Weight factor

Take PMF as an example to calculate: Standardized impact potential value is 0.33 mPE_{China}, and the weight factor is 0.61, so the Weighted impact potential value calculation:

$$0.33 \times 0.61 = 0.20\text{mPE}$$

Table 18

Table 18 Standardized and weighted environmental impact potentials (Table 9 in the article)

Environmental impact indicator	Standardized benchmark [104, 112] (kg·person^{-1}·a^{-1})	Standardized impact potential (mPE$_{China}$)	Weight factor [104, 112]	Weighted impact potential (mPE$_{China}$)
GWP	8700	0.34	0.83	0.28
AP	36	0.18	0.73	0.13
EP	61	0.12	0.73	0.09
PMF	18	0.33	0.61	0.20
Total				0.70

Appendix D Cost analysis of Jatropha oil

In order to have a better understanding of Jatropha oil cost, its overall cost during plantation and extraction are analysed.

Jatropha plant stage:

1. Fertilizer: 51.99 kg of nitrogen fertilizer, 14.47 kg of P_2O_5, and 9.648 kg of K_2O are needed for producing 2.68 t of Jatropha seeds, which is equivalent to 76.108 kg compound fertilizer. The price of compound fertilizer is 180 RMB/50 kg (one bag). Therefore, fertilizer cost is:

$$180 \times (76.108 \div 50) = 274\text{RMB} = 43.15\text{USD}$$

2. Transportation of fertilizer and Jatropha seeds: transporting 76.108 kg of fertilizer and 2.68 t of Jatropha seeds consumes 6.64 L of diesel, thus the transportation cost during seed production is:

$$5.17 \times 6.64 = 34.33\text{RMB} = 5.41\text{USD}$$

3. Labor input: manual weeding, fertilizer application, picking Jatropha seeds and driver are included. Manual weeding requires 2 people a day, and Jatropha picking requires 2 people for 2 days. Fertilizer application and driver transportation need one person a day in total. Therefore, the labor cost during seed production is:

$$150 \times (2 \times 1 + 2 \times 2 + 1 \times 1) = 1050\text{RMB} = 165.35\text{USD}$$

4. Agricultural water: the yield of Jatropha seeds is 5 t/hm^2, thus 2.68 t of Jatropha seeds need 0.536 hm^2 of land. Agricultural irrigation water costs 16.54 USD/ha (105 RMB/ha) (Jiangsu Provincial Price Bureau). Therefore, the agricultural water cost during the seed production is:

$$105 \times 0.536 = 56.28\text{RMB} = 8.86\text{USD}$$

Oil extraction:

1. Electricity consumed by oil extraction: the oil extraction process requires 7.93 kW·h of electricity to process 1.608 t of Jatropha seeds, thus the electricity consumption cost during seed production is:

$$0.6 \times 7.93 = 4.76\text{RMB} = 0.75\text{USD}$$

2. Staff, separation of shell and nut: It takes 2 people 2 days to separate the shells and nuts of Jatropha seeds, and 1 person 2 days to extract the oil. Therefore, the calculation results in this paper are:

$$150 \times (2 \times 1 + 2 \times 2) = 900\text{RMB} = 141.73\text{USD}$$

3. Transport seed cake back to the field: Transporting 0.804 t seed cake consumes 1.94 L diesel, and the transport driver here is included in the transportation fertilizer calculated above. Therefore, the calculation results in this paper are:

$$5.17 \times 1.94 = 10.03\text{RMB} = 1.58\text{USD}$$

Table 19

Table 19 Life cycle cost of production Jatropha oil (1.07 t, Table 13 in the article)

Cost categories	Description	Cost (USD)
Jatropha plant stage		
Fertilizing	Fertilizer cost: N, P_2O_5, K_2O	43.15
Diesel	Transportation of fertilizer and Jatropha seeds	5.41
Labor	Manual weeding, fertilizer application, picking Jatropha seeds and driver	165.35
Water	Agricultural water	8.86
Oil extraction		
Electricity	Electricity consumed by oil pressing equipment	0.75
Labor	Staff, separation of Jatropha seeds and driver	141.73
Diesel	Transport seed cake back to the field	1.58
Total		366.83

*Agricultural irrigation water 16.54 USD/ha (105 RMB/ha) (Jiangsu Provincial Price Bureau)

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Data availability All the data is available in the manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Conflict of interest The authors declare no competing interests.

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