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# A LCA Based Biofuel Supply Chain Analysis Framework*

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**Abstract** This paper presents a life cycle assessment (LCA) based biofuel supply chain (SC) analysis framework which enables the study of economic, energy and environmental (3E) performances by using multi-objective optimization. The economic objective is measured by the total annual profit, the energy objective is measured by the average fossil energy (FE) inputs per MJ biofuel and the environmental objective is measured by greenhouse gas (GHG) emissions per MJ biofuel. A multi-objective linear fractional programming (MOLFP) model with multi-conversion pathways is formulated based on the framework and is solved by using the $\varepsilon$-constraint method. The MOLFP problem is turned into a mixed integer linear programming (MILP) problem by setting up the total annual profit as the optimization objective and the average FE inputs per MJ biofuel and GHG emissions per MJ biofuel as constraints. In the case study, this model is used to design an experimental biofuel supply chain in China. A set of the weekly Pareto optimal solutions is obtained. Each non-inferior solution indicates the optimal locations and the amount of biomass produced, locations and capacities of conversion factories, locations and amount of biofuel being supplied in final markets and the flow of mass through the supply chain network (SCN). As the model reveals trade-offs among 3E criteria, we think the framework can be a good support tool of decision for the design of biofuel SC.
**Keywords** biofuel, life cycle assessment, supply chain, optimization

## 1 INTRODUCTION

Diminishing fossil fuel resources and increasing concern about greenhouse effect worldwide urge the development of biofuels [1]. Expecting the use of biofuels may reduce the GHG emissions and FE consumptions, many countries have adopted policies to promote the development of biofuels. In 2009, the new European Union Directive set aims at reaching a 10% share of renewable energy by 2020. Also, GHG emissions should be greatly reduced according to this directive. China plans to focus on biofuels converted from energy crops and cooking oil to ensure the food security according to the Renewable Energy Law passed in 2005. Standards have also been established on the fuel mixture of 10% ethanol and 90% gasoline (E10) and the fuel mixture of 10% biodiesel and 90% diesel (D10). Many provinces in China have replaced fossil gasoline for E10 under the requirement of National Development and Reform Commission.

There are abundant resources of biomass in China. The amount of crop residue that can be used for biofuel production is 300 million tons and China also has 7 million ha of potential land for planting energy crops (sweet sorghum, cassava, *etc*.) [2]. While the Middle and Long Term Development Plan of Renewable Energy requires that the annual bioethanol and biodiesel production should reach a minimum of 10 million and 2 million tons by 2020, respectively. The production of them is 1.9 million tons and 0.31 million tons in 2008, respectively [3]. Because of the limited availability of biomass in certain seasons, loss in biomass storage, economic problems and the concern whether biofuel can ease the problem of globe warming, most factories produce much less than the maximum capacity [4].

LCA is a method to study the impact in the life cycle of a product. It has become an important decision making tool for biofuel because it is very important to study the 3E performance before building factories for a certain biofuel pathway. Many studies have been carried out on biofuels in China [5-13]. Most of them focus on a unique single pathway and have not compared it to other pathways [6-9, 11-13]. The results of these studies are significantly different from each other even for the same biofuel pathway [6, 7, 11-13]. The conclusions of these studies are geographically dependent or national averaged. Thus, they cannot describe the situation of the biofuel industry in China accurately.

To solve these problems, it is necessary to integrate LCA with SC modeling by using geographically dependent LCA results in the model. SC modeling is often used for minimizing cost or maximize profit. Most early studies on biofuel SC use economic objective [14-18] thus ignoring the environmental aspects. Using multi-objective model and LCA to study both the economic and environmental impact in biofuel SC are now attracting the interest of researchers. But to the best of our knowledge, no such study has been done in China. Zamboni *et al*. [18] carried out an MILP model to minimize the overall operating cost for bioethanol SC in Northern Italy. Later they extended their model to a multi-objective one by using GHG emissions as another objective [19]. Another multi-objective MILP model for biomass-to-liquid SC was formulated and tested on the state of Iowa by You *et al* [20]. Other evaluation criteria are also reported, such as footprint [21], IMPACT 2002+ [22], Eco-indicator 99 [23], *etc*. Researchers have also paid much attention to the difference

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between centralized and distributed systems [16, 20].

In this paper an LCA based biofuel SC analysis framework is proposed, under which a single-period multi-objective model is formulated. In this framework, a method to integrate LCA with biofuel SC is provided. More complicated SC model can be built (ones that considering multi-period, uncertainty, carbon trading *etc*.) by adding other supply chain constraints to the basic framework. The study of trade-offs between the 3E goals is enabled in our framework. We also use this model to investigate the difference between the distributed and the centralized systems. In a distributed system, biofuel is firstly transported to pretreatment factories and converted to an intermediate product. The intermediate product is then converted to biofuel in biofuel production factories. In a centralized system, biomass is directly converted to biofuel in integrated factories. The model is solved by using $\varepsilon$-constraint method [24] to see how the FE inputs and GHG emissions limits influence the total economic profit and SCN.

## 2 PROBLEM STATEMENT

In our problem, a set of biofuel pathways for producing bioethanol and biodiesel are involved. It is necessary assess the 3E performances of the whole SC. LCA is used for calculating the energy and environment performances.

The SCN superstructure like the one in Fig. 1 is shown, in which potential locations of biomass feedstock, pretreatment factories, integrated factories, biofuel production factories and markets are included. Biomass can be firstly transported from biomass feedstock to pretreatment factories to be converted to some high energy density form and then converted to biofuel in biofuel production factories. Also, biomass can be directly converted to biofuel in integrated factories. After being blended with fossil gasoline and diesel, biofuels (E10 and D10) are consumed in markets.

The input parameters for this problems are:

(1) Maximum amount of biomass that can be provided in each biomass feedstock locations;

(2) Maximum and minimum capacities, fixed costs, variable costs of pretreatment factories, biofuel production factories and integrated factories;

(3) Maximum and minimum demand for E10 and D10;

(4) Distance between nodes in the biofuel SC;

(5) Transportation cost per ton-km;

(6) LCA results.

The objectives are minimizing average FE inputs and GHG emissions per MJ biofuel while maximizing total annual profit by making following decisions:

(1) Output of each kind of biomass in biomass feedstock locations;

(2) Sizes, technologies, locations of pretreatment factories, biofuel production factories and integrated factories;

(3) Locations of markets;

(4) Amount of substance being transported between the nodes in the biofuel SC.

## 3 LCA BASED SC ANALYSIS FRAMEWORK

In our LCA based SC analysis framework, the LCA results are used as inputs for objective functions in the model as the information flows as shown in Fig. 2.

Well-to-wheels (WTW) analysis is used for all biofuel pathways. WTW analysis includes two stages in biofuel life cycle, well-to-pump (WTP) and pump-to-wheel (PTW). WTP studies all the upstream stages including: biomass cultivation, biomass transportation, fuel production and intermediate product transportation (if any). Fuel production, distribution and consumption are studied in PTW analysis. WTW analysis is used because the biofuel SC to be studied includes both the upstream and downstream of biofuel.

To integrate LCA result with SC modeling, it is necessary divide the life cycle of biofuel according to the stage division of SC. In SC modeling, the FE inputs and GHG emissions of the whole SC can be divided into four parts: biomass production, fuel production, fuel consumption and transportation. The sum of influences led by biomass cultivation and biomass collection is used as the data inputs for the biomass production part. Though E10 or D10 may behave differently when combusted in engines, it can be still assumed that the influence in the fuel consumption stage can be offset by the carbon sink in biomass cultivation without losing much in accuracy. Thus, both parts can be ignored in LCA. All kinds of transportation (biomass, intermediate product and biofuel) are included in the transportation part.

Based on the process data, how much basic fuel (gasoline, diesel, natural gas, electricity, *etc*.) is used

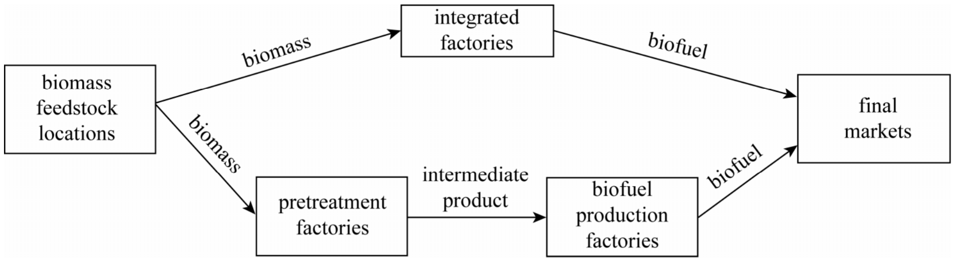


**Figure 1 The structure of biofuel supply chain in this paper**

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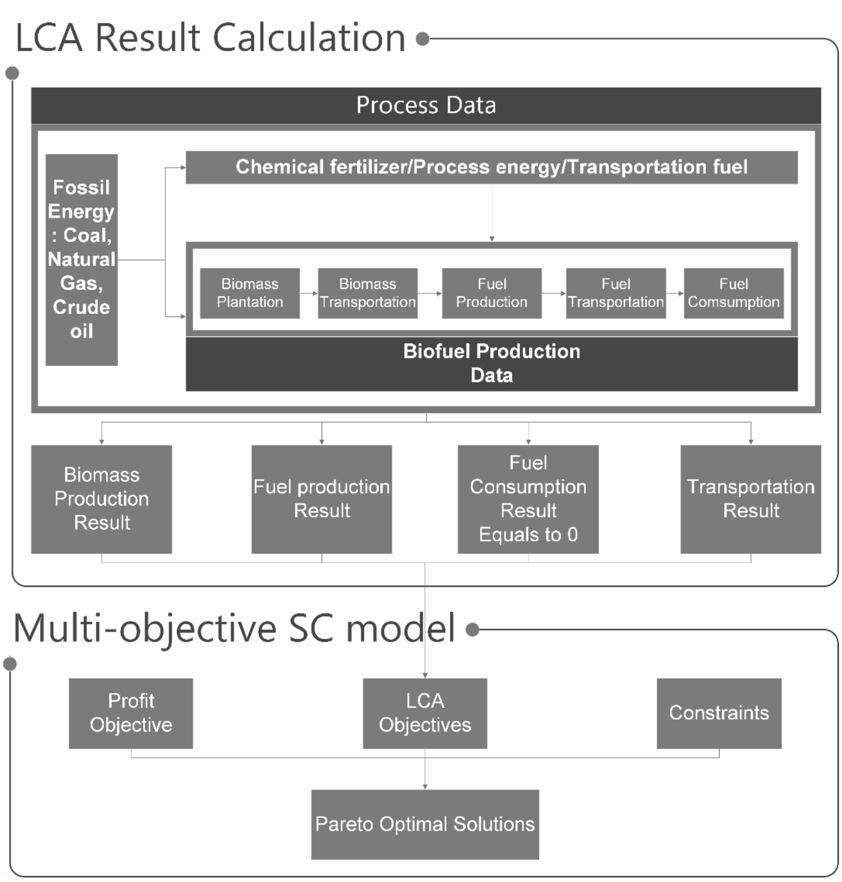


**Figure 2 LCA based SC analysis framework**

during the life cycle of the other raw materials (fertilizer, methanol *etc*.) used in the SC can be analyzed. By multiplying the FE inputs and GHG emissions data by the amount of basic fuel used, the FE inputs and GHG emissions of all the other raw materials can be known.

$$F_i = \sum_x F_x \times A_{x,i} \tag{1}$$

$$G_i = \sum_x G_x \times A_{x,i} \tag{2}$$

Where $F_i$ is the FE inputs for the other raw material $i$; $F_x$ is the FE inputs for the basic fuel $x$ and $A_{x,i}$ is the amount of basic fuel $x$ used when producing other raw material $i$. Eq. (2) calculates the GHG emissions ($G_i$) in a similar way.

The LCA result of biofuel can be calculated in the same way. For each stage, EF inputs $F_\mathrm{s}$ and GHG emissions $G_\mathrm{s}$ can be given by multiplying the FE inputs and GHG emissions of all the raw materials ($F_x$, $F_i$, $G_x$, $G_i$) by the amount of raw materials used in that stage ($A_{x,\mathrm{s}}$, $A_{i,\mathrm{s}}$).

$$F_\mathrm{s} = \sum_x F_x \times A_{x,\mathrm{s}} + \sum_i F_i \times A_{i,\mathrm{s}} \tag{3}$$

$$G_\mathrm{s} = \sum_x G_x \times A_{x,\mathrm{s}} + \sum_i G_i \times A_{i,\mathrm{s}} \tag{4}$$

## 4 MODEL FORMULATION

### 4.1 LCA model

Here we adopt the results of Tsinghua-CA3EM model. Tsinghua-CA3EM model [5] is a model for automotive fuel based on the GREET model (http://greet.es.anl.gov/) and the national conditions for China such as the over use of fertilizer in biomass cultivation and the dominance of coal utilization. Firstly, FE inputs and GHG emissions are calculated for all the basic fuels. When calculating GHG emissions, all the GHG is converted to their $CO_2$ equivalents according to their global warming potential (GWP) value under the guidance of Intergovernmental Panel on Climate Change (IPCC).

### 4.2 Supply chain model

To formulate a supply chain model, some subscripts, decision variables and input variables are needed. The detailed information about these subscripts and variables can be found in the nomenclature.

#### 4.2.1 *Constraints*

The sum of the flow from biomass feedstock locations to biomass factories must not exceed the maximum

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amount of biomass provided from that location.

$$\forall r,b \quad \sum_t \sum_l \sum_c f_{t,r,b,l,c} + \sum_T \sum_{l'} \sum_{c'} f_{T,r,b,l',c'} \le A_{r,b} \quad (5)$$

If a biomass feedstock location is not selected, no biomass can be transported from that place. If it is selected, the big M will ensure these constraints are redundant.

$$f_{t,r,b,l,c} \le Y_t M \quad (6)$$

$$f_{T,r,b,l',c'} \le Y_T M \quad (7)$$

As this model is a static one, all the biomass being transported to factories is required to be converted to products (biofuel or intermediate product) at a certain conversion rate.

$$\forall t,l,c \quad \sum_r \sum_b y_{t,r,b} f_{t,r,b,l,c} = \sum_m f_{t,l,c,m} \quad (8)$$

$$\forall T,l',c' \quad \sum_r \sum_b y'_{T,r,b} f_{T,r,b,l',c'} = \sum_{l''} \sum_{c''} f_{T,l',c',l',c'} \quad (9)$$

Similar constraints are defined for biofuel production factories to describe the biomass production process.

$$\forall T,l'',c'' \quad \sum_{l'} \sum_{c'} f_{T,l',c',l'',c''} y''_T = \sum_m f_{T,l'',c'',m} \quad (10)$$

It is assumed that for each technology and each type of factory, no more than one factory can be built at a potential factory location.

$$\forall t,l \quad \sum_c X_{t,l,c} \le 1 \quad (11)$$

$$\forall T,l' \quad \sum_{c'} X_{T,l',c'} \le 1 \quad (12)$$

$$\forall T,l'' \quad \sum_{c''} X_{T,l'',c''} \le 1 \quad (13)$$

All the factories must receive an inflow greater than 75% of its capacity to ensure the accuracy because the scale effect is used to extrapolate the cost and LCA data. Besides, if the factory exists, the sum of inflow can't exceed its capacity. When the factory does not exist, nothing is allowed to be transported to it.

$$\forall t,l,c \quad \frac{3}{4} a_{t,c} X_{t,l,c} \le \sum_r \sum_b f_{t,r,b,l,c} \le a_{t,c} X_{t,l,c} \quad (14)$$

$$\forall T,l',c' \quad \frac{3}{4} a_{T,c'} X_{T,l',c'} \le \sum_r \sum_b f_{T,r,b,l',c'} \le a_{T,c'} X_{T,l',c'} \quad (15)$$

$$\forall T,l'',c'' \quad \frac{3}{4} a_{T,c''} X_{T,l'',c''} \le \sum_{l'} \sum_{c'} f_{T,l',c',l'',c''} \le a_{T,c''} X_{T,l'',c''} \quad (16)$$

For any selected market location, the amount of biofuel consumed should be between the minimum and maximum demand. $\sum_{t \in F}$ and $\sum_{T \in F}$ are used to denote all types of biofuels that are mixed with fossil gasoline or fossil biodiesel before being used.

$$\forall m,F \quad L_{F,m} Y_m \le \sum_{t \in F} \sum_l \sum_c f_{t,l,c,m} + \sum_{T \in F} \sum_{l''} \sum_{c''} f_{T,l'',c'',m} \quad (17)$$

$$\forall m,F \quad L_{F,m} Y_m \ge \sum_{t \in F} \sum_l \sum_c f_{t,l,c,m} + \sum_{T \in F} \sum_{l''} \sum_{c''} f_{T,l'',c'',m} \quad (18)$$

To have a bio-fuel supply chain with scale, at least $n$ final markets must be chosen.

$$\sum_m Y_m \ge n \quad (19)$$

### 4.2.2 *Objective functions*

The first objective function is the total annual profit ($P$) which equals income ($I$) minus cost ($C$). For this problem, it is assumed that all the revenue comes from selling biofuels and the price will not vary between markets.

$$P = I - C \quad (20)$$

$$I = \sum_t \sum_l \sum_c \sum_m f_{t,l,c,m} p_t + \sum_t \sum_l \sum_c \sum_m f_{T,l'',c'',m} p_T \quad (21)$$

The cost ($C$) has three parts, biomass acquisition cost ($C_1$), fuel production cost ($C_2$) and transportation cost ($C_3$).

$$C = C_1 + C_2 + C_3 \quad (22)$$

Eq. (23) expresses the biomass acquisition cost, which is proportional to the biomass transported from biomass locations to all types of factories.

$$C_1 = \sum_t \sum_r \sum_b \sum_l \sum_c f_{t,r,b,l,c} o_{r,b} + \sum_t \sum_r \sum_b \sum_{l'} \sum_{c'} f_{T,r,b,l',c'} o_{r,b} \quad (23)$$

Fuel production cost consists of two parts: variable cost and fixed cost. Variable cost is proportional to the amount of raw material processed. If a factory exists, the fixed cost is a constant regardless of the output of that factory.

$$C_2 = C_4 + C_5 \quad (24)$$

$$C_4 = \sum_t \sum_r \sum_b \sum_l \sum_c f_{t,r,b,l,c} o_{t,b,c} + \sum_t \sum_r \sum_b \sum_{l'} \sum_{c'} f_{T,r,b,l',c'} o_{T,b,c'} + \sum_T \sum_{l'} \sum_c \sum_{l''} \sum_{c''} f_{T,l',c',l'',c''} o_{T,c''} \quad (25)$$

$$C_5 = \sum_t \sum_l \sum_c X_{t,l,c} O_{t,c} + \sum_t \sum_{l'} \sum_{c'} X_{T,l',c'} O_{T,c'} + \sum_t \sum_{l''} \sum_{c''} X_{T,l'',c''} O_{T,c''} \quad (26)$$

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It is assumed that all the transportation is done by trucks powered by diesel, and thus the transportation cost can be formulated as:

$$C_3 = o_3 \times \Big(\sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} D_{r,l}$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} D_{r,l'} +$$
$$\sum_T\sum_{l'}\sum_{c'}\sum_{l''}\sum_{c''} f_{T,l',c',l'',c''} D_{l',l''} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} D_{l,m} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} D_{l'',m}\Big) \quad (27)$$

Total GHG emissions and FE inputs can be calculated by replacing $C$ to $E$ or $G$ except that no fixed term is needed.

$$E = E_1 + E_2 + E_3 \quad (28)$$

$$E_1 = \sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} e_{r,b} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} e_{r,b} \quad (29)$$

$$E_2 = \sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} e_{t,b,c} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} e_{T,b,c'} +$$
$$\sum_T\sum_{l'}\sum_{c'}\sum_{l''}\sum_{c''} f_{T,l',c',l'',c''} e_{T,c''} \quad (30)$$

$$E_3 = e_3 \times \Big(\sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} D_{r,l} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} D_{r,l'} +$$
$$\sum_T\sum_{l'}\sum_{c'}\sum_{l''}\sum_{c''} f_{T,l',c',l'',c''} D_{l',l''} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} D_{l,m} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} D_{l'',m}\Big) \quad (31)$$

$$G = G_1 + G_2 + G_3 \quad (32)$$

$$E_1 = \sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} g_{r,b} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} e_{r,b} \quad (33)$$

$$E_2 = \sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} g_{t,b,c} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} g_{T,b,c'} +$$
$$\sum_T\sum_{l'}\sum_{c'}\sum_{l''}\sum_{c''} f_{T,l',c',l'',c''} g_{T,c''} \quad (34)$$

$$E_3 = g_3 \times \Big(\sum_t\sum_r\sum_b\sum_l\sum_c f_{t,r,b,l,c} D_{r,l} +$$
$$\sum_t\sum_r\sum_b\sum_{l'}\sum_{c'} f_{T,r,b,l',c'} D_{r,l'} +$$
$$\sum_T\sum_{l'}\sum_{c'}\sum_{l''}\sum_{c''} f_{T,l',c',l'',c''} D_{l',l''} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} D_{l,m} +$$
$$\sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} D_{l'',m}\Big) \quad (35)$$

To get the average FE inputs and GHG emissions per MJ biofuel, it is necessary divide the total term by the lower heating value of all the biofuel being produced.

$$\overline{G} = \frac{G}{\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} L_t + \sum_t\sum_l\sum_c\sum_m f_{T,l',c',m} L_T} \quad (36)$$

$$\overline{E} = \frac{E}{\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} L_t + \sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} L_T} \quad (37)$$

This problem is a MOLFP problem. To solve this problem, the weight sum method [25], reference point approach [26] or $\varepsilon$-constraint method [24] can be used. When solving MOLFP problem by using the first two methods, the problem is still in a non-linear form which is hard to solve. If we use $\varepsilon$-constraint method and reformulate Eqs. (36) and (37) as constraints, an MILP problem will be got instead. After dividing the range of $\overline{G}$, $\overline{E}$ to intervals, the Pareto-optimal solutions can be obtained by solving MILP problems on each grid point.

$$E \le \varepsilon_1 \Big(\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} L_t + \sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} L_T\Big) \quad (38)$$

$$G \le \varepsilon_2 \Big(\sum_t\sum_l\sum_c\sum_m f_{t,l,c,m} L_t + \sum_t\sum_l\sum_c\sum_m f_{T,l'',c'',m} L_T\Big) \quad (39)$$

## 5 CASE STUDY

Because of the lack of detailed statistical data for China, the framework and our model are used to design an experimental biofuel SC in which only biodiesel (BD) pathway is considered.

The nation is divided into provinces, and we choose 19 provinces to be potential biomass feedstock locations, 14 capital cities to be potential locations for factories, and 18 capital cities to be potential markets. The highway distance is used as the distance between nodes. Since the distribution of biomass is dispersed, 100 km between biomass feedstock locations and factories is added as a collecting range. Also, it is assumed that all the transportation is done by diesel trucks. Only 1% of the total amount of rapeseed [27] in each

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province is used for the production of biodiesel and 10% of potential land [28] for energy crop can be used for the plantation of *jatropha* fruit [29].

Unit emissions, FE inputs and costs will decrease while the fixed cost increases nonlinearly.

The difference led by the choice between centralized and distributed systems can be investigated. In a centralized system, integrated factories have greater capacity than biofuel production factories. Thus, the SC may benefit more from the scale effect. The distributed system may reduce the cost of transporting biomass, which is in a low energy density form by converting biomass to preliminarily processed oil in pretreatment factories.

The maximum demand in the final market is estimated by the number of trucks and cars in each province and the assumption that each truck or car will consume 1.5 t of gasoline or diesel. The minimum demand is set to be 60% of the maximum demand. The price of each product is set to be the price in the Chinese market in 2012.

All the input variables are listed in Table 1-8 in the Appendix [4, 9, 30, 31].

To solve the problem, the value of $\varepsilon_1$ and $\varepsilon_2$ is set large enough to guarantee that the constraints Eqs. (38) and (39) are redundant. By doing this, the actual values of $\varepsilon_1$ and $\varepsilon_2$ can be obtained, and used to be the upper bounds. The lower bounds are obtained by letting the other constrain be redundant and gradually tightening the constraint. The search stops when the model becomes infeasible and the current value of $\varepsilon_1$ or $\varepsilon_2$ is set to be its lower bound.

## 6 RESULT AND DISCUSSION

Because constraints Eqs. (38) and (39) do not require the actual values equal to $\varepsilon_1$ and $\varepsilon_2$, it is necessary to calculate the actual value of the objectives after solving the problem. The distribution of Pareto-optimal solutions is not widely distributed because there is only one biofuel pathway in the case. But it can be still seen in Fig. 3 that the optimal solutions are on a convex surface.

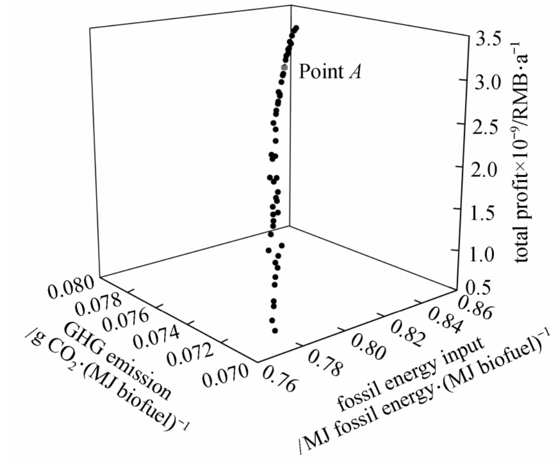


**Figure 3 Pareto-optimal solutions** (Point *A* indicates a SCN that makes a profit of $2.937\times10^9$ CNY·a$^{-1}$ while needs 0.83 MJ fossil energy and emits 0.0769 g $CO_2$ for every MJ biofuel)

One representative point (Point *A*) in Fig. 3 is chosen for a detailed analysis. Fig. 4 (a), (b) and (c) show the allocation of GHG emissions, FE inputs and costs for each stage of BD pathway, respectively. Due to the difficulty of biomass planting and the molecular similarity between the preliminarily processed oil obtained from the energy crop and the biodiesel, biomass planting accounts for the largest proportion.

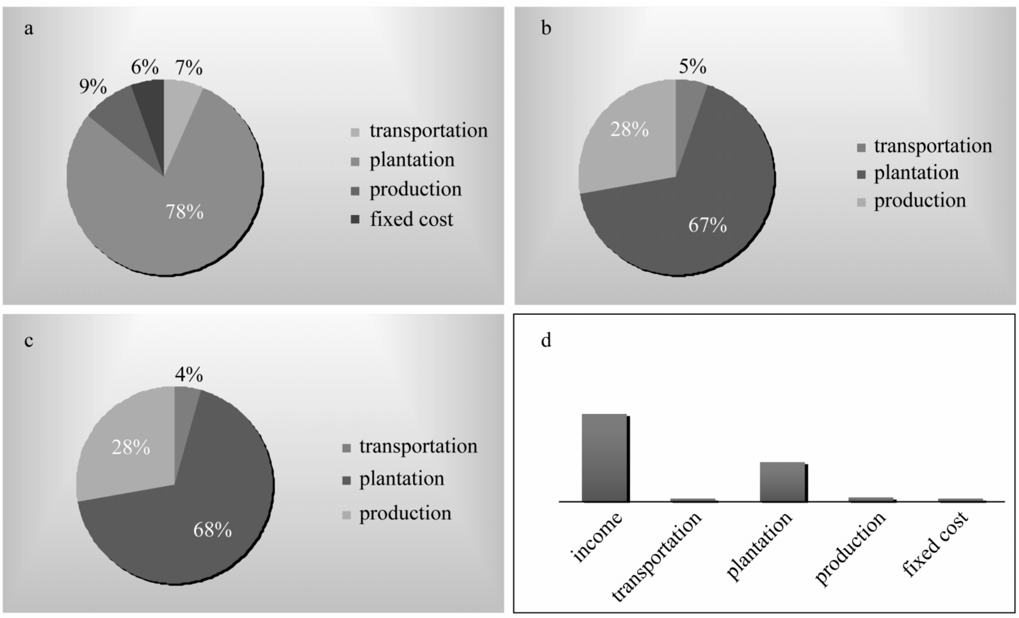


**Figure 4 Breakdown analysis for the BD pathway**

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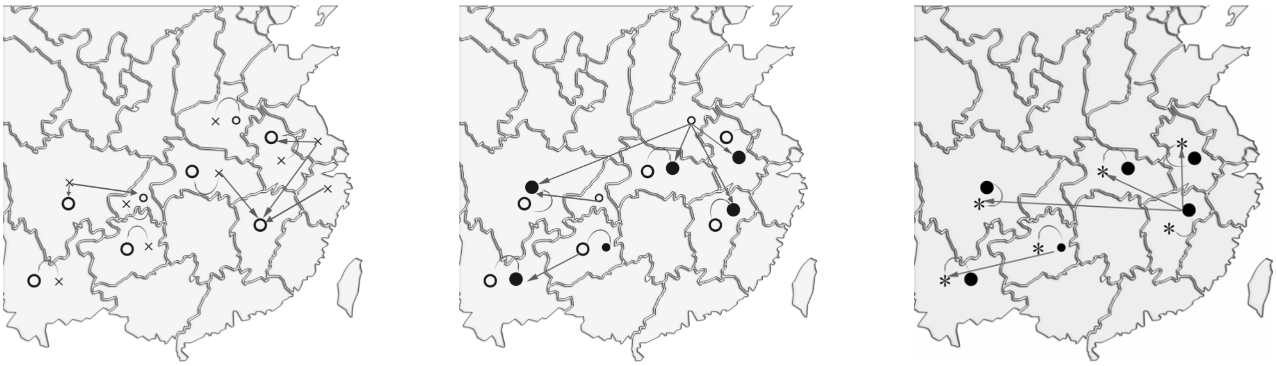
(a) Flow network from biomass feedstock locations to integrated factories

(b) Flow network from integrated factories to markets

**Figure 5 Flow network for the centralized BD pathway for the solution at Point *A***
● large BD factory; • small BD factory; × biomass location; * market; ⟶ flow



(a) Flow network from biomass feedstock locations to pretreatment factories

(b) Flow network from pretreatment factories to biofuel production factories

(c) Flow network from biofuel production factories to markets

**Figure 6 Flow network for the distributed BD pathway for the solution at Point *A***
○ large pretreatment factory; ∘ middle pretreatment factory; ● large biofuel production factory; • middle biofuel production factory; × biomass location; * market; ⟶ flow

Figure 4 (d) shows the comparison between the income and costs. As the estimated cost from literature is very ideal, income excess costs greatly.

A further check of Pareto-optimal solutions reveals that all the Pareto-optimal solutions adopt the centralized system. The production term in the BD pathway is fairly large, so the scale effect of using conversion factory with greater capacity is more preferable to the lower transportation costs of the distributed system. If a distributed system at point A in the model is chosen in the BD pathway, the total profit decreases from $2.937\times10^9$ $CNY\cdot a^{-1}$ to $1.782\times10^9$ $CNY\cdot a^{-1}$, and the network structure differs significantly in the two systems.

Figures 5 and 6 show the flow network of the centralized and the distributed systems, respectively. From these two figures, it can be concluded that in the distributed system, biomass is more likely to be converted locally and then be transported to further factories for biofuel production.

## 7 CONCLUSIONS

In this study, an LCA based biofuel SC analysis framework is proposed. The 3E performance can be analyzed by adding LCA objectives to ordinary SC model under this framework. A static biofuel SC model with multi-conversion pathways is formulated as a MOLFP problem and is solved by using the $\varepsilon$-constraint method. In the case study, this model is used to design an experimental bio-fuel supply chain in China. Two biomass types and one pathway are considered. A set of the Pareto-optimal solutions is obtained. The choice between distributed systems and centralized systems is also taken into account. The result shows that the plantation of the biomass accounts for the biggest part of the cost, FE inputs and GHG emissions. Furthermore, the centralized system performs better than the distributed system because of the great scale effect.

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It should be mentioned that though the model proposed is experimental because of the limited data, the model can be greatly extended under the guidance of our framework by using the follows.

(1) Using updated basic LCA data;

(2) Analyzing the combustion behavior of biofuels in detail;

(3) Adding other criteria such as IMPACT 2002+, Eco-indicator 99, *etc*.;

(4) Using multi-period SC model;

(5) Considering uncertainties in product pricing, demand change, and technology improvement.

## NOMENCLATURE

| | |
|---|---|
| $A_{r,b}$ | maximum amount available for biomass $b$ at biomass location $r$, $t \cdot a^{-1}$ |
| $a_{T,c'}$ | capacity of pretreatment factory with capacity type $c'$ in biofuel pathway $T$, $t \cdot a^{-1}$ |
| $a_{T,c''}$ | capacity of biomass production factory with capacity type $c''$ in biofuel pathway $T$, $t \cdot a^{-1}$ |
| $a_{t,c}$ | capacity of integrated factory with capacity type $c$ in biofuel pathway $t$, $t \cdot a^{-1}$ |
| $D_{l,m}$ | distance between potential integrated factory location $l$ and potential market at location $m$, km |
| $D_{l',l''}$ | distance between potential pretreatment factory location $l'$ and potential biofuel production factory location $l''$, km |
| $D_{l'',m}$ | distance between potential biofuel production factory location $l''$ and potential market at location $m$, km |
| $D_{r,l}$ | distance between biomass feedstock location $r$ and potential integrated factory location $l$, km |
| $D_{r,l'}$ | distance between biomass feedstock location $r$ and potential pretreatment factory location $l'$, km |
| $e_3$ | FE input of transportation, $MJ \cdot t^{-1} \cdot km^{-1}$ |
| $e_{T,b,c'}$ | FE inputs of producing intermediate product using biomass $b$ in pretreatment factory with capacity type $c'$ in biofuel pathway $T$, $MJ \cdot t^{-1}$ |
| $e_{T,c''}$ | FE inputs of producing biofuel using intermediate product in biofuel production factory with capacity type $c''$ in biofuel pathway $T$, $MJ \cdot t^{-1}$ |
| $e_{r,b}$ | FE inputs of producing biomass $b$ at biomass location $r$, $MJ \cdot t^{-1}$ |
| $e_{t,b,c}$ | FE inputs of producing biofuel using biomass $b$ in integrated factory with capacity type $c$ in biofuel pathway $t$, $MJ \cdot t^{-1}$ |
| $f_{T,r,b,l',c'}$ | flow of biomass $b$ from biomass feedstock location $r$ to pretreatment factory at location $l'$ with capacity type $c'$ in biofuel pathway $T$, continuous |
| $f_{T,l',c',l'',c''}$ | flow of intermediate product from pretreatment factory at location $l'$ with capacity type $c'$ to biofuel production factory at location $l''$ with capacity type $c''$ in biofuel pathway $T$, continuous |
| $f_{T,l'',c'',m}$ | flow of biofuel from biofuel production factory at location $l''$ with capacity type $c''$ to market at location $m$ in biofuel pathway $T$, continuous |
| $f_{t,l,c,m}$ | flow of biomass from integrated factory at location $l$ with capacity type $c$ to market at location $m$ in biofuel pathway $t$, continuous |
| $f_{t,r,b,l,c}$ | flow of biomass $b$ from biomass feedstock location $r$ to integrated factory at location $l$ with capacity type $c$ in biofuel pathway $t$, continuous |
| $g_3$ | GHG emissions of transportation, $g\ CO_2 \cdot t^{-1} \cdot km^{-1}$ |
| $g_{r,b}$ | GHG emissions of producing biomass $b$ at biomass location $r$, $g\ CO_2 \cdot t^{-1}$ |
| $g_{T,b,c'}$ | GHG emissions of producing intermediate product using biomass $b$ in pretreatment factory with capacity type $c'$ in biofuel pathway $T$, $g\ CO_2 \cdot t^{-1}$ |
| $g_{T,c''}$ | GHG emissions of producing biofuel using intermediate product in biofuel production factory with capacity type $c''$ in biofuel pathway $T$, $g\ CO_2 \cdot t^{-1}$ |
| $g_{t,b,c}$ | GHG emissions of producing biofuel using biomass $b$ in integrated factory with capacity type $c$ in biofuel pathway $t$, $g\ CO_2 \cdot t^{-1}$ |
| $L_{F,m}$ | minimum demand for mixed fuel $F$ in market $m$, $t \cdot a^{-1}$ |
| $L_T$ | lower heating value of bifuel produced by pathway $T$, $MJ \cdot t^{-1}$ |
| $L_t$ | lower heating value of bifuel produced by pathway $t$, $MJ \cdot t^{-1}$ |
| $M$ | big $M$ to ensure some constraint is redundant when a binary variable equals to 1 |
| $O_{t,c}$ | fixed cost of integrated factory with capacity type $c$ in biofuel pathway $t$, $CNY \cdot a^{-1}$ |
| $O_{T,c'}$ | fixed cost of integrated factory with capacity type $c'$ in biofuel pathway $T$, $CNY \cdot a^{-1}$ |
| $O_{T,c''}$ | fixed cost of integrated factory with capacity type $c''$ in biofuel pathway $T$, $CNY \cdot a^{-1}$ |
| $o_3$ | unit cost of transportation $CNY \cdot t^{-1} \cdot km^{-1}$ |
| $o_{r,b}$ | cost of producing biomass $b$ at biomass location $r$, $CNY \cdot t^{-1}$ |
| $o_{T,b,c'}$ | cost of producing intermediate product using biomass $b$ in pretreatment factory with capacity type $c'$ in biofuel pathway $T$, $CNY \cdot t^{-1}$ |
| $o_{T,c''}$ | cost of producing biofuel using intermediate product in biofuel production factory with capacity type $c''$ in biofuel pathway $T$, $CNY \cdot t^{-1}$ |
| $o_{t,b,c}$ | cost of producing biofuel using biomass $b$ in integrated factory with capacity type $c$ in biofuel pathway $t$, $CNY \cdot t^{-1}$ |
| $P_T$ | price of biofuel produced in biofuel pathway $T$, $CNY \cdot t^{-1}$ |
| $P_t$ | price of biofuel produced in biofuel pathway $t$, $CNY \cdot t^{-1}$ |
| $U_{F,m}$ | maximum demand for mixed fuel $F$ in market $m$, $t \cdot a^{-1}$ |
| $X_{T,l',c'}$ | indicating whether a factory for biofuel pathway $T$ at location $l'$ with capacity type $c'$ exist, binary |
| $X_{T,l'',c''}$ | indicating whether a factory for biofuel pathway $T$ at location $l''$ with capacity type $c''$ exist, binary |
| $X_{t,l,c}$ | indicating whether a factory for biofuel pathway $t$ at location $l$ with capacity type $c$ exists, binary |
| $Y_m$ | indicating whether we should choose $m$ as a market, binary |
| $Y_T$ | indicating whether we should choose biofuel pathway $T$, binary |
| $Y_t$ | indicating whether we should choose biofuel pathway $t$, binary |
| $y_{t,r,b}$ | conversion rate from biomass to biofuel in biofuel pathway $t$ for biomass $b$ at biomass location $r$ |
| $y'_{T,r,b}$ | conversion rate from biomass to intermediate product in biofuel pathway $T$ for biomass $b$ at biomass location $r$ |
| $y''_T$ | conversion rate from intermediate product to biofuel in biofuel pathway $T$ |

### Subscripts

| | |
|---|---|
| $b$ | biomass type |
| $c$ | capacity type for integrated factories |
| $c'$ | capacity type for pretreatment factories |
| $c''$ | capacity type for biofuel production factories |
| $F$ | gasoline or diesel |
| $l$ | potential locations for integrated factories |
| $l'$ | potential locations for pretreatment factories |
| $l''$ | potential locations for biofuel production factories |
| $m$ | potential markets |
| $r$ | biomass feedstock locations |
| $T$ | biofuel pathway with distributed system |
| $t$ | biofuel pathway with centralized system |

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## APPENDIX

**Table A1 Distance between provinces** (km)*

| | Anhui | Fujian | Gansu | Guangdong | Guangxi | Guizhou | Hainan | Hebei | Henan |
|---|---|---|---|---|---|---|---|---|---|
| Anhui | 0 | 939 | 1575 | 1236 | 1626 | 1586 | 1816 | 936 | 579 |
| Fujian | 939 | 0 | 2312 | 929 | 1531 | 1667 | 1474 | 1837 | 1434 |
| Gansu | 1575 | 2312 | 0 | 2327 | 2266 | 1706 | 2737 | 1207 | 1113 |
| Guangdong | 1236 | 929 | 2327 | 0 | 604 | 1124 | 589 | 1881 | 1482 |
| Guangxi | 1626 | 1531 | 2266 | 604 | 0 | 581 | 479 | 2070 | 1671 |
| Guizhou | 1586 | 1667 | 1706 | 1124 | 581 | 0 | 1053 | 1960 | 1561 |
| Hainan | 1816 | 1474 | 2737 | 589 | 479 | 1053 | 0 | 2479 | 2080 |
| Hebei | 936 | 1837 | 1207 | 1881 | 2070 | 1960 | 2479 | 0 | 425 |

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**Table A1** (Continued)

| | Anhui | Fujian | Gansu | Guangdong | Guangxi | Guizhou | Hainan | Hebei | Henan |
|---|---|---|---|---|---|---|---|---|---|
| Henan | 579 | 1434 | 1113 | 1482 | 1671 | 1561 | 2080 | 425 | 0 |
| Heilongjiang | 2228 | 2993 | 2741 | 3395 | 3559 | 3507 | 3970 | 1530 | 1926 |
| Hubei | 389 | 923 | 1381 | 1031 | 1220 | 1193 | 1629 | 895 | 516 |
| Hunan | 762 | 920 | 1654 | 731 | 881 | 840 | 1300 | 1205 | 806 |
| Jilin | 1958 | 2722 | 2470 | 3124 | 3288 | 3225 | 3674 | 1260 | 1656 |
| Jiangsu | 173 | 917 | 1746 | 1398 | 1782 | 1742 | 1996 | 915 | 674 |
| Jiangxi | 437 | 582 | 1754 | 803 | 1197 | 1155 | 1401 | 1229 | 873 |
| Liaoning | 1684 | 2439 | 2180 | 2875 | 3016 | 2938 | 3425 | 966 | 1351 |
| Inner Mongolia | 1531 | 2388 | 1111 | 2429 | 2619 | 2189 | 3028 | 820 | 976 |
| Shandong | 646 | 1562 | 1584 | 1850 | 2039 | 1929 | 2448 | 303 | 435 |
| Shanxi | 1004 | 1861 | 1007 | 1902 | 2091 | 1659 | 2500 | 245 | 473 |
| Shaanxi | 932 | 1738 | 644 | 1740 | 1619 | 1062 | 2338 | 865 | 479 |
| Sichuan | 1518 | 2103 | 1333 | 1986 | 1271 | 714 | 1742 | 1575 | 1195 |
| Tianjin | 958 | 1785 | 1531 | 2164 | 2328 | 2300 | 2737 | 317 | 718 |
| Xinjiang | 3555 | 4215 | 1912 | 4233 | 4169 | 3612 | 4640 | 3076 | 3015 |
| Yunnan | 2083 | 2165 | 2168 | 1394 | 798 | 510 | 1258 | 2422 | 2068 |
| Zhejiang | 423 | 635 | 2011 | 1302 | 1722 | 1681 | 1901 | 1178 | 939 |
| Chongqing | 1271 | 1799 | 1460 | 1478 | 934 | 377 | 1405 | 1539 | 1206 |

| | Heilongjiang | Hubei | Hunan | Jilin | Jiangsu | Jiangxi | Liaoning | Inner Mongolia | Shandong |
|---|---|---|---|---|---|---|---|---|---|
| Anhui | 2228 | 389 | 762 | 1958 | 173 | 437 | 1684 | 1531 | 646 |
| Fujian | 2993 | 923 | 920 | 2722 | 917 | 582 | 2439 | 2388 | 1562 |
| Gansu | 2741 | 1381 | 1654 | 2470 | 1746 | 1754 | 2180 | 1111 | 1584 |
| Guangdong | 3395 | 1031 | 731 | 3124 | 1398 | 803 | 2875 | 2429 | 1850 |
| Guangxi | 3559 | 1220 | 881 | 3288 | 1782 | 1197 | 3016 | 2619 | 2039 |
| Guizhou | 3507 | 1193 | 840 | 3225 | 1742 | 1155 | 2938 | 2189 | 1929 |
| Hainan | 3970 | 1629 | 1300 | 3674 | 1996 | 1401 | 3425 | 3028 | 2448 |
| Hebei | 1530 | 895 | 1205 | 1260 | 915 | 1229 | 966 | 820 | 303 |
| Henan | 1926 | 516 | 806 | 1656 | 674 | 873 | 1351 | 976 | 435 |
| Heilongjiang | 0 | 2360 | 2672 | 282 | 2119 | 2581 | 556 | 1680 | 1546 |
| Hubei | 2360 | 0 | 356 | 2112 | 548 | 369 | 1863 | 1470 | 872 |
| Hunan | 2672 | 356 | 0 | 2424 | 918 | 395 | 2175 | 1754 | 1200 |
| Jilin | 282 | 2112 | 2424 | 0 | 1849 | 2311 | 287 | 1410 | 1276 |
| Jiangsu | 2119 | 548 | 918 | 1849 | 0 | 598 | 1600 | 1518 | 639 |
| Jiangxi | 2581 | 369 | 395 | 2311 | 598 | 0 | 2065 | 1829 | 1065 |
| Liaoning | 556 | 1863 | 2175 | 287 | 1600 | 2065 | 0 | 1162 | 1007 |
| Inner Mongolia | 1680 | 1470 | 1754 | 1410 | 1518 | 1829 | 1162 | 0 | 930 |
| Shandong | 1546 | 872 | 1200 | 1276 | 639 | 1065 | 1007 | 930 | 0 |
| Shanxi | 1759 | 942 | 1226 | 1489 | 1100 | 1303 | 1200 | 527 | 528 |
| Shaanxi | 2364 | 808 | 999 | 2094 | 1106 | 1112 | 1804 | 972 | 893 |
| Sichuan | 3086 | 1143 | 1195 | 2816 | 1669 | 1498 | 2519 | 1685 | 1603 |
| Tianjin | 1226 | 1175 | 1464 | 956 | 912 | 1377 | 666 | 630 | 340 |
| Xinjiang | 4728 | 3351 | 3559 | 4459 | 3652 | 3727 | 4168 | 3011 | 3364 |
| Yunnan | 3989 | 1724 | 1335 | 3724 | 2239 | 1653 | 3433 | 2552 | 2436 |
| Zhejiang | 2359 | 816 | 920 | 2089 | 278 | 581 | 1799 | 1786 | 902 |
| Chongqing | 3038 | 897 | 892 | 2768 | 1423 | 1287 | 2478 | 1668 | 1568 |

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**Table A1** (Continued)

| | Shanxi | Shaanxi | Sichuan | Tianjin | Xinjiang | Yunnan | Zhejiang | Chongqing |
|---|---|---|---|---|---|---|---|---|
| Anhui | 1004 | 932 | 1518 | 958 | 3555 | 2083 | 423 | 1271 |
| Fujian | 1861 | 1738 | 2103 | 1785 | 4215 | 2165 | 635 | 1799 |
| Gansu | 1007 | 644 | 1333 | 1531 | 1912 | 2168 | 2011 | 1460 |
| Guangdong | 1902 | 1740 | 1986 | 2164 | 4233 | 1394 | 1302 | 1478 |
| Guangxi | 2091 | 1619 | 1271 | 2328 | 4169 | 798 | 1722 | 934 |
| Guizhou | 1659 | 1062 | 714 | 2300 | 3612 | 510 | 1681 | 377 |
| Hainan | 2500 | 2338 | 1742 | 2737 | 4640 | 1258 | 1901 | 1405 |
| Hebei | 245 | 865 | 1575 | 317 | 3076 | 2422 | 1178 | 1539 |
| Henan | 473 | 479 | 1195 | 718 | 3015 | 2068 | 939 | 1206 |
| Heilongjiang | 1759 | 2364 | 3086 | 1226 | 4728 | 3989 | 2359 | 3038 |
| Hubei | 942 | 808 | 1143 | 1175 | 3351 | 1724 | 816 | 897 |
| Hunan | 1226 | 999 | 1195 | 1464 | 3559 | 1335 | 920 | 892 |
| Jilin | 1489 | 2094 | 2816 | 956 | 4459 | 3724 | 2089 | 2768 |
| Jiangsu | 1100 | 1106 | 1669 | 912 | 3652 | 2239 | 278 | 1423 |
| Jiangxi | 1303 | 1112 | 1498 | 1377 | 3727 | 1653 | 581 | 1287 |
| Liaoning | 1200 | 1804 | 2519 | 666 | 4168 | 3433 | 1799 | 2478 |
| Inner Mongolia | 527 | 972 | 1685 | 630 | 3011 | 2552 | 1786 | 1668 |
| Shandong | 528 | 893 | 1603 | 340 | 3364 | 2436 | 902 | 1568 |
| Shanxi | 0 | 610 | 1319 | 551 | 2875 | 2166 | 1363 | 1283 |
| Shaanxi | 610 | 0 | 714 | 1168 | 2549 | 1570 | 1320 | 687 |
| Sichuan | 1319 | 714 | 0 | 1864 | 3239 | 841 | 1950 | 322 |
| Tianjin | 551 | 1168 | 1864 | 0 | 3426 | 2787 | 1152 | 1832 |
| Xinjiang | 2875 | 2549 | 3239 | 3426 | 0 | 4066 | 3915 | 3364 |
| Yunnan | 2166 | 1570 | 841 | 2787 | 4066 | 0 | 2176 | 884 |
| Zhejiang | 1363 | 1320 | 1950 | 1152 | 3915 | 2176 | 0 | 1704 |
| Chongqing | 1283 | 687 | 322 | 1832 | 3364 | 884 | 1704 | 0 |

* Data source: http://map.baidu.com.

**Table A2 Demand for bio-fuel in possible markets [30]**

| | Maximum demand for BD/$t\cdot a^{-1}$ | Minimum demand for BD/$t\cdot a^{-1}$ | | Maximum demand for BD/$t\cdot a^{-1}$ | Minimum demand for BD/$t\cdot a^{-1}$ |
|---|---|---|---|---|---|
| Anhui | 105000 | 63000 | Jilin | 57500 | 34500 |
| Fujian | 50300 | 30200 | Jiangxi | 54700 | 32800 |
| Guangxi | 65300 | 39200 | Liaoning | 128900 | 77300 |
| Guizhou | 43800 | 26300 | Shanxi | 104600 | 62700 |
| Hebei | 179800 | 107900 | Shaaxi | 61300 | 36800 |
| Henan | 207600 | 124600 | Sichuan | 122500 | 73500 |
| Heillongjiang | 80900 | 48600 | Tianjin | 20300 | 12200 |
| Hubei | 74800 | 44900 | Yunnan | 95700 | 57400 |
| Hunan | 100900 | 60500 | Chongqing | 58700 | 35200 |

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**Table A3 Plantation information about Jatropha fruit [5, 10, 29-31]**

| Location | Maximum amount available /t·a$^{-1}$ | Fossil energy inputs during plantation/MJ·(t biomass)$^{-1}$ | GHG emissions during plantation /g $CO_2$·(t biomass)$^{-1}$ | Plantation cost /CNY·(t biomass)$^{-1}$ | Conversion rate to preliminarily processed oil |
|---|---|---|---|---|---|
| Guangdong | 185000 | 6921 | 661.5 | 1315 | 0.33 |
| Guangxi | 210000 | 6921 | 661.5 | 1315 | 0.33 |
| Guizhou | 200000 | 6921 | 661.5 | 1315 | 0.33 |
| Hainan | 40000 | 6921 | 661.5 | 1315 | 0.33 |
| Sichuan | 310000 | 6921 | 661.5 | 1315 | 0.33 |
| Yunnan | 340000 | 6921 | 661.5 | 1315 | 0.33 |

**Table A4 Plantation information about rapeseed [5, 10, 29-31]**

| Location | Maximum amount available/t·a$^{-1}$ | Fossil energy inputs during plantation /MJ·(t biomass)$^{-1}$ | GHG emissions during plantation /g $CO_2$·(t biomass)$^{-1}$ | Plantation cost /CNY·(t biomass)$^{-1}$ | Conversion rate to preliminarily processed oil |
|---|---|---|---|---|---|
| Anhui | 190000 | 7401 | 681.7 | 1786 | 0.37 |
| Gansu | 25900 | 8769 | 807.7 | 2117 | 0.37 |
| Guizhou | 74000 | 9164 | 844.1 | 2212 | 0.37 |
| Henan | 78100 | 6725 | 619.4 | 1623 | 0.37 |
| Hubei | 235000 | 7088 | 652.9 | 1711 | 0.37 |
| Hunan | 107000 | 9563 | 880.8 | 2309 | 0.37 |
| Jiangsu | 167000 | 5793 | 533.6 | 1398 | 0.37 |
| Jiangxi | 40100 | 14034 | 1292 | 3388 | 0.37 |
| Inner Mongolia | 31300 | 12487 | 1150 | 3014 | 0.37 |
| Qinghai | 28300 | 7839 | 722.1 | 1892 | 0.37 |
| Shaanxi | 29400 | 8263 | 761.1 | 1995 | 0.37 |
| Sichuan | 165000 | 6934 | 638.7 | 1674 | 0.37 |
| Xinjiang | 12100 | 7796 | 718.1 | 1882 | 0.37 |
| Yunnan | 26200 | 7919 | 729.4 | 1912 | 0.37 |
| Zhejiang | 43500 | 6971 | 642.2 | 1683 | 0.37 |
| Chongqing | 31000 | 7879 | 725.7 | 1902 | 0.37 |

**Table A5 Information about integrated factory [5, 10, 29-31]**

| Capacity /t·a$^{-1}$ | Processing GHG emissions /MJ·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Processing fossil energy inputs /g $CO_2$·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Processing cost /CNY·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Fixed cost /CNY·a$^{-1}$ |
|---|---|---|---|---|
| 100000 | 3253/3520 | 301.3/324.8 | 179.9/189.8 | 13540000 |
| 200000 | 3035/3284 | 281.1/303.1 | 167.8/177.1 | 22000000 |
| 500000 | 2769/2996 | 256.5/276.5 | 153.1/161.6 | 41770000 |

**Table A6 Information about two steps factory [5, 10, 29-31]**

| Pretreatment factories | | | | |
|---|---|---|---|---|
| Capacity/t·a$^{-1}$ | Processing GHG emissions /MJ·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Processing fossil energy inputs /g $CO_2$·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Processing cost /CNY·(t biomass)$^{-1}$ (*Jatropha* fruit/rapeseed) | Fixed cost /CNY·a$^{-1}$ |
| 50000 | 481.4/403.2 | 49.01/41.05 | 36.54/28.25 | 363100 |
| 100000 | 449.2/376.2 | 45.73/38.30 | 34.10/26.36 | 590000 |
| 200000 | 419.1.351.0 | 42.67/35.73 | 31.81/24.60 | 958400 |

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**Table A6** (Continued)

| Biofuel production factories | | | | |
|---|---|---|---|---|
| Capacity/t·a$^{-1}$ | Processing GHG emissions /MJ·t$^{-1}$ | Processing fossil energy inputs /g $CO_2$·t$^{-1}$ | Processing cost /CNY·(t biomass)$^{-1}$ | Fixed cost /CNY·a$^{-1}$ |
| 31500 | 8496 | 774.4 | 441.8 | 12950000 |
| 63000 | 7927 | 722.5 | 412.2 | 21030000 |
| 100000 | 7569 | 689.9 | 393.6 | 29070000 |

**Table A7 Information about transportation [10]**

| Transportation cost/CNY·t$^{-1}$·km$^{-1}$ | Transportation GHG emissions/g $CO_2$·t$^{-1}$·km$^{-1}$ | Transportation fossil energy inputs/MJ·t$^{-1}$·km$^{-1}$ |
|---|---|---|
| 0.35 | 0.1215 | 1.587 |

**Table A8 Other information about products and pathways**

| Product | Price/CNY·t$^{-1}$ | Lower heating value/MJ·kg$^{-1}$ |
|---|---|---|
| bio-diesel | 8600 | 37000 |

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