BIOMASS AND BIOENERGY 56 (2013) 342–350

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Assessment of the biomass energy potentials and environmental benefits of *Jatropha curcas* L. in Southwest China

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ARTICLE INFO

Article history:
Received 17 September 2011
Received in revised form
24 May 2013
Accepted 28 May 2013
Available online 19 June 2013

Keywords:
Marginal land
Jatropha curcas L.
Life cycle analysis
Net energy
Greenhouse gas emission

ABSTRACT

Jatropha curcas L. (JCL) is believed to be the most promising tree species used to produce biodiesel in China. Due to its abundant marginal land resource and good meteorological conditions, Southwest China is the major region to develop JCL. With Southwest China being taken as the study area in this paper, multi-factor comprehensive analysis is used to identify marginal land resources suitable to JCL plantation and make suitability assessment, thus obtaining their spatial distribution, suitability degree and total amount. With life cycle analysis (LCA), the life cycle net energy and greenhouse gas emission reduction capacity of marginal land resources with different suitability degrees used to produce biodiesel are investigated. Based on the research results, the life cycle model is expanded to obtain the potentiality of total net energy production and greenhouse gas emission reduction of large-scale plantation of JCL in southwest China. The results show that the area of land resources suitable and moderately suitable for JCL plantation is 1.99×10^6 ha and 5.57×10^6 ha, respectively. If all of these land resources are put into use, the maximum net production potential of biodiesel from JCL would be 1.51×10^8 GJ/a, and the total greenhouse gas emission reduction capacity 1.59×10^7 t/a in Southwest China.

1. Introduction

As an important renewable new energy, biofuel (including biofuel ethanol and biodiesel) has attracted extensive attention of governments and enterprises throughout the world [1]. To safeguard national energy security, to reduce greenhouse gas emission and to promote the living standard of peasants are the major causes driving the rapid development of biofuel industry [2]. At present, developed countries in Europe and America and some developing countries have formulated the plans to develop biofuel, and large-scale development is underway. China is one of the major producing countries of biofuel, ranking the fifth in the world in 2009 in terms of total production [3]. However, due to the scarcity of China's farm land resources, Chinese government issued a policy in 2007, to restrict the expansion of biofuel using grain as raw material in order to safeguard food security. Meanwhile, the development focus is shifted to the biofuel made from other raw material other than grain. Forestry biodiesel has the advantages of "not using the grain intended for human consumption and not

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0961-9534/$ – see front matter
http://dx.doi.org/10.1016/j.biombioe.2013.05.030

occupying the land intended for grain production", thus attracting the attention of many developing countries including China [1]. *Jatropha curcas* L. (JCL) is considered to be the most promising tree species used to produce biodiesel [1,4]. Southwest China has the richest land resources suitable for energy plants development and with concentrated distribution. Moreover, because of its better meteorological conditions of temperature, precipitation and humidity, Southwest China is the major area for the development of JCL [5]. The local government has established development plan for JCL. For example, Yunnan, Sichuan and Guizhou have come up with such plan since 2006, attempting to plant 1667 thousand hectares of JCL using marginal land resources in the next 15 years.

China's biodiesel industry using JCL as raw material is witnessing rapid development. However, the development of biodiesel industry is still faced with many uncertainties, among which the accurate estimation of the potentiality of raw material supply, net energy production and greenhouse gas (GHG) emission reduction is the most crucial issue. Currently, the appraisals of biodiesel supply potential of JCL, i.e. the researches on the quantity and quality of land resources suitable for JCL plantation, have been many [1,5]. The analysis of regional energy potential of JCL is mostly limited to this aspect, while the appraisal outcome of net energy production potential of JCL is rare. The appraisal of GHG emission reduction potential is little more than rough estimation in most cases, without the quantitative estimation based on scientific statistics and approaches. Therefore, operable techniques and approaches should be developed so that the accurate appraisal of supply potential of raw materials, net energy production potential and GHG emission reduction potential in the exploitation and utilization of biofuel from JCL can be achieved. It is hoped that this appraisal will provide statistical support for the formulation of environmental protection policy, GHG emission reduction policy and related industry policy by national and local government.

In the appraisal of net energy production potential and GHG emission reduction potential, life cycle analysis (LCA) has been proven to be a feasible method [6–10]. LCA is a method to appraise and analyze the environmental impact and energy consumption of a product or system in the entire life cycle from the acquisition of raw material, production, usage to post-usage treatment [6]. LCA has been widely applied in the appraisal research on bioenergy impact [7–10]. At present, the researches on life cycle net energy and GHG emission reduction of energy plants cultivated on marginal land resources of different suitability degrees remain to be conducted. Moreover, the researches on the estimation of regional total net energy production potential and GHG emission reduction potential by integrating marginal land resources suitable for energy plants cultivation with LCA are also rare.

Five provinces in Southwest China, including Yunnan, Guangxi, Guizhou, Sichuan and Chongqing, are taken as the study areas in this paper. First, the potentiality, degree and spatial distribution of marginal land resources suitable for planting JCL are determined. Next, LCA-based analytical model of net energy production potential and GHG emission reduction potential of biodiesel produced from JCL is established. By this means, the analysis and appraisal of maximum net energy amount and GHG emission reduction potential of biodiesel from JCL in Southwest China can be achieved, thus offering technical methods and typical cases for analysis of development potentials and environmental benefits of biofuels derived from energy plants.

2. Method

The research is conducted in the following procedures:

(1) Identification and appraisal of marginal land suitable for JCL planting: multi-factor comprehensive analysis is adopted to identify marginal land resources suitable for JCL planting and conduct suitability appraisal. By this means, their spatial distribution, suitability degree and total amount are obtained.
(2) LCA net energy and GHG emission reduction capacity of biofuel from JCL: LCA is used to study the life cycle net energy amount and GHG emission reduction capacity of biodiesel produced from JCL for marginal land resources of different suitability degrees.
(3) Estimation of total net energy production potential and GHG emission reduction potential derived from large-scale planting of JCL in Southwest China: on the basis of the research results mentioned above, life cycle model is expanded, to obtain the net energy production potential and GHG emission reduction potential derived from large-scale planting of JCL in Southwest China.

2.1. *Identification and appraisal of marginal land resources suitable for JCL planting*

Adopting the criteria for determining marginal land resources suitable for JCL plantation by Zhuang et al. [5] and using multi-factor comprehensive analysis, the potentiality and suitability of marginal land resources suitable for JCL planting are investigated in this paper in the following procedures: (1) based on existing literature and expert consultancy, JCL's requirements on temperature, water, slope and soil quality are set, with the natural conditions classified as suitable, moderately suitable and unsuitable (Table 1) [1,11]; (2) based on suitability classification, multi-factor comprehensive analysis on land resource suitability is conducted [10]; (3) based on the results of multi-factor comprehensive appraisal, suitability analysis is conducted on various types of land resources according to the criteria of marginal land resource suitable for JCL planting [1,10,12]; (4) based on the restraint conditions of economy, society and environment, the results of multi-factor comprehensive appraisal are corrected.

2.2. *LCA net energy and GHG emissions of biodiesel derived from JCL*

The life cycle of biodiesel derived from JCL is the entire process from planting to combustion of biodiesel in engine cylinder, mainly including plantation, fruit transportation, JCL oil extraction and biodiesel production, biodiesel transportation, distribution and combustion in engine cylinder (Fig. 1). In this

Table 1 – Temperature, moisture, land slope and soil quality under three categories of land suitability for JCL plantation [1,12].

Constraints	Detail constraints	Suitable	Moderate suitable	Unsuitable
Temperature condition	Annual mean temperature/°C	≥20	17 ∼ 20	≤17
	Annual extreme minimum temperature/°C	≥2	0 ∼ 2	≤0
Water condition	Thornthwaite humidity index	−33.3 ∼ 100	−66.7 ∼ −33.3	>100 or <−66.7
Terrain conditions	Average slope	≤15°	15° ∼ 25°	≥25°
Soil quality	Soil depth/cm	≥75	30 ∼ 75	≤30
	Organic contents/%	≥3.5	1.5 ∼ 3.5	≤1.5
	Soil texture/%	≥30	10 ∼ 30	≤10

process, material and energy such as diesel, electricity, coal and fertilizer are consumed, with biodiesel and byproducts as the major output.

Part of the statistic data such as fruit production of JCL used in this study are acquired through field investigation; while other statistics, such as the energy consumption parameters and the production statistics of gasoline, chemical fertilizers and fire coal, are adopted from related literature materials published in China and in foreign countries [7–9,13,14], or acquired from GREET database of Argonne National Laboratory in America [15]. The statistics acquired abroad are corrected according to the specific situation of Southwest China.

2.2.1. *LCA net energy of biodiesel produced from JCL*

Net energy value (NEV) and energy ratio (ER) are key parameters evaluating the efficiency of life cycle energy of biodiesel produced from JCL [8,9]. The NEV is the energy supplied by biodiesel minus the energy consumed in the life cycle of biodiesel [9]. ER is the ratio of energy supplied by biodiesel to that consumed by biodiesel in its life cycle [8]. NEV and ER can be calculated using the following equations:

$$NEV = BE - (FE_1 + FE_2 + FE_3 + FE_4 + FE_5 - FE_6) \quad (1)$$

$$ER = BE/(FE_1 + FE_2 + FE_3 + FE_4 + FE_5 - FE_6) \quad (2)$$

Here, BE is the energy contained in the biodiesel; FE_1, FE_2, FE_3, FE_4 and FE_5 are the energy consumed during the stages of plantation, fruit transportation, JCL oil extraction and biodiesel production, biodiesel transportation, distribution, respectively; FE_6 is the energy allocation by the byproducts. The above factors can be calculated according to Refs. [9,16].

2.2.2. *LCA GHG emission reduction of biodiesel produced from JCL*

GHG emissions mainly include CO_2, CH_4 and N_2O, whose emission is either direct or indirect. According to the corresponding global warming potential (GWP) value, the weight of these three greenhouse gases are converted into respective CO_2 equivalents ($CO_{2,e}$). The total emission of GHG is calculated using the formula below [17]:

$$GHG_{LCA} = 23CH_{4,LCA} + 296N_2O_{LCA} + CO_{2,LCA} \quad (3)$$

Here, GHG_{LCA} is the LCA GHG ($CO_{2,\ e}$) emission; $CH_{4,\ LCA}$ is the LCA CH_4 emission; N_2O_{LCA} is the LCA N_2O emission; $CO_{2,\ LCA}$ is the LCA CO_2 emission.

Net GHG reduction value (NGRV) is the key parameter to evaluate the GHG emission reduction capacity of biodiesel produced from JCL in its life cycle [9]. It is the result of the LCA GHG emission of conventional diesel with equal energy value minus the biodiesel pathway's LCA GHG emission.

$$NGRV = GHG_{LCA,CD} - GHG_{LCA,biofuel} \quad (4)$$

Here, $GHG_{LCA;\ CD}$ is the LCA GHG emission of conventional diesel; $GHG_{LCA;\ biofuel}$ is the biodiesel pathway's LCA GHG emission which can be calculated using the formula below:

$$GHG_{LCA,biofuel} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 - C_{avoided} \quad (5)$$

Here, C_1, C_2, C_3, C_4, C_5 and C_6 are the LCA GHG emissions during the stage of plantation, fruit transportation, JCL oil extraction and biodiesel production, biodiesel transportation, distribution, and biodiesel combustion, respectively; $C_{avoided}$ is the GHG allocation by the byproducts. The above factors can be calculated according to Refs. [9,16].

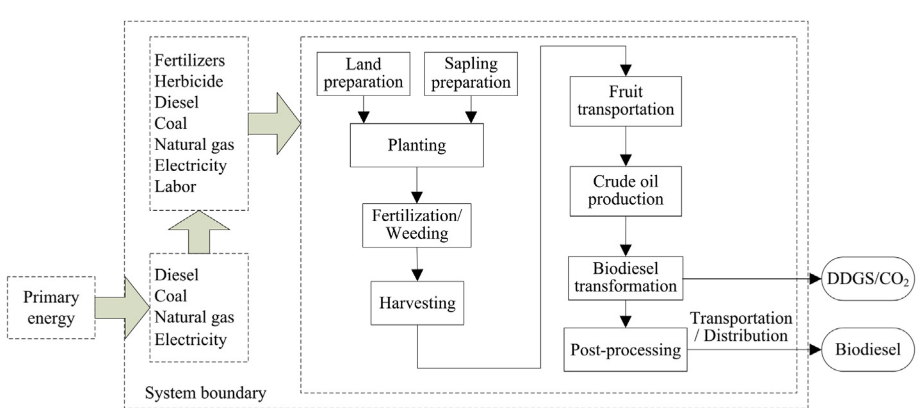

Fig. 1 – Framework for the life cycle of biodiesel produced from JCL. Modified after Refs. [7,9].

Table 2 – Basic parameters of JCL biodiesel pathways.

LCA pathways	Amount	Data source
Plantation		
N fertilizer (kg/hm^2)	97	[9]
P fertilizer (kg/hm^2)	27	[9]
K fertilizer (kg/hm^2)	18	[9]
Herbicide (kg/hm^2)	5	Field visit
Electricity (kwh/hm^2)	11	[8,9]
Diesel (L/hm^2)	18	[10,13]
Fruit transportation distance (km)	250	[9]
Biodiesel production (MJ/L)	9.946	[20]
Biodiesel transportation distance (km)	300	[9]
Biodiesel distribution (kwh/L)	0.0007	Field visit
Sharing ratio of the by-product (%)	40	[9]

Table 3 – LCA GHG emission for the materials input. Adapted from Refs. [8,10,15].

	CH_4	N_2O	CO_2
N fertilizer (g/t)	1634.4	69.1	1,519,548.1
P fertilizer (g/t)	121.9	1.0	432,112.7
K fertilizer (g/t)	896.0	7.0	655,492.0
Herbicide (g/t)	31,954.0	234.5	23,496,370.0
Diesel (g/L)	0.02	0.075	3199.46
Electricity (g/kwh)	0.004	0.005	413.452
Coal (g/t)	31.110	21.110	2,695,731.51

2.2.3. *Determination of basic parameters in the model*

On the basis of field investigation and existing literature, the average per unit area yield of land moderately suitable for JCL planting is determined as 2.7 t/ha, while that of land suitable for JCL planting is 5 t/ha. Researches show that 5.5 t of CO_2 per ha is absorbed annually by JCL [18]. Through field investigation, the absorption amount of CO_2 for land of suitable degree and that of moderately suitable degree is determined as 3.733 t/ha and 2.016 t/ha, respectively.

Basic parameters of the JCL biodiesel pathways are listed in Table 2, while the emission parameters of main inputs are listed in Table 3. The production and transformation process of biodiesel includes two stages, i.e. crude oil production from JCL and transformation to biodiesel, and the statistics are obtained from the calculation of related statistics [18–20]. According to field investigation and related literature, hydroelectric power accounts for 40%, while thermal electric power accounts for 60% in the electric power composition in Southwest China [8].

2.3. *Estimation of net energy production potential and GHG emission reduction potential of large-scale JCL planting in Southwest China*

2.3.1. *Analysis of total net energy production potential of JCL in Southwest China*

Through the combination of LCA net energy of JCL biodiesel and the information of marginal land resources, the LCA model is expanded to estimate the amount of net energy production potential of the entire area of land suitable for JCL planting. Thus, the model of total net energy production potential of biodiesel produced from JCL in Southwest China is obtained [16,21,22] and the method can be extrapolated to other regions with different energy plants.

$$\mathrm{SumNEV} = \sum_{i=1}^{n} (\mathrm{NEV}_i \times x_i) \tag{6}$$

Here, SumNEV is the amount of net energy production potential of the entire area; i is the suitability degrees of marginal land resources; x_i is the area of marginal land with degree i.

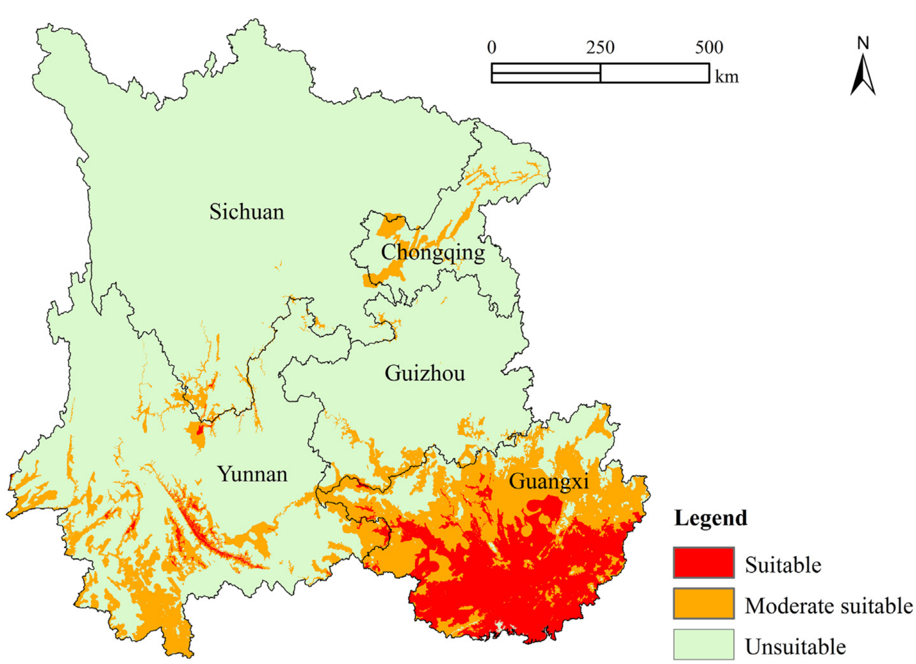

Fig. 2 – Spatial distribution of land suitable for JCL planting based on multi-factor comprehensive analysis.

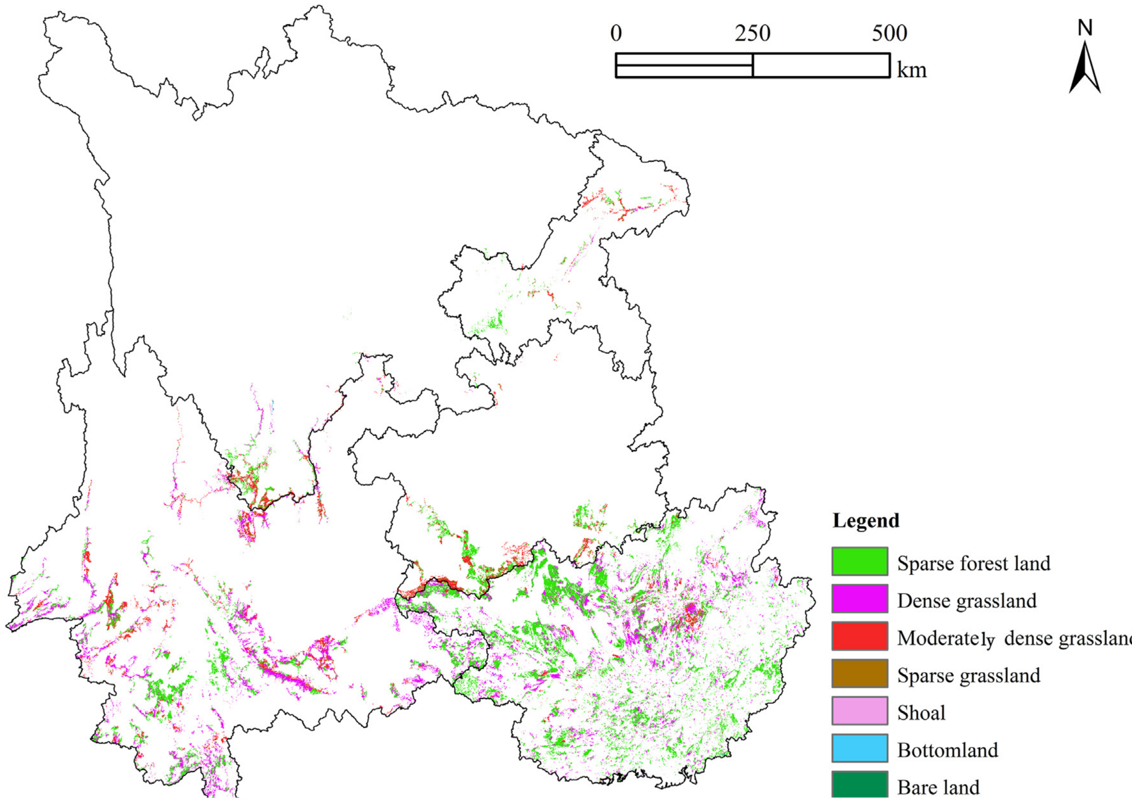

Fig. 3 – Spatial distribution of land use types suitable and moderately suitable for JCL planting.

2.3.2. *Analysis of total GHG emission reduction potential of biodiesel produced from JCL in Southwest China*

Through the combination of LCA GHG emission reduction of JCL biodiesel and the information of marginal land resources, the LCA model is expanded to estimate the amount of GHG emission reduction capacity of the entire area of land suitable for JCL planting. Thus, the model of total GHG emission reduction capacity of biodiesel produced from JCL in Southwest China is obtained [16,22,23].

$$\mathrm{SumGHG} = \sum_{i=1}^{n} (\mathrm{NGRV}_i \times x_i) \quad (7)$$

Here, SumGHG is the amount of GHG emission reduction capacity of the entire area; i is the suitability degrees of marginal land resources; x_i is the area of marginal land with degree i.

3. Results and discussion

3.1. *Results of suitability appraisal of land resources for JCL planting*

Multi-factor comprehensive analysis is conducted (Section 2.1) to calculate the amount of land resources suitable

Table 4 – Areas of land suitable and moderate suitable for JCL plantation in Southwest China (10^4 ha).

Land use types	Guangxi		Yunnan		Guizhou		Sichuan		Chongqing		Total	
	S	MS	S	MS	S	MS	S	MS	S	MS	S	MS
Sparse forest land	115.3	137.80	5.30	81.42	0.02	29.03	0.17	11.76	0	8.12	120.8	268.13
Dense grassland	50.31	70.3	12.62	108.51	0	0.17	0.11	3.41	0	1.12	63.03	183.51
Moderate dense grassland	8.16	9.79	3.22	44.39	0.93	24.40	1.00	12.01	0	6.92	13.31	97.51
Sparse grassland	0.25	0.59	0.57	2.765	0.05	2.91	0.07	0.29	0	0.19	0.93	6.73
Shoal	0.15	0	0	0	0	0	0	0	0	0	0.15	0
bottomland	1	0.54	0.12	0.45	0	0	0	0.23	0	0.03	1.14	1.25
Bare land	0.087	0	0	0.15	0	0	0	0	0	0	0.09	0.15
Total	175.26	219.02	21.83	237.69	1	56.51	1.35	27.7	0	16.38	199.45	557.28

Note: S-Suitable land; MS-Moderately suitable land.

Table 5 – LCA energy consumption for JCL biodiesel.

Stages	Suitable land			Moderately suitable land		
	MJ/ha	Percentage	MJ/L	MJ/ha	Percentage	MJ/L
Plantation	6985.112	26.013	3.873	6985.112	39.434	7.171
Fruit transportation	1403.793	5.228	0.778	758.048	4.280	0.778
Biodiesel production	17,939.45	66.809	9.946	9687.303	54.69	9.946
Biodiesel transportation	510.470	1.901	0.283	275.654	1.556	0.283
Biodiesel distribution	13.257	0.049	0.007	7.159	0.040	0.007
Total	26,852.082	100	14.887	17,713.276	100	18.186

for large-scale development of JCL. The results are shown in Figs. 2, 3, and Table 4, from which the following conclusions are reached:

(1) Generally speaking, the area of land suitable and moderately suitable for JCL planting is 1.99×10^6 ha and 5.57×10^6 ha, respectively, among which the suitable land resources are predominated by sparse forest land and grassland.
(2) Suitable land resources are mainly concentrated in Guangxi, accounting for 87.9% of suitable land resources in the five provinces, with sparse forest land and dense grassland taking up the largest proportion. There are also suitable land resources in Yunnan, totaling 2.18×10^5 ha. The area of suitable land resources is relatively smaller in the remaining three provinces, since JCL has higher demands on temperature, which is the largest factor restricting its plantation.

3.2. *Results of the analysis of LCA net energy and GHG emissions of biodiesel produced from JCL*

3.2.1. *Analysis of LCA net energy of biodiesel produced from JCL*

Through the analysis of energy consumption of biodiesel produced from JCL at each stage of life cycle, the energy input of biodiesel production using JCL as raw material is thus obtained (Table 5, Figs. 4 and 5). It can be known from Table 5 that although land types of different suitability degree have significant influence on energy consumption during the stage of raw material planting, the energy consumption in the stage of biodiesel production and transformation is the largest in the entire life cycle, being 9.946 MJ/L. Next comes that in the planting stage due to the input of large quantities of fertilizers and herbicides. During this stage, energy consumption for the development of biodiesel on the two land types of different suitability degrees (suitable and moderately suitable) is 3.873 MJ/L and 7.171 MJ/L, respectively. The life cycle energy consumption of biodiesel on the two land types of different suitability degree is 14.887 MJ/L and 18.186 MJ/L, respectively.

The life cycle NEV of diesel produced from JCL on the suitable land is 18.713 MJ/L, with the ER of 2.257, when the energy of byproduct is not considered; while that on the moderately suitable land is 15.414 MJ/L, with the ER of 1.848. It can be seen that net energy surplus of biodiesel produced from JCL is larger, with higher energy efficiency. If the energy of byproduct is considered (Table 6), the NEV and ER for both land types are considerably increased. The NEV for the suitable land reaches 24.668 MJ/L, with ER of 3.762; while that for the moderately suitable land reaches 22.689 MJ/L, with ER of 3.079.

3.2.2. *Analysis of LCA GHG emission reduction of biodiesel produced from JCL*

By accumulating the GHG emission in each stage of life cycle, the total emission of biodiesel production using JCL as raw materials (without considering the energy allocation of byproducts) is thus obtained (Table 7).

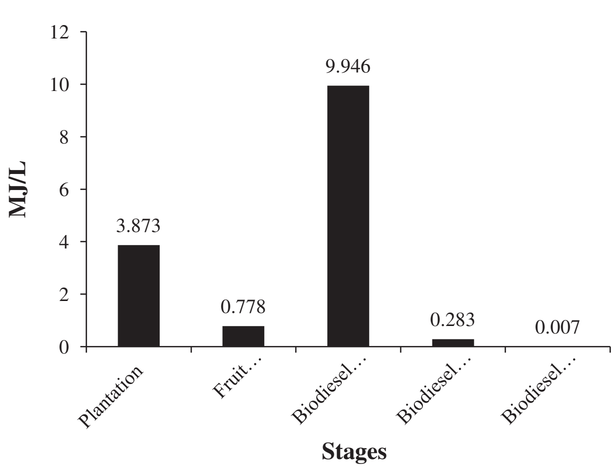

Fig. 4 – LCA energy consumptions of each process for JCL biodiesel (suitable land).

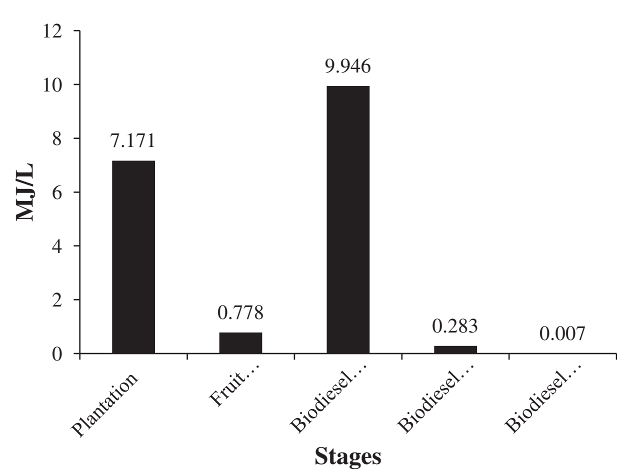

Fig. 5 – LCA energy consumptions of each process for JCL biodiesel (moderately suitable land).

Table 6 – Allocation results of energy consumption for JCL biodiesel.

Suitable degrees	Before allocation		After allocation	
	NEV (MJ/L)	ER	NEV (MJ/L)	ER
Suitable land	18.713	2.257	24.668	3.762
Moderate suitable land	15.414	1.848	22.689	3.079

For CH_4 emission, the proportion in the stage of oil extraction and biodiesel production is the largest, followed by that in the stage of plantation and transportation, while that in biodiesel distribution and combustion is the smallest. N_2O emission in the stage of combustion is the largest among all the stages of the life cycle, with small emission in other stages. Since photosynthesis requires CO_2 absorption in vegetation growth, CO_2 emission at this stage is negative [13]; while among other stages, that in the stage of combustion is the largest. After the reduction by photosynthesis, the GHG emission for the biodiesel production using land of suitability and moderately suitability is 1.31×10^6 g/t and 1.51×10^6 g/t, respectively (Table 7); the corresponding NGRV is 2.26×10^6 g/t and 2.05×10^6 g/t, respectively (Table 8).

Using byproduct allocation coefficient (0.4) [9], the LCA GHG emissions for the JCL biodiesel after byproduct allocation are calculated (Table 9). The results show that byproduct allocation plays an important role in the reduction of total LCA GHG emission. The analytical results show that the production of biodiesel from JCL can effectively reduce GHG emission.

3.2.3. *Sensitivity analysis*

By increasing or decreasing the input factors of life cycle by 10%, the sensitivity analysis is conducted. The results show that the LCA net energy amount and GHG emission reduction statistics are insensitive to such variations mentioned above, which is consistent with the conclusion by Ou et al. [9]. Thus, the results of sensitivity analysis are not listed here.

3.3. *Estimation of the potentiality of total net energy production and GHG emission reduction of large-scale JCL planting in Southwest China*

Based on the results achieved in Sections 3.1 and 3.2, Formula 6 and 7 are used to calculate total net energy production potential and GHG emission reduction potential of large-scale JCL planting in Southwest China.

3.3.1. *Total net energy production potential*

Results show that (Table 10) the maximum total net energy production potential of biodiesel produced from JCL in the five provinces in Southwest China is 1.51×10^8 GJ. If the production of biodiesel proceeds according to this plan, the total net energy amount of biodiesel produced annually is equivalent to 2.38×10^6 tons of diesel; if the land resources of suitability degree are only utilized, the maximum total net energy production potential of biodiesel is 6.73×10^7 GJ, which is capable of replacing 1.06×10^6 tons of diesel.

Provincial statistics show that the total net energy production potential of Guangxi is the largest among the five provinces (Fig. 6), totaling 9.20×10^7 GJ, followed by Yunnan with total net energy production potential of 4.31×10^7 GJ. The land resources of suitability degree in the other three provinces are limited, with smaller total net energy production potential.

3.3.2. *Total GHG emission reduction potential*

The total GHG emission reduction model is used to calculate the total GHG emission reduction potential of biodiesel produced from JCL in five provinces in Southwest China without

Table 7 – LCA GHG emission of biodiesel produced from JCL (g/ha).

Stages	Suitable land				Moderately suitable land			
	CH_4	N_2O	CO_2	GHG	CH_4	N_2O	CO_2	GHG
Plantation	338.13	9.43	−3382851.17	−3371586.88	338.13	9.43	−1665517.83	−1654253.55
Fruit transportation	300.26	5.80	265,661.63	274,895.90	162.14	3.13	143,457.28	148,443.82
Biodiesel production	1079.23	3.84	549,060.50	577,186.40	582.78	2.08	296,492.70	311,680.70
Biodiesel transportation	90.99	1.76	80,503.52	83,301.81	49.13	0.95	43,471.90	44,983.03
Biodiesel distribution	0.05	0.07	5481.37	5502.36	0.03	0.04	2959.94	2971.39
Combustion	34.70	160.15	4,366,182.39	4,414,773.97	18.74	86.48	2,357,738.49	2,383,977.96
Total (g/ha)	1843.35	181.05	1,884,038.24	1,984,073.60	1150.95	102.10	1,178,602.48	1,237,803.35
g/t	1216.61	119.49	1,243,465.24	1,309,488.58	1406.72	124.79	1,440,514.14	1,512,870.77

Table 8 – Comparison of LCA GHG emissions for the JCL biodiesel and conventional diesel (g/t).

	Suitable land				Moderately suitable land			
	CH_4	N_2O	CO_2	GHG	CH_4	N_2O	CO_2	GHG
Emission	1216.61	119.49	1,243,465.24	1,309,488.58	1406.72	124.79	1,440,514.14	1,512,870.77
NGRV	2672.32	−5.20	2,192,760.76	2,258,018.73	2482.22	−10.51	1,995,711.86	2,054,636.54

Table 9 – LCA GHG emissions for the JCL biodiesel after byproduct allocation (g/t).

	CH_4	N_2O	CO_2	GHG
Conventional diesel	3888.937	114.288	3,436,226.000	3,567,507.309
Suitable land	729.968	71.694	746,079.144	785,693.147
Moderately suitable land	844.031	74.877	864,308.484	907,722.459

Table 10 – Total net energy production potential of JCL planting in Southwest China.

Provinces	Suitable land (10^4 ha)	SumNEV (10^4 GJ)	Moderately suitable land (10^4 ha)	SumNEV (10^4 GJ)
Guangxi	175.26	5915.722	219.02	3288.366
Yunnan	21.83	736.849	237.69	3568.677
Guizhou	1	33.754	56.51	848.441
Sichuan	1.35	45.568	27.7	415.888
Chongqing	0.000	0.000	16.38	245.929
Subtotal	199.440	6731.894	557.3	8367.301
Total		15,099.194		

considering the byproduct allocation (Table 11). The results show that the total GHG emission reduction potential of JCL biodiesel is 1.59×10^7 t in the five provinces in Southwest China.

Provincial statistics show that the total emission reduction potential of Guangxi is the largest among the five provinces, totaling 9.68×10^6 t, followed by Yunnan province with total emission reduction of about 4.74×10^6 t; that in other provinces is smaller (Fig. 7).

3.4. *Comparative analysis with existing researches*

The researches on the net energy amount and the GHG emission reduction of JCL planting in China using LCA are

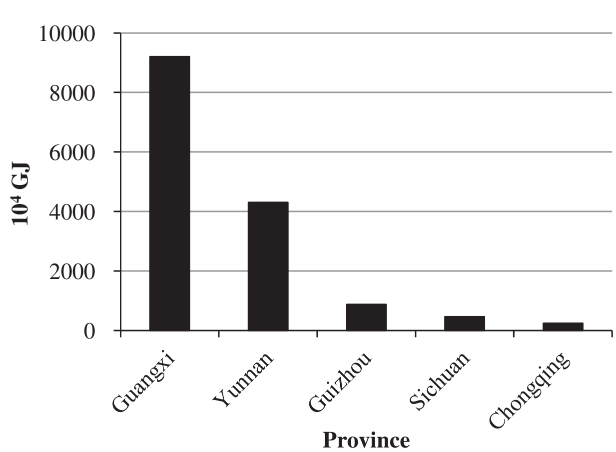

Fig. 6 – Provincial statistics of total net energy production potential of biodiesel produced from JCL in the five provinces.

Table 11 – Total GHG emission reduction potential of JCL planting in Southwest China.

Provinces	Suitable land (10^4 ha)	SumGHG (10^4 t)	Moderately suitable land (10^4 ha)	SumGHG (10^4 t)
Guangxi	175.26	599.607	219.02	368.187
Yunnan	21.83	74.686	237.69	399.573
Guizhou	1	3.421	56.51	94.997
Sichuan	1.35	4.619	27.7	46.566
Chongqing	0.000	0.000	16.38	27.536
Subtotal	199.440	682.332	540.920	909.323
Total		1591.655		

rare. This study makes a comparison with the research results by Ou et al. [9].

When the byproduct allocation is not considered, the NEV of biodiesel produced from JCL is larger than 0, with the ER larger than 1, whether the land of suitability degree or of moderately suitability degree is utilized to develop the JCL biodiesel. This indicates that JCL has good energy production potential. The ER of biodiesel produced from JCL is 2.257 and 1.848 for land of suitability degree and land of moderately suitability degree, respectively. The calculation results are close to the result of 2.004 calculated by Ou et al. [9].

If the byproducts allocation is not considered, CH_4 emission and CO_2 emission of biodiesel produced from JCL are less than that of diesel. Only N_2O emission is larger than that of diesel; the GHG emission of biodiesel is significantly less than that of diesel, which is similar to that by Ou et al. [9]. Meanwhile, the byproduct allocation has an important role in improving the amount of net energy and the capacity of GHG emission reduction, thus the utilization efficiency of byproducts should be improved.

By comparing the net energy and the capacity of GHG emission reduction of biodiesel produced from JCL which is planted on two different degrees of land, it is thus known that the increase of per unit area yield can effectively improve net energy and the capacity of GHG emission reduction. The research and development of high-yield energy plants for the improvement of per unit area yield is conductive to boosting the feasibility of biofuel production.

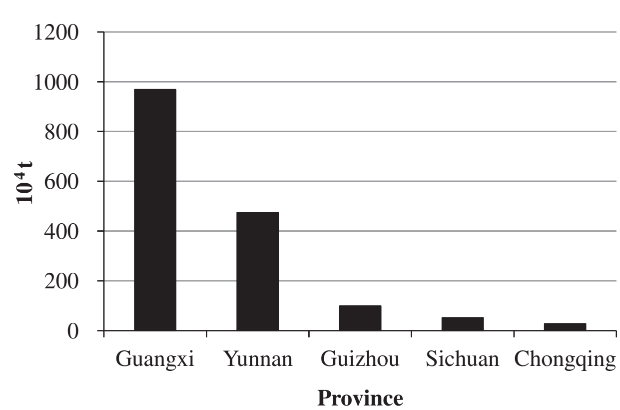

Fig. 7 – Provincial statistics of total GHG emission reduction potential of biodiesel produced from JCL in the five provinces.

4. Conclusion

Through the combination of multi-factor comprehensive analysis and LCA, the marginal land resources, total net energy production and GHG emission reduction potential of the JCL biodiesel are estimated in Southwest China. Following conclusions have been achieved:

(1) The area of land suitable and moderately suitable for JCL planting is 1.99×10^6 ha and 5.57×10^6 ha, respectively, among which the suitable land resources are predominated by sparse forest land and grassland. Suitable land resources are mainly concentrated in Guangxi and Yunnan, accounting for 98.8% of suitable land resources in the five provinces.
(2) The life cycle energy consumption of biodiesel on the two land types of different suitability degree is 14.887 MJ/L and 18.186 MJ/L, respectively. The energy consumption in the stage of biodiesel production and transformation is the largest in the entire life cycle, being 9.946 MJ/L. Next comes that in the planting stage due to the input of large quantities of fertilizers and herbicides. The GHG emission for the biodiesel production using land of suitability and moderately suitability is 1.31×10^6 g/t and 1.51×10^6 g/t, respectively; the corresponding NGRV is 2.26×10^6 g/t and 2.05×10^6 g/t, respectively. The analytical results show that the production of biodiesel from JCL can effectively receive net energy and reduce GHG emission.
(3) The maximum total net energy production potential of biodiesel produced from JCL in Southwest China is 1.51×10^8 GJ. If the production of biodiesel proceeds according to this plan, the total net energy amount of biodiesel produced annually is equivalent to 2.38×10^6 tons of diesel. The total net energy production potentials of Guangxi and Yunnan, totaling 9.20×10^7 and 4.31×10^7 GJ, respectively, are the largest among the five provinces.
(4) The total GHG emission reduction potential of JCL biodiesel is 1.59×10^7 t in the five provinces in Southwest China. Provincial statistics show that the total emission reduction potential of Guangxi is the largest among the five provinces, totaling 9.68×10^6 t, followed by Yunnan province with total emission reduction of about 4.74×10^6 t; that in other provinces is smaller.

Acknowledgments

This research was supported and funded by the Chinese Academy of Sciences (Grant No. KZZD-EW-08) and State Key Laboratory of Resources and Environmental Information Systems of China.

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