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Article

Net Energy, CO_2 Emission and Land-Based Cost-Benefit Analyses of *Jatropha* Biodiesel: A Case Study of the Panzhihua Region of Sichuan Province in China

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Abstract: Bioenergy is currently regarded as a renewable energy source with a high growth potential. Forest-based biodiesel, with the significant advantage of not competing with grain production on cultivated land, has been considered as a promising substitute for diesel fuel by many countries, including China. Consequently, extracting biodiesel from *Jatropha curcas* has become a growing industry. However, many key issues related to the development of this industry are still not fully resolved and the prospects for this industry are complicated. The aim of this paper is to evaluate the net energy, CO_2 emission, and cost efficiency of *Jatropha* biodiesel as a substitute fuel in China to help resolve some of the key issues by studying data from this region of China that is well suited to growing *Jatropha*. Our results show that: (1) *Jatropha* biodiesel is preferable for global warming mitigation over diesel fuel in terms of the carbon sink during *Jatropha* tree growth. (2) The net energy yield of *Jatropha* biodiesel is much lower than that of fossil fuel, induced by the high energy consumption during *Jatropha* plantation establishment and the conversion from seed oil to diesel fuel step. Therefore, the energy efficiencies of the production of *Jatropha* and its conversion to biodiesel need to be improved. (3) Due to current low profit and high risk in the study area, farmers have little incentive to continue or increase *Jatropha* production. (4) It is necessary to provide more subsidies and preferential policies for *Jatropha* plantations if this industry is to grow. It is also necessary for local government to set realistic objectives and make rational plans to choose proper sites for *Jatropha* biodiesel development and the work reported here should assist that effort. Future research focused on breading high-yield varieties, development of efficient field management systems, and detailed studies lifecycle environmental impacts analysis is required to promote biologically and economically sustainable development of *Jatropha* biodiesel and to assist government agencies in setting realistic objectives and appropriate and advantageous policies for the regions and the country.

Keywords: substitute energy; *Jatropha curcas*; biodiesel; net energy; CO_2 emission; land suitability assessment; cost-benefit analysis

1. Introduction

With its rapid economic development in the last few decades, China has become the largest energy consumer in the world. China's aggregate energy consumption rose to 2.43 billion tons of oil equivalent in 2010, accounting for 20.3% of global energy consumption [1]. Reportedly, China has accounted for nearly three quarters of world energy demand growth in recent years [2]. As China is in the process of rapid industrialization, urbanization and modernization, it is expected that energy consumption will continue to increase [3]. However, the coal-dominant energy structure in China leads to many significant problems, such as shortages of resources, high CO_2 emissions and severe environmental pollution [4–8].

In recent years more people have come to realize that substituting renewable energy can contribute significantly to global climate change mitigation and is also important for national energy security [9–11]. It can play a strong role in reducing greenhouse gas emissions and helping achieve sustainable development of all the substitute energy sources, so bioenergy is currently regarded as the renewable carbon-based energy source with the highest potential, for it is the only renewable carbon resource that can be directly converted to liquid fuel [12,13]. Known for being renewable, biodegradable, nontoxic and environmental friendly, biofuels have showed high potential in coping with the worldwide energy crisis and increasingly serious environmental problems [14,15]. The production and utilization of biofuel will reduce dependence on petroleum, improve environmental quality, mitigate greenhouse gas emissions, alleviate rural poverty and promote rural development. As a substitute to fossil fuels, biodiesel has attracted worldwide attention [16–18]. The Chinese government also has recognized the importance of developing biofuel sources, and thus understanding energy efficiency and CO_2 emission reduction for each candidate source become critical factors in forming policy decisions. In 2006, the National Development and Reform Commission of China set an aim that biofuel will provide 15% of the total transportation energy needs by 2020 [19]. Since then, various research programs have been carried out and relevant technologies have been developed and used for commercial applications. In the current debate, biofuels are generally divided into "first-generation" and "second-generation" biofuels, based on the types of feedstocks and processing technologies. The first generation biofuels are generally derived from sources like starch, sugar, animal fats and vegetable oil. Relatively simple processing of the biomass is required to produce a finished fuel. The two main first-generation liquid biofuels are biodiesel and bioethanol, representing about 15% and 85% of the current global production respectively [20]. For biodiesel production, the feedstocks include vegetable oils, used frying oil or animal fat. The major components of vegetable oils and animal fats are triacylglycerides (TAGs), which consist of three long-chain fatty acids linked to a glycerol backbone. Since natural oils are too viscous to be used in modern diesel engines, they are usually directly blended with diesel, or converted into biodiesel through a transesterification reaction with methanol. Through the transesterification reaction alkyl esters (methyl esters), generically known as biodiesel, are formed and their properties are very close to those of petroleum diesel. On the other hand, bioethanol can be produced from any biomass which contains appreciable amounts of sugar or materials that can be converted into sugar. It is derived from saccharification, fermentation, and distillation of biomass feedstock, such as starch, sugar, cellulosic materials, *etc*. The available feedstocks consist of sugarcane, sweet sorghum, sugar beet, maize and wheat and many other agricultural products.

There is a growing international recognition that while growth in biofuel offers new opportunities for sustainable agricultural development, it also bears significant risks [16]. The first generation biofuels, whose feedstocks are agricultural crops, are contributing to the rise of food prices and may have negative impacts on food security and the environment [17,18]. However, the second generation biofuels extracted from lignocellulosic materials, will not compete with food production on cultivated land, and can be more conducive to significantly mitigating GHG than the first generation biofuels [19,20]. In recognition of the advantages of second generation biofuel production much attention has been paid to woody oil plants, among which *Jatropha curcas* (*Jatropha* for short) is considered a promising feedstock species for biodiesel production. Many countries, especially those in South America, Africa and south Asia, including India, Mali, Nicaragua, Tanzania, and Zimbabwe, have carried out large-scale *Jatropha* biodiesel programs [21–23]. *Jatropha*, known as being highly adaptable to a wide range of soil and climatic conditions, is a multipurpose shrub or small tree commonly used for fencing, erosion prevention and land reclamation. It produces seeds which have rich non-edible oil (35%–48%) and this has led *Jatropha* to receive worldwide consideration as a preferred feedstock for biodiesel production. It is widely described in the literature as a vigorous drought and pest tolerant plant that can grow on barren eroded lands under harsh climatic conditions [24,25].

Although biodiesel extraction from *Jatropha* has become a booming business in China, it will inevitably face many challenges and uncertainties as a new industry [26,27]. To be a viable substitute for fossil diesel, biodiesel should yield a positive energy balance, produce environmental benefits, be economically feasible, and possible to produce in large quantities without compromising food security [28–30]. Careful calculation of net energy, CO_2 emissions and cost efficiency are therefore critical to rigorously assess *Jatropha* biodiesel as a sustainable energy resource [31–33]. In addition, it is necessary to analyze land suitability for *Jatropha* plantation in China [34,35] as is true for any region or country attempting to develop *Jatropha* as an energy crop. While those above questions have not yet been addressed completely, efforts are containing.

The aim of this paper is to evaluate the net energy, CO_2 emission, and cost efficiency of *Jatropha* biodiesel production as a substitute diesel fuel in China, based on data from the Panzhihua region of Sichuan province which has had significant experience with this production system. The rest of the paper is organized into five sections. The study area is discussed in the second section, the methodology is described in the third section and the data sources are presented in the fourth section.

Results and discussion are presented in the fifth section and a summary and conclusions are put forth in the sixth section, along with policy recommendations based on the results.

2. Study Area

Panzhihua is a prefecture-level city located where the Jinsha River and the Yalong River converge in the southwest of Sichuan Province, ranging from 101°8′ to 102°15′ E and 26°5′ to 27°21′ N. It covers an area of 7434 km^2 and is regarded as the first industrial city in the upper reaches of the Yangtze River.

Panzhihua is characterized by a monsoon-influenced subtropical climate with concentrated precipitation, modest annual temperature differences, large daily temperature differences, abundant sunshine (2300–2700 hours in total each year) and strong solar radiation (578–628 kJ/cm^2). The annual average temperature is around 20.3 °C. The annual precipitation ranges from 700 to 1600 mm, much of which occurs from June to September.

Panzhihua is currently the major *Jatropha* plantation region in Sichuan Province. The total area of *Jatropha* forests is up to 253.33 km^2, including 93.33 km^2 original and secondary forests, 40 km^2 planted forest for ecological conservation and 120 km^2 planted forest for energy. A large area of energy plantation has been afforested since 2006, with areas of 13.33 km^2, 66.66 km^2, and 40 km^2 in 2006, 2007 and 2008 respectively. The sponsors for *Jatropha* plantations in Panzhihua are the PetroChina Company Limited and the local Forestry Bureau, while the farmers participate in *Jatropha* plantation in the form of leasing land and supplying labor.

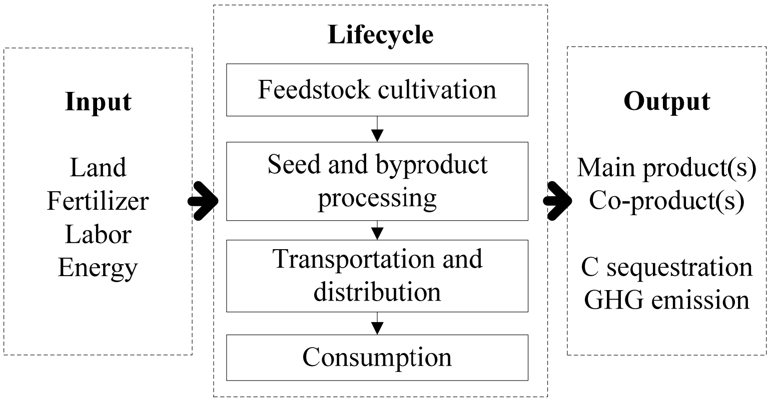
Jatropha was mainly planted in barren mountains above 1600 m. There are two reasons for this arrangement. Most significantly, lower elevation land with relatively better land quality is used to plant subtropical fruits such as late-maturing mango and pomegranate for the pursuit of higher profits. Importantly, however, *Jatropha* on the higher elevation barren hillsides can contribute much to land reclamation, water conservation and soil erosion mitigation. Planting *Jatropha* in highland areas can make more challenging the problems of field management and productivity improvement. The benefits from land reclamation, water conservation, and soil erosion mitigation have not been quantified and are not included in this analysis.

3. Methodology

3.1. Lifecycle Assessment Framework of Jatropha *Biodiesel Production System*

As a process where the material and energy flow within a system are quantified and evaluated, lifecycle assessment (LCA) is widely applied in the energy research field [36–39]. In this study, LCA was used to account for the material and energy in the lifecycle production system of *Jatropha* biodiesel. The entire lifecycle begins with *Jatropha* planting (source) and ends at fuel combustion (wheel). It consists of three stages: feedstock stage, fuel stage, fuel combustion and energy conversion stage [39–41]. The feedstock stage refers to the production of *Jatropha* seeds, while the fuel stage involves seed and byproduct processing, transportation, storage and distribution of *Jatropha* biodiesel. The last stage, fuel combustion and energy conversion, comes when *Jatropha* biodiesel is consumed. The framework is illustrated in Figure 1.

Figure 1. The lifecycle production system of *Jatropha* biodiesel.



The production of *Jatropha* seeds involves the establishment and maintenance of *Jatropha* plantations, seeds harvest, and their preliminary treatment. *Jatropha* trees are mainly propagated with seedlings, since the survival rate of plantations established with cuttings is low and micro-propagation is more costly than seedlings. Generally speaking, the inputs include land, labor, seedlings, fertilizers, machines and energy during the process of *Jatropha* plantation establishment.

The main outputs of *Jatropha* trees are their seeds with a high content of non-edible oil (35%–48%). The harvested fruits are dried in sunlight followed by husk removal. The husks are viewed as a co-product and a substitute for coal. In addition, other biomass products including leaves and latex are also co-products, which can be used as medicine. The co-products, while potentially important, are not currently commercial products and the impacts are not well quantified. Their potential energy and economic contributions are not included in this analysis.

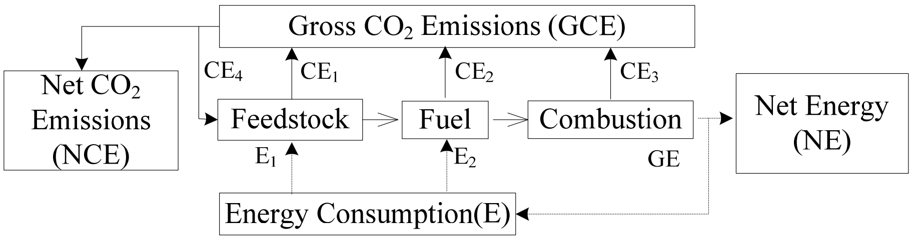
In the *Jatropha* biodiesel production chain, there are a series of possible environmental impacts to be concerned with, especially the carbon sequestration and greenhouse gas (GHG) emissions. We focus on the carbon balance analysis in the following paragraphs, as they have a significant influence on the environment and the global climate. In this analysis, we assumed that *Jatropha* plantation mainly occurred on marginal land. The time horizon for the project of *Jatropha* plantation lasts for 25 years. The *Jatropha* seed oil is directly blended with diesel for utilization. There is some other required information in the planning of *Jatropha* plantation establishment and utilization. For example, the planting density of *Jatropha* is approximately 1650 trees ha^{-1} on average, other information needed is shown in subsequent tables and text as it is required for the analysis.

3.2. Energy and Carbon Balance Analysis

An energy balance analysis was included in the lifecycle assessment so as to assess the feasibility and sustainability in the production system of *Jatropha* biodiesel. The energy balance can be quantified by comparing the energy inputs required in each LCA stage, and comparing the total required energy inputs with the embodied energy of the biodiesel product [42–46]. In this analysis, net energy was used to measure energy efficiency, since it is the net energy yield that measures the true value of an energy resource to society [47–49]. The net energy available from a fuel is equal to: NE = GE − E, where GE is the gross energy produced by the fuel during its combustion and E is the total energy consumption during its lifecycle production, in this case in Figure 2, below where E1 and E2 represent the energies consumed during the feedstock growth and production and fuel production stages, respectively. The overall concept is shown in Figure 2. Both direct and indirect energy inputs are involved in the production system of *Jatropha* biodiesel. Direct energy inputs include diesel consumed in transportation, and coal and electricity consumed in oil extraction and refining. Indirect energy inputs are embodied in a variety of non-energy inputs, such as fertilizers and labor.

Accordingly, the gross CO_2 emissions (GCE) from a fuel include the direct CO_2 emissions during the stage of fuel combustion and indirect CO_2 emissions at the stages of feedstock and fuel, defined as: GCE = CE1 + CE2 + CE3, where CE1, CE2, and CE3 represent CO_2 emissions during the stages of feedstock production, fuel production, and fuel combustion respectively [38,39]. The net CO_2 emissions (NCE) from a fuel are equal to: NCE = GCE − CE4, where CE4 represent absorption of CO_2 during the stage of feedstock production.

Figure 2. Net energy and gross CO_2 emissions in the production system of *Jatropha* biodiesel.



3.3. Land Suitability Evaluation

Relevant indicators should be selected to help to evaluate land suitability for *Jatropha* plantation use. Several studies have examined the correlation between *Jatropha* production and natural conditions, and there is a consensus that climate, terrain, and soil quality are key factors to *Jatropha* growth [34,35]. Based on literature review and expert interview, we summarized the suitable conditions for *Jatropha* plantation and these are shown below (Table 1).

Table 1. Suitable conditions for *Jatropha* plantations.

Characteristic	Tolerance Parameters
Annual mean temperature (°C)	≥17
Annual extreme minimum temperature (°C)	≥0
Thornthwaite humidity index	−66.7~100
Effective accumulated temperature above 10 °C	≥5000
Sunshine hours	≥1000
Soil depth (m)	≥0.3
Average slope (°)	≤25
Altitude (m)	≤1800

3.4. Cost-Benefit Analysis

An evaluation of the financial cost and income over time that lead to profits from *Jatropha* production provides for an overall cost benefit analysis from *Jatropha* plantations in the area studied.

According to the experts, the lifecycle of a *Jatropha* plantation is about 25 years in length and can be divided into three periods: the planting period (the first year), the rearing period (from the second year to the fifth year) and full bearing period (from the sixth year to the 25th year). There is no harvest in the planting period, and it is assumed that *Jatropha* will have a constant yield in the full bearing period. Since large areas of planting *Jatropha* began in Panzhihua in 2006, the yield of *Jatropha* seeds in full bearing period was projected by experts. We do not include any costs or benefits from harvesting the stems at the end of the 25 year period as the economics are uncertain for that activity.

We use Net Present Value (NPV) as a measure to analyze the profitability of *Jatropha* plantations as an economic operation. The calculation formula of NPV is as follows:

$$\mathrm{NPV} = \sum_{t=0}^{n} (\mathrm{CI} - \mathrm{CO})_t \, (1 + i_c)^{-t} \quad (1)$$

where CI is the current year income, which is determined by the price and yield of *Jatropha* seeds; CO is the current year cost, including the cost of land, labor and materials such as seeding and fertilizer; i_c is the discount rate, which is set to 0.72%.

We also assume that the prices of input and output are invariable over the time studied and the exchange rate between USD and RMB is 1:6.479. The price of each *Jatropha* bare root seeding is 0.18 RMB and the repair planting rate is 15%. The price of compound fertilizer is 1500 RMB/ton, and the price of organic fertilizer (oil cake) is 1,300 RMB/ton. The average labor price for the year 2005, 2006 and 2007 is 35 RMB per day, which is used for the labor cost estimation. The current price of *Jatropha* seeds is 2 RMB/kg, which is used for the income estimation. Unlike other input costs measured by the prices, it is rather difficult to estimate the cost of land. In our analysis, the cost of land used for *Jatropha* plantation is expressed as the opportunity cost, *i.e.*, the profitability of alternative land uses.

4. Data

4.1. Land Use Data

Land use data set is developed by the Chinese Academy of Sciences from Landsat TM/ETM scenes at a spatial resolution of 30 m × 30 m [50,51]. The data set contains 6 first class land use categories and 25 second order land use categories. In this study, land categories were reclassified into 8 classes: cultivated land, closed forest, shrub, open forest, barren/grass land, water area, build-up area and unused land.

4.2. Geophysical Data

The meteorological data, consisting of annual mean temperature, annual extreme minimum temperature, humidity index, effective accumulated temperature and sunshine hours were derived from China Meteorological Bureau data, which was originally filed in the form of text, and then we interpolated the text information into 1 km × 1 km grid pixel data using the Kriging method. The Kriging algorithm is a general method of statistical interpolation that can be applied within any discipline to sampled data from random fields that satisfy the appropriate mathematical assumptions, to interpolate the site-based data into the surface [52]. Information on the terrain slope was derived from DEM data at a scale of 1:250,000. Soil property data were gathered from the second national soil survey of China, and were interpreted into 1 km × 1 km grid pixel data using the Kriging method.

4.3. Social and Economic Data

The social and economic data mainly refer to the input and output of *Jatropha* plantations, which were collected from Forestry Bureau of Panzhihua or by our investigations, including questionnaire surveys, field research and structured interviews carried out in Panzhihua, Sichuan Province, in April 2011. The input of *Jatropha* plantation consists of *Jatropha* afforestation cost and maintenance cost in the later stage. Specifically speaking, the input can be classified into seedling, labor, fertilizer and land. We consider the seeds of *Jatropha* as the only output. The parameters of energy consumption and CO_2 emission are derived from the literature [27,48,53].

5. Results

5.1. Energy and Carbon Balance Analysis of Jatropha *Biodiesel Production*

Net energy is an important index to measure energy efficiency. We estimated the source to pump energy consumption and net energy yield of *Jatropha* biodiesel (Table 2). The net energy yield of *Jatropha* biodiesel is 0.03 MJ/MJ, much lower than that of fossil fuel (0.76 MJ/MJ for conventional gasoline). The low net energy is mainly caused by the high energy consumption during *Jatropha* plantation and fuel conversion stages. At the stage of feedstock cultivation, energy attributed to fertilizer is the main energy input, *i.e.*, the energy inputs for the production of these fertilizers. Because of a low level of mechanization, the activities of fruit collection and drying, husk removal, planting and tending are completed by hand and energy input of labor is included. At the stage of fuel conversion, the energy input is mainly used in the extraction and refining of *Jatropha* oil. Although net energy yield of *Jatropha* biodiesel production is relatively low, the net energy is renewable. For the long term, more productive *Jatropha* varieties and more energy efficient conversion technologies need to be developed to increase the returns from cultivation and reduce the energy consumption during the fuel conversion process.

We also analyzed carbon sequestration and CO_2 emission in the production process of *Jatropha* biodiesel (Table 3). Carbon sequestration is mainly attributed to absorption of CO_2 through photosynthesis during *Jatropha* tree growth. The major CO_2 emissions stem from the application of fertilizers, transportation of seeds and fertilizers, oil extraction and refining. The net carbon sequestration of *Jatropha* biodiesel production is 8343 kg/ha In addition, at the stage of fuel combustion, CO_2 emission rate of *Jatropha* biodiesel is 74.6 g CO_2/MJ, which is similar to that of diesel (74.7 g CO_2/MJ). Hence, as the cost efficient carbon sink, *Jatropha* biodiesel is a better choice as a type of substitute energy.

Table 2. Energy input and net energy yield of *Jatropha* biodiesel production.

Item	Quantity
Feedstock stage	
Fertilizer (MJ/kg)	9.39
Labor (MJ/kg)	0.26
Transportation (MJ/kg)	0.17
Fuel stage	
Oil extraction (MJ/kg)	2.70
Refining (MJ/kg)	0.42
Total energy input (MJ/kg)	12.93
Jatropha biodiesel output (MJ/kg)	13.3
Net energy (MJ/ MJ)	0.03

Table 3. The carbon balance of *Jatropha* biodiesel production.

Source of CO_2 Emission	Quantity of CO_2 Equivalent (kg/ha)
Application of fertilizers	45735
Transportation of seeds and fertilizers	1808
Oil extraction and refining	39114
Jatropha plantation *	−95000
Net carbon balance	−8343

* The average annual rate of carbon sequestration is set to 3800 kg/(ha·a) during the lifecycle of a *Jatropha* plantation.

5.2. Land Resources for Jatropha *Plantation*

According to our estimation, 1.72×10^5 ha land is suitable for *Jatropha* plantation in Panzhihua, located in the dry-hot valley of the Jinsha and Yalong Rivers (Table 4 and Figure 3). Cultivated land, barren/grass land and open forest are the major potential land sources for *Jatropha* plantation.

Table 4. Land suitable for *Jatropha* plantation in Panzhihua.

Type of Land	Suitable Land (ha)	Available suitable land (ha)
Cultivated land	54150	1080
Closed forest	24230	0
Shrub	7830	0
Open forest	42240	21100
Barren/grass land	43650	21800
Unused land	340	170
Total	172440	44200

In order to avoid land competition with agriculture and other industries, we also considered the social-economic restrictions of *Jatropha* plantation. Firstly, biofuel development should not compete for land with food production. We assumed that there would be only 2% of suitable cultivated land that could be used for *Jatropha* plantation, which can be used as fences around crop fields.

Figure 3. Spatial distribution of suitable land for *Jatropha* plantation in Panzhihua.

Secondly, considering that closed forest and bush play an important role in ecological conservation, we excluded the lands from land conversion from *Jatropha* plantation use. Thirdly, although barren/grass land, open forest and unused land are suitable for *Jatropha* plantation, we must consider the land demand of other sectors and difficulties in land preparation and management. Therefore, we assumed that 50% of the barren/grass, open forest and unused land were suitable for *Jatropha* growth and could be available. Due to these constraints mentioned above, the area of available suitable land for *Jatropha* plantation shrinks, and the available potential land for *Jatropha* plantation is made up mostly of open forest and barren/grass land (Table 4).

5.3. Cost-Benefit Analysis of Jatropha *Plantation*

Jatropha are mainly planted on marginal land in Panzhihua. As a consequence, there is almost no land use competition between *Jatropha* plantations and food production at the local level. This is also a result of the high cost of high quality land which is capable of profitable agricultural production. The cost of land was estimated in terms of the opportunity cost, based on the net gross margin of crop cultivation. The net profit of planting subtropical fruit such as late-mature mango and pomegranate is as high as 15,576 USD/year·ha. At lowest economic return in agricultural use, a net margin of 2,176 USD/year·ha is obtained from corn cultivation. Based on our field survey, the cost of land for *Jatropha* plantations is about 35 USD/ha.

Based on this investigation and estimation (Table 5), the total cost of *Jatropha* afforestation is 9,266.47 RMB (1,430 USD) per hectare in the three-year afforestation period. The cost in the first year is much higher than those of the following years, for it contains the seedling cost, labor cost of land preparation and planting as well as significant fertilizer cost. In the first year, labor cost is the largest expense which accounts for 59.83% of the total cost, followed by fertilizer cost. Fertilizer cost becomes the largest expense in the second and the third years, which exceeds half of the total cost in both years. With the rapid economic development, the average labor price showed a huge increase, from 35 RMB (5.4 USD) per day in 2005, 65 RMB (10 USD) per day in 2008, to 90 RMB (13.9 USD) per day in 2010. The estimated labor cost in this study is quite conservative and labor cost will account for a larger proportion of the total cost in *Jatropha* afforestation in the future.

Table 5. Cost of planting *Jatropha* for the first three years.

Item	The First Year	The Second Year	The Third Year
Seedling cost (USD/ha)	46	0	0
Compound fertilizer (kg/ha)	825	146	213
Organic fertilizer (kg/ha)	0	825	825
Fertilizer cost (USD/ha)	191	199	215
Labour hour of land preparation (hour/ha)	40	0	0
Labour hour of planting (hour/ha)	11	0	0
Labour hour of weeding (hour/ha)	19	19	19
Labour hour of fertilizering (hour/ha)	5	6	6
Total labour hour (hour/ha)	75	25	25
Total labour cost (USD/ha)	405	134	136
Land cost (USD/ha)	35	35	35
Total cost (USD/ha)	676	368	386

According to this estimation (Table 6), the labor cost and fertilizer cost are the main inputs in the lifecycle of *Jatropha* plantation. Since most *Jatropha* is planted on low-quality land, the yield is limited and the profits are negative during the planting and rearing periods. The NPV of benefit of *Jatropha* plantation is very sensitive to the price of *Jatropha* seeds. If we use the current price of *Jatropha* seeds, 2 RMB/kg, to calculate, the benefit NPV is 25772 RMB (3978 USD) per hectare and it is economically feasible to plant *Jatropha*. But if the price of *Jatropha* seeds drops to 1.5 RMB/kg, as expected, the benefit NPV will be −41 RMB (−6.3 USD) per hectare.

Table 6. Accounting of the inputs and outputs for a *Jatropha* plantation.

Item	Planting Period	Rearing Period	Full Bearing Period
Seedling cost (USD/year·ha)	46	0	0
Labor cost (USD/year·ha)	405	182	183
Fertilizer cost (USD/year·ha)	191	207	238
Land cost (USD/year·ha)	35	35	35
Total cost (USD/year·ha)	676	423	456
Yield (kg/year·ha)	0	750	2250
Income (USD/year·ha)	0	232	695
Profit (USD/year·ha)	−676	−192	238

6. Concluding Remarks

It is of great importance to develop renewable energy alternatives to ensure energy security and permit sustainable development. Since biofuels can help reduce dependence on petroleum, improve environmental quality and mitigate greenhouse gas emissions it can be utilized as an important substitute energy in coping with urgent worldwide energy and environmental needs. Biofuel has achieved rapid development in China, incentivized recently by the ambitious plan which is formulated under the *guidelines of enhancing the financial and taxation policy support for developments of bioenergy and biochemical industry* from the Chinese government. Nevertheless, we understand that the Chinese central government needs to make rational planning decisions and consider the energy efficiency, CO_2 emissions, lifecycle costs and land resources when expanding the bioenergy programs.

Our case study indicates that *Jatropha* biodiesel has lower total CO_2 emissions than diesel fuel does, mainly thanks to the absorption of CO_2 through photosynthesis during the *Jatropha* tree growth stage. Hence, *Jatropha* biodiesel is a good substitute for diesel fuel from the viewpoint of global warming mitigation. However, the net energy yield of *Jatropha* biodiesel is much lower than that of fossil fuel. The lower net energy is mainly caused by high energy consumption during *Jatropha* plantation establishment and the fuel conversion stage. Although the net energy yield of *Jatropha* biodiesel production is relatively low, the net energy is renewable. In the long run, more productive *Jatropha* varieties and more energy efficient conversion technologies are needed to increase the returns for the growing system and reduce energy consumption during the fuel conversion process. This will make diesel produced from *Jatropha* more competitive economically and in energy utilization.

Due to low profit and high risks under current market condition, farmers have little incentive to maintain or increase *Jatropha* production. It is necessary to provide more subsidies and preferential policies to the planters of *Jatropha* if more is to be produced. While there are about 1.03 million hectares of barren land existing in Southwest China that could be used for growing *Jatropha*, the quality of barren land varies widely. *Jatropha* might indeed grow on this marginal land, but it is not clear that seed quality and yields would be sufficiently high, or that available plots would be sufficiently large to achieve financial profits. The local government should carefully set realistic objectives and plan rationally to choose potentially profitable sites for *Jatropha* biodiesel development. In addition, future research focused on breeding high-yield varieties, continued development of advantageous field management techniques and more detailed lifecycle environmental impact analyses are also needed to facilitate the difficult decisions that need to be made and promote growth and sustainable development of *Jatropha* biodiesel production in China, based on this study of the Panzhihua region of Sichuan Province.

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