Short Communication

The Next Generation Feedstock of Biofuel: *Jatropha* or *Chlorella* as Assessed by Their Life-Cycle Inventories

Pu Peng 1,* and Wenguang Zhou 2,*

1 State Key Laboratory of Catalytic Material and Reaction Engineering, Research Institute of Petroleum Processing, SINOPEC, 18 Xue Yuan Road, Beijing 100083, China
2 Center for Biorefining, Bioproducts and Biosystems Engineering Department, University of Minnesota, 1390 Eckles Ave., Saint Paul, MN 55108, USA

* Authors to whom correspondence should be addressed; E-Mails: pengpu2000@163.com (P.P.); zhouw@umn.edu (W.Z.); Tel.: +86-10-8236-8382 (P.P.); +1-612-867-7173 (W.Z.); Fax: +86-6231-1290 (P.P.); +1-612-624-3005 (W.Z.).

Received: 19 May 2014; in revised form: 18 June 2014 / Accepted: 19 June 2014 / Published: 1 July 2014

**Abstract:** Promising energy crops such as *Jatropha curcas Linnaeus* (*JCL*), which are planted on marginal lands, or microalgae such as *Chlorella*, which are cultivated in ponds located on mudflats or deserts, have been regarded with high hopes to solve the shortage of food crops and increase the amount of biodiesel (Fatty Acid Methyl Ester, FAME) production. However, the annual yields of biomass and transport fuels (t/ha) of both are still unclear and often exaggerated in the literature. Large portions of *JCL* biomass, including tree trunks and leaves, can also be used to generate electricity along with FAME, which is produced from seed lipids. Meanwhile, lipid extracted algae (LEA) are composed of proteins, polysaccharides, and lipids other than glycerides which are unable to be esterified to form FAME and much more abundant in the microalgae than oil cake in the oil crops. Therefore, it has been strongly suggested that not only transesterification or esterification but also Fischer-Tropsch (FT) process and bio-electricity generation should be considered as routes to produce biofuels. Otherwise, the yield of biofuel would be extremely low using either *JCL* or *Chlorella* as feedstock. The Life-Cycle Inventories (LCI) of the biofuel processes with whole biomass of *JCL* and *Chlorella* were compared based on their net energy ratio (NER) and CO₂ emission saving (CES). It was shown that the technological improvement of irrigation, cultivation, and processing for either economic-crops or microalgae were all necessary to meet the requirements of commercial biofuel production.
Keywords: biodiesel; biofuel; jatropha; microalgae; Chlorella; LCA; LCI

1. Introduction

The need for sustainable biofuels can be attributed to both an increase in energy consumption and the tighter restriction of greenhouse gas (GHG) emissions. It was believed that the use of biodiesel instead of fossil diesel resulted in a significant reduction in CO₂ emission. The development of biodiesel (Fatty Acid Methyl Ester, FAME) has led to large-scale success in the EU and US with the use of rape seed and soybean, respectively, during the past 10 years. The EU hopes to radically cut GHG emissions and reduce dependency on fossil fuels by encouraging the production and use of sustainable biofuels. The arable land used for biodiesel production is around 3 M·ha (million hectares). Meanwhile, similar research has been conducted in other countries such as Brazil, Thailand, West Africa, and China. There have been more difficulties in China as there is much less arable and marginal land and a lower climate temperature than the countries in South Asia, Southeast Asia, and Africa.

Until 2008, US and EU biodiesel production was up to over 2 million tons (M t) and nearly 10 M t, respectively [1]. However, 10 M t corresponds to only 3% of diesel consumption in the EU and is far from the RED (Renewable Energy Directive) 10% target established by 29 European countries (E27 plus Norway and Switzerland) by 2020. In order to meet the gap between the 3% and 10% and to find more sustainable feedstock, many sources have been tested including microorganisms, wastes, agricultural and forestry residues, energy crops, and even used frying oils (UFO) or animal fats. However, among the wastes, economic-crops, and algae, it is still not clear which will prevail. Many kinds of economic plants such as tree legumes have been selected as candidates for feedstock of sustainable biofuel production [1], but the planting of dedicated energy crops often leads to carbon stock change, known as land use change (LUC) [2], which sheds doubt on the predicted positive GHG balance (positive CES). In contrast, microalgae are able to be cultivated in ponds or PBR (photobioreactor) located on mudflats or deserts with near zero carbon stock. Meanwhile, other advanced biofuels such as hydro-treated vegetable oil (HVO), FT-diesel distillate (Green diesel), FT-jet-fuel distillate (Green jet fuel) are also candidates produced by Fischer-Tropsch synthesis and hydro treatment, which may be more compatible with existing fuel infrastructures, offer other technical benefits and be prepared with wider feedstocks. Cherubini’s [3] comprehensive literature review on biofuel development has shown that there is now an increasing number of papers dealing with lignocellulosic biomass, sugarcane, or palm oil in developing countries in South-Eastern Asia. By contrast, few studies are currently available on the promising feedstock of JCL (Jatropha curcas Linnaeus). JCL is a shrub and toxic tree with a smooth gray bark and an average height of 4 m (up to 6 m), belonging to the family Euphorbiaceae. This native species to Central America was introduced to the Cape Verde islands by Portuguese sailors in the 16th century, then to Guinea Bissau from where it spread across Africa and Asia. Its natural habitat are arid and semi-arid zones but it has also been found in damp tropical regions such as North Vietnam and Thailand. JCL starts producing seeds within 1 year of growth, but the maximum
productivity is after 4 or 5 years (typical JCL yields in the first 5 years are 0.5 t/ha, 1.5 t/ha, 3.0 t/ha 5.0 t/ha, 6.0 t/ha). Its average life span is over 20 years (up to 50 years) [3,4].

In this paper, the JCL demonstration cases implemented in Thailand, India, and West Africa are reviewed and compared with several laboratory works of microalgae, such as Chlorella, to further contrast their LCI (life-cycle inventory) of culturing, extracting, producing, and processing. The prospective productivities (annual yield) of both feedstocks are compared and discussed to readdress the exaggerated results often found in the literature.

2. Methodology

2.1. Boundaries, Functional Units, and Allocation

LCI analysis involves creating an inventory of flows. Inventory flows include inputs of water, energy, feedstock, fertilizer etc. and outputs of CO₂ emission, biofuel products, land, and water. The input of water and fertilizer are converted into power, which can be used for manufacturing and irrigating, whereas the output of land and water has not been considered. To develop the inventory, a flow model of the technical system was constructed using data from the inputs and outputs, and gave a clearer picture of the technical system boundaries. LCI results would be very different if different boundaries (1: biomass-system; 2: transport fuel system; 3: well (culturing) to wheel system; or 4: by-product included system) were accepted, as shown in Figure 1.

Figure 1. Life-Cycle Inventories (LCI) flow model of biofuel and conventional fossil fuel with different boundaries. (a) Biofuel production; (b) Fossil fuel production.

The data used in LCI must be related to the functional unit (FU) defined in the goal and scope. There are four types of FU identified in the LCI of bioenergy systems to compare: (1) given feedstock; (2) different feedstock; (3) dedicated energy crops; (4) Multiple final products, i.e., input, output, agricultural land or year unit. The output unit and energy basis (GJ or MJ) were selected as functional units in this paper. All the outputs of the bioenergy systems expressed through other energy units were
converted with the conversion factor (1 kg biodiesel = 37.8 MJ or 1 kg fossil diesel = 42.8 MJ) to compare the results published in different literatures. The FU of the power input was also converted with the conversion factor (1 kWh = 3.6 MJ).

Allocation in life cycle assessment (LCA) is carried out to attribute the total environmental impact to the different products of a system. This concept is extremely important for bioenergy systems, which are usually characterized by multiple products (e.g., electricity and heat from CHP application, rape-cake and glycerin from biodiesel production), and has a large influence on the final results [5].

2.2. Energy Balance and Fossil Fuel Saving

The NER (net energy ratio) of a system is defined as the ratio of the total output energy utilized from produced liquid biofuel and residual biomass (produced energy output) over the input energy required in the “production stage”, which includes PBR (photobioreactor) construction and materials, nutrition production, and planting (culturing) operation (primary energy input). NER is also called the energy yield. The NEB (net energy balance) is the difference between the effective energy produced and that required in the “production stage”. If the bioenergy system is economically viable, then NER and NEB are larger than one and zero, respectively [6].

\[
\text{NER} = \frac{\text{Total energy output}}{\text{Total energy input}}
\]

\[
\text{NEB} = \text{Total energy output} - \text{Total energy input}
\]

2.3. Environmental Balance and GHG Saving

CO₂ was the only greenhouse gas (GHG) considered in this paper, and CEB (CO₂ emission of biofuel) in combustion of biofuel was calculated with either kg or MJ as the functional unit.

\[
\text{CEB (CO₂ kg/kg)} = \text{mass (kg of biofuel combusted)} \times \text{C content (normalized)} \times \frac{44}{12} = 2.86
\]

\[
\text{CEB (CO₂ g/MJ)} = 1000 \times \frac{2.86}{\text{energy (MJ producing from 1 kg biofuel)}} = 1000 \times \frac{2.86}{37.8} = 75.7
\]

where 0.78 was used as the carbon content of biodiesel and, assuming all of the carbon in biodiesel was converted to CO₂; 44/12, is the ratio of molecular weight of CO₂ and atomic weight of C. CO₂ emission in the “production stage” is calculated as equivalent CO₂ emission from coal-fired electricity generation (0.83 kg CO₂/KWh), which is much greater than that from natural gas (0.11 kg~0.24 kg·CO₂/KWh) but close to that from wood chips (0.82 kg CO₂/KWh) [7]. The CO₂ emission from coal-fired electricity in China (~1 kg CO₂/KWh) is even higher due to the use of low-grade coal.

CES (CO₂ emission saving) would be used to show the CO₂ emission balance of biofuel and compared to CEF (CO₂ emission of fossil fuel used in the production of biofuel).

\[
\text{CES} \text{ (%) = } 100 \times \left[1 - \frac{(\text{CEF} + \text{CEB} + \text{CEU})}{\text{CEF}}\right]
\]

Assuming CEU (CO₂ emission in upstream of biofuel production) to be zero, CEF to be 83.8 g CO₂/MJ fossil fuel, and CEB −75.7 g CO₂/MJ biofuel, the maximum CES is up to 90%, assuming that GEF, GEB and CEU (CO₂ emission upstream of biofuel production) are 83.8 g, 75.7 g and 0 g CO₂/MJ fossil fuel, respectively. In fact, CES is strongly dependent on the upstream process and boundary shown in Figure 1, which means, it would be much less than 90%. CEU is usually large and
even larger than CEB (CES become negative) depending on the energy consumed in the upstream process and the electricity source of coal, fuel oil, or natural gas-fired power station.

3. Results and Discussion

The industrial production of JCL is a fairly recent development. Almost 0.9 M·ha, 0.765 M·ha (0.32 M·ha in Senegal), and 0.12 M·ha of JCL farm have been established to date in Asia, Africa, and Latin America, respectively, but it is still far from the targets of 5 M·ha by 2010 and 13 M·ha to be achieved by 2015 [5]. Meanwhile, the prices of JCL seed have increased from 0.10 $/kg in 2005 to 0.34 $/kg in 2011 [4].

3.1. Fertilizer and Watering in JCL Plantation

In Thailand, a demonstration of JCL plantation was conducted by Kasetsart University, in which annual crop cutting was set within an area of 1 ha (hectare) and a crop density of 2 m × 1 m or two trees per m² was utilized. Land preparation was comprised of plowing, harrowing, and a furrowing process using a tractor with an engine of 75 hp to adjust the soil condition for the new cutting set; ternary (N–P–K: 15–15–15) fertilizer was applied with a rate of 650 kg/ha per year; weedicides and insecticides were also used for the general maintenance of the plantation; the pumping rate was 4.5 m³/m² per year for watering and manual harvesting [6].

In India, the yield of JCL increased from 1.5 t/ha (rain-fed) to 5.9 t/ha (irrigated) when double fertilizers and an additional 105 kg/ha diesel were used in the irrigation mode as compared with the rain-fed mode [7].

In West Africa (Mali and Ivory Coast), JCL planting was up to 1500 ha in 2007, and at least 2000 ha more in 2008. Two 5-ha experimental fields with plantation densities of 1111 plants·ha⁻¹ were selected with contrasting soil conditions. Ternary fertilizer was only applied during the first three years: 100 kg/ha in the 1st year, 150 kg/ha in the 2nd year, 200 kg/ha in the 3rd year, whereas both 248 kg/ha ternary fertilizer and 201 kg/ha of ammonium nitrate were applied in the 4th year [6].

3.2. Productivities of Biomass, JME and By-Products

The yield hypotheses had a significant impact on the GHG and energy balances of JME (Jatropha Methyl Ester). The weight of each fresh fruit and seed was around 10–15 g and 2–4 g, respectively. The annual yield of JCL fresh fruit was about 16 t/ha. The yield of seed was widely spread from 0.1 to10 t/ha [8] and an increase of 1 t/ha of seeds resulted in a 10% reduction in fossil energy use compared to the baseline value of 4 t/ha. An increase of 1 t/ha of seed production from the baseline of 4 t/ha resulted in a 10% reduction in fossil energy usage. Thus, it appears critical to pursue large-scale field cultivation experiments of JCL.

The yield of co-products such as wood, leaves, and seed shells, are 4 t, 2 t, and 0.8 t (dry weight), respectively from the process of JCL plantation. Press cake (91.5 kg, dry weight) is obtained when 1 FU (1 GJ of JME) is produced [9]. All of them can be used as combustion fuels to produce heat or power to replace part of fossil fuel energy used in the JME production while the biodiesel production is developed for commercialization.
Sunil K et al. [7] reported details of inventory requirements for the farming, oil extraction, biodiesel production, and transportation stages for the entire JME production process in India. The oil percentage of JCL seed ranged from 21.0%–48.2%, and oil seeds were assumed to be sun-dried. The energy required for harvesting, handling, and storing of oil seeds, oil, and biodiesel, and the separation of husk from the seeds were neglected due to the cheap and abundant labor force available.

3.3. Energy Balance (Net Energy Use)

The selected JME projects of energy balance expressed in NER (energy yield) and environmental balance expressed in biofuel CO\(_2\) emission factor per GJ energy are shown in Table 1.

<table>
<thead>
<tr>
<th>Author</th>
<th>Energy Output/MJ</th>
<th>Energy Input/MJ</th>
<th>NER (^1)</th>
<th>CES (^2)/%</th>
<th>Plantation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ndong (2009)</td>
<td>1</td>
<td>0.21</td>
<td>4.7</td>
<td>72</td>
<td>Mali/baseline</td>
<td>[5]</td>
</tr>
<tr>
<td>Ndong (2009)</td>
<td>1</td>
<td>1.8</td>
<td>11</td>
<td>77</td>
<td>irrigation/motorized</td>
<td>[5]</td>
</tr>
<tr>
<td>Achten (2008)</td>
<td>1</td>
<td>0.886</td>
<td>1.1</td>
<td>77</td>
<td>50%Faming E</td>
<td>[10]</td>
</tr>
<tr>
<td>Achten (2008)</td>
<td>1</td>
<td>0.16</td>
<td>6.3</td>
<td>93</td>
<td>17%Faming E</td>
<td>[10]</td>
</tr>
<tr>
<td>Prueksakorn (2006)</td>
<td>1</td>
<td>0.88</td>
<td>1.1</td>
<td>72</td>
<td>Thailand</td>
<td>[9]</td>
</tr>
<tr>
<td>Prueksakorn (2006)</td>
<td>1</td>
<td>17.88</td>
<td>21.5</td>
<td>72</td>
<td>Thailand</td>
<td>[9]</td>
</tr>
<tr>
<td>Kumar (2012)</td>
<td>37.27</td>
<td>21.83</td>
<td>1.7</td>
<td>54</td>
<td>Irrigated</td>
<td>[7]</td>
</tr>
<tr>
<td>Kumar (2012)</td>
<td>37.27</td>
<td>27.6</td>
<td>1.4</td>
<td>40</td>
<td>Rain-fed</td>
<td>[7]</td>
</tr>
<tr>
<td>Kumar (2012)</td>
<td>37.27 107.8</td>
<td>1.5–8.6</td>
<td>50–107</td>
<td>Irrigated</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>Pandey (2011)</td>
<td>1</td>
<td>0.578</td>
<td>1.73</td>
<td>23</td>
<td>Five years (^4)</td>
<td>[6]</td>
</tr>
</tbody>
</table>

\(^1\) NER was calculated by dividing the biodiesel energy as the sole energy output by the total energy consumed, which is oil yield and allocation mode-dependent; \(^2\) conventional diesel emit 83.8 kg CO\(_2\)-eq/GJ diesel; \(^3\) NER was estimated as a ratio of biodiesel energy and net allocated process energy to biodiesel; \(^4\) averaged by the total yield (energy) of 5 years (3.92 t JME, 161.65 GJ) and NEB = 161.65 – 93.51 = 68.14 MJ.

Robert et al. [5] proposed a very detailed LCI analysis on the JEM project in West Africa in which an allocation analysis was also included. The energy yield (the ratio of biodiesel energy output to fossil energy input) was 4.7. In other words, 4.7 MJ of energy was produced from 1 MJ of fossil fuel consumed to produce JME (bondary 2). Biofuel production requires direct (electricity, fuels, natural gas) and indirect (manufacturing of agricultural inputs, methanol etc.) energy consumption. In the allocation of energy expense, cultivation accounted for only 12%, which is even less than the 15% in the transport of seeds, oilcake, and unrefined JCL oil. Transesterification requires 61% of the energy expense. In an alternative scenario, all co-products and JME are considered as output energy sources. The motorization and irrigation for the first three years were also included in JCL production with a high consumption of fuel and irrigation water, which resulted in the energy yield being lowered down to only 1.8 compared to 4.7 in the baseline scenario. Meanwhile, GHG savings compared to fossil diesel was only marginal (11%), only one-sixth of the baseline scenario.

In a Thailand demonstration test [9], the allocation for energy expenses of transesterification, irrigation, and fertilization processes was approximately 40% (0.197 GJ for producing steam),
23% (0.205 GJ) and 22% (0.198 GJ), respectively. The highest energy consumption was in the process of transesterification (61%) and other energy expenses were from using diesel, electricity, and producing fertilizer. Others are from 100 kg of fertilizer with the chemical formula 15–15–15 (energy consumption for transportation of fertilizer is excluded). The consumption of diesel for water pumping is a main contributor to energy expense in the irrigation process. JCL plantation requires the process of land preparation once every 5 years as the stems are cut every year but a new plantation is made every five years. The residue (by-product)-produced energy is 17.883 GJ, whereas JME-produced energy is only 1 GJ. The highest energy by-product is wood, which produces an amount of energy of 10.289 GJ.

3.4. Environmental Balance (GHG Emission)

Achten [10] deducted GHG emissions from the production phase of JME and considered the energy content of the co-products in calculating the CES (GHG emissions from JME). The result was about 77% compared to the GHG emission using fossil diesel. In total, the production and combustion of JME emitted 23.5 g CO₂e/MJ JME. The allocation of emitted CO₂ accounted for 52% in cultivation, while the shares of the transesterification and final combustion steps were 17% and 16%, respectively. Large shares of the emissions occurring during the agricultural step were due to fertilizers.

It is assumed that the energy consumed in the production stage is from 100% fossil fuel fired power plants. In India, fossil fuel contributes to 64% of electricity generation, whereby 52% of electricity is generated in coal-fired power plants, and the other 12% stem from natural gas (11%) and oil (1%). The rest is derived from from hydro (23%), nuclear (3%) and renewable materials (10%) [6]. In China, coal is the major component of fossil fuel in electricity generation (80%), resulting in more CO₂ emissions.

Sunil [7] compared energy and environmental balances of irrigated and rain-fed scenarios. Seed annual yields of irrigated (5.9 t/ha, Farming energy: 9333 MJ/t JME; Farming emission: 680 kg CO₂/t JME) and rain-fed (1.5 t/ha, Farming energy: 15098 MJ/t JME; Farming emission: 1114 kg CO₂/t JME) scenarios are closely related.

It was found that the utilization of JME saved more energy and emitted less CO₂ (saving 1.2 GJ/ha; emitting 80 kg CO₂/ha per year) than direct use of JCL oil (saving 1.0 GJ/ha; 67 kg·CO₂/ha per year) based on the comparison of energy and environmental balance in Central India [11].

3.5. Life Cycle Costs

It has been reported that the total cost of JME without externalities is higher than the current market retail selling price of diesel in Thailand [12]. The cost allocations are 62.62%, 25.27% and 12.12% for agricultural, bio-diesel production, and environmental processes, respectively. The highest expenditure are the operation costs at the agricultural stage such as fertilizers, insecticide, and electricity for water pumping systems, especially in the dry season.

Generally, production of JME costs less than palm oil, soybean diesel costs more, and the cost of rapeseed diesel is the highest [13]. As a commercially viable option, microalgae will require further improvements in genetic and metabolic engineering to obtain promising strains and produce higher yields of oil. Moreover, development of equipment and methodologies for cost-effective culturing, harvesting, and processing are also required, as year-round production of biofuels requires constant,
reliable feedstock supply [14]. While microalgae are projected as a future feedstock of biodiesel, production costs are much higher than for terrestrial crops, in the range of US$2 to $22 per liter [1]. In addition, the entire microalgae biomass has to be used to produce biofuel, otherwise the yield of biofuel is too low to be accepted [15].

3.6. Situation in China

It is widely hoped that JME production will offer a newer, more sustainable energy source. That, however, has yet to be proven. In 2007, the global output of biodiesel (FAME) was 8.82 Mt, but only 0.1 Mt in China, and there has been no obvious change since then in suffering from arable land limitation [1]. Therefore, there has been more effort to search for energy crops in China than in the EU, US, and even Asia countries, such as India and Thailand. However, the climate is not suitable to plant JCL on most of the land in China. Although Southwest China is considered as a prospective area to plant JCL, it has been discovered that both prospective planting areas and yields of seed have been overestimated after comprehensive consideration using the Agro Ecological Zone method. Based on the remote sensing data on land use, meteorological, soil and land slope, and suitable environment for JCL plantation in Southwest China, the potential land to expand JCL areas was only 0.15 M·ha up until 2008, which is far from the government goal (1.667 M·ha by 2020). Although the moderately suitable land was increased to 1.433 M·ha after softening the terms, the poor yield of seed on the moderate land would most likely destroy the balance of both energy and environment (NER and CES become minus value) [16].

In China, the yield of fresh fruit, dried seed, and extracted oil are be less than in countries in the tropic zone, and there is little data from farming sites. The prospective yield of JCL seeds and JME are often exaggerated and questionable. For instance, the JME yield (5 t/ha) and farming (planting) energy (160 MJ/t JME) were accepted in a published LCA research. Nevertheless, the energy of soybean farming is as high 2497 MJ/t FAME as usual and the average yield of JCL seed in the tropic zone is only 4 t/ha (the JME content is less than 40% of JCL seed). A misleading NER of JME (2.004) even higher than soybean oil (0.981) was proposed based on an unconfirmed JCL annual yield (5 t/ha) in the Hainan province of China, which was greatly overestimated and even over the yield obtained in the tropical zone [17]. The reasonable annual yield of JME is 1–2 t/ha based on demonstration tests in Thailand [9], Malaysia [4], and West Africa [5] where a JME content of 30%–50% is usually accepted.

3.7. Comparison with Microalgae

It is known that microalgae have attracted the spotlight around the world during the past years and have been considered to be very hopeful competitors to replace terrestrial plants as feedstock in the next generation of biofuels. One reason for the superiority of microalgae is that fresh water and arable land are not necessary for culturing. Waste, saline, or brackish water, and land resources, such as mudflats or deserts, are all usable for microalgae culturing so that there is no interference in food production as was the case for the first generation of biofuels [13]. Another benefit of microalgae is the high expected yield of biomass, which can be higher than 100 t/ha, and the oil content, which can be higher than 70% of dry weight in the form of triglycerides [18]. However, these are only speculations
based on the excessively optimistic assumptions or laboratory data using minimalistic culturing volumes of several milliliters to liters, which largely deviate from the larger scale culturing results either in ponds or PBRs. Although *Chlorella*, *Diatom*, *Scenedesmus*, *Tetraselmis*, *Nannochloropsis*, and *Haematococcus pluvialis* were preferred as hopeful candidates, the real potential of their productivity was not clear until their production was realized at a large scale. The resulting differences between published biomass and oil (lipid) yield potentials are up to 16-fold [19].

The NER of JME oil and algal oil were selected to quantify the energy balance and to associate it with both the boundaries of LCI and the yield of algal biomass and lipid. Meanwhile, CES was selected to quantify the GHG balance. Some of the calculated NER and CES based on published LCA results are summarized in Table 2, and some are laboratory data and extremely exaggerated. The results are dependent on the manner of culturing (pond or PBR), harvesting, biomass yield, lipid content, and the boundary. NER for *Nannochloropsis* cultivation process is 4.33 for flat-plate PBR but 7.01 for raceway ponds, indicating that both processes are energetically favorable for biomass production (boundary 1) [20]. NER decreases to below one when the harvesting stage was included (boundary 2) (except for HRJ or wet harvesting) indicating that dewatering is the most energy consuming process in the upstream (shown in Table 2). The NER is strongly dependent on the yield of biomass or lipid and varies as much as six-fold depending on the source [21]. In order to attain the energy benefit (NER > 1, overestimated LCI data (biomass yield or lipid fraction) were often accepted in the published papers [18,22].

<table>
<thead>
<tr>
<th>Author</th>
<th>Yield 1 t/ha</th>
<th>Lipid % (D W)</th>
<th>Output MJ</th>
<th>Input MJ</th>
<th>NER %</th>
<th>CES 2 %</th>
<th>Cultivation</th>
<th>Algal Species</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalnes (2012)</td>
<td>25.0</td>
<td>83.6</td>
<td>85.8</td>
<td>0.97</td>
<td>−2</td>
<td>57</td>
<td>Dewatering</td>
<td>Nannochloropsis</td>
<td>[23]</td>
</tr>
<tr>
<td>Kalnes (2012)</td>
<td>25.0</td>
<td>83.6</td>
<td>59.0</td>
<td>1.42</td>
<td>57</td>
<td>HRJ</td>
<td>Dewatering</td>
<td>Nannochloropsis</td>
<td>[23]</td>
</tr>
<tr>
<td>Batan (2010)</td>
<td>91</td>
<td>42.5</td>
<td>1</td>
<td>0.93</td>
<td>0.93</td>
<td>29</td>
<td>PBR bags</td>
<td>Nannochloropsis</td>
<td>[24]</td>
</tr>
<tr>
<td>Lardon (2009)</td>
<td>62</td>
<td>17.5</td>
<td>103.8</td>
<td>106.4</td>
<td>0.98</td>
<td>29</td>
<td>Dry</td>
<td>Chlorella vulgaris</td>
<td>[25]</td>
</tr>
<tr>
<td>Lardon (2009)</td>
<td>62</td>
<td>17.5</td>
<td>146.8</td>
<td>41.4</td>
<td>3.55</td>
<td>29</td>
<td>Wet</td>
<td>Chlorella vulgaris</td>
<td>[25]</td>
</tr>
<tr>
<td>Xu (2011)</td>
<td>128</td>
<td>40.0</td>
<td>37.2</td>
<td>27.5</td>
<td>1.35</td>
<td>41</td>
<td>Tubular</td>
<td><em>P. tricornutum</em></td>
<td>[21]</td>
</tr>
<tr>
<td>Vasudevan (2012)</td>
<td>76</td>
<td>25.0</td>
<td>9.2</td>
<td>32</td>
<td>0.3</td>
<td>−232</td>
<td>Dry Extract</td>
<td>Algae</td>
<td>[26]</td>
</tr>
<tr>
<td>Vasudevan (2012)</td>
<td>76</td>
<td>25.0</td>
<td>9.2</td>
<td>3.7</td>
<td>2.5</td>
<td>37</td>
<td>Wet Extract</td>
<td>Algae</td>
<td>[26]</td>
</tr>
</tbody>
</table>

1 Yield of algal biomass per year; 2 minus means net GHG emission but not fixation.

If FAME is considered as the only product of algal fuel (Boundary 3), it is almost impossible for NER and CES to be >1 and >0, respectively (net energy and CO2 emission reduction are positive) as large amounts of energy are consumed in the dehydration and extraction processes as shown in Table 2 [21].

In fact, current commercial microalgae production is only focused on a few high-value products used mainly for human nutritional supplements, including entire algal biomasses, such as those of *Spirulina (Arthrospira)* (3000 t/a) and *Chlorella* (2000 t/a), and extracted products, including β-carotene, Astaxanthin, and docosahexanoic acid (DHA). The total annual yield of microalgal biomass (dry matter basis) around the world is only about 10 Kt. However, the total revenue of the microalgae-containing
products is up to several billion dollars per year, with a typical selling price of $5000 to $100,000 per dry ton of biomass or extracted products [27]. The biomass of microalgae is also used as live feeds in aquaculture, and in wastewater treatment systems with a lower price in the culturing stage [28]. Over 90% of the world’s commercial microalgae production uses shallow, open, paddle wheel mixed raceway type ponds, in addition to open circular ponds for Chlorella production in Japan.

In China, the productions of *Spirulina* (*Arthrospira*) and *Chlorella* are sold as nutrients, and high nutrition feeds have increased rapidly recently. The annual yields of *Spirulina* (*Arthrospira*) and *Chlorella* have attained up to 3000 t and 1000 t, respectively. The protein content and lipid content of *Spirulina* sold as a nutrient are as high as 60% and less than 10%, respectively. *Chlorella*, with a lower protein content and a higher lipid content than *Spirulina*, is recommended to be used as feedstock for biodiesel, although the price makes it too expensive to be used nowadays. A several-fold increase in algal biomass or lipid production is not feasible by cultivation in either low-nitrogen nutrient or CO₂-rich environments. When low-N nutrients are used in algal cultivation, lipid content increases but the yield of biomass usually decreases [29]. The improvement of biomass yield with additional (5%–14%) CO₂ aeration is only 1.5 times and difficult to double compared with air aeration without additional CO₂. In the lipid fraction, there are not only triglyceride (TAG) and free fatty acids (FFA) but also sterols, terpenes and hydrocarbons, which are unable to be transesterified or esterified to form FAME so that the yield of FAME would be lower than the lipid content of *Chlorella* [22].

Besides FAME (biodiesel), in order to increase the yield of algal biofuels, other hydrocarbon fuels including methane and FT-fuel have to be considered as algal biofuels produced from the lipid extracted fraction (Lipid Extracted Algae, LEA) which are difficult to esterify to form FAME [23]. Even now, the algal biofuel has not been produced in China due to the low algal biomass productivity and the complexity of the algal biomass. This is also the reason why the species of microalgae are often not specified in the literature of LCA, easily misleading the reader, as the productivity and lipid composition of various species of microalgae are very different and dependent on the area and time of culturing. Handler summarized the worldwide LCA results of the prior literature and investigated the wide variance in predicted environmental impacts from microalgae cultivation in open-air raceway ponds and deduced a very wide range of CO₂ emission (0.1–4.4 g CO₂e/g microalgae) [30].

### 3.8. The Difficulties of Commercialization

#### 3.8.1. Jatropha

*JCL* has been successfully planted on a large scale, especially in Asia and Africa where planting areas are near to 1 M·ha. The seed yield ranges from 4 to 5 t/ha in higher areas but is relatively area and climate dependent. The oil content ranges from 20% to 50% and typically lies between 30% and 40%, depending on the culturing area and conditions. The energy and environmental balance of culturing, harvesting, and processing show *JCL* to be a preferable sustainable feedstock for biofuel. The use of JME shows more favorable results in energy saving and CO₂ emission than direct use of *JCL* oil.

In the subtropical zone and even in the south of China, the feasibility of *JCL* cultivation must be carefully considered. The yield of *JCL* oil is dependent on the climate and planting area. The published
data from tropical zones such as south Asia, south-east Asia and Africa are not suitable for the LCI in China. The real, domestic and large-scale planting data strongly suggests the acceptance as LCI instead of published data from different zones of the world.

In the environmental balance assessment of JME, the CO₂ emission due to LUC was not considered in the paper. Based on the accomplished production scale in South Asia, Southeast Asia, and West Africa, Jatropha may be more easily accessible as the next generation feedstock of biodiesel provided there is enough land with proper climate, and the CO₂ emission resulting from LUC can be avoided at the same time.

3.8.2. Microalgae

The cultivation of microalgae, even that of Chlorella and Spirulina, is still in the beginning stages. The biggest farm for culturing Spirulina is only 0.1 M·ha scale, which is much less than big JCL farms up to 1 M·ha scale. Therefore, more demonstration farms or projects need to be created to verify the feasibility for microalgae to become the feedstock for biofuel in the future.

The triglyceride and FFA (free fatty acid) contents in the lipid fraction of microalgae are much smaller than in the lipid fraction of JCL. Therefore, the biodiesel yield cannot be directly deduced from the lipid content of microalgae.

The lipid in microalgae should be referred to as bio-crude other than biodiesel. All bio-crude or biomass has to be processed to produce sustainable bio-energy instead of biodiesel (FAME), so that biohydrogenated diesel (BHD), FT-fuel, bio-gas, bio-power, and bio-heat can be produced and used together. The NER and NEB are hardly larger than one and they are positive. CES is also rarely positive if the energy prepared from LEA is not accounted for at the present stage.

4. Conclusions

The biomass yields of both JCL and Chlorella per hectare have to be further increased by using the high efficiency irrigation systems for JCL plantation and well-designed PBR for Chlorella cultivation so as to benefit economically and environmentally. Moreover, it is strongly suggested that not only transesterification or esterification but also the Fischer-Tropsch process and bio-electricity generation should be considered as routes to produce biofuels. Otherwise, the yield of biofuel will be extremely low using either JCL or Chlorella as feedstock. Overall, there is a long way to go for either Jatropha or Chlorella to become real second generation feedstocks at the scale corresponding to first generation feedstock.

Acknowledgments

This work was supported by the National Basic Research Program of China through the “Fundamental of Chemistry and Engineering for High-Efficiency and Sustainable Oil Refining Technologies” (project number: 2012CB224806).
Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCL</td>
<td><em>Jatropha curcas</em> Linnaeus</td>
</tr>
<tr>
<td>FAME</td>
<td>Fatty Acid Methyl Ester</td>
</tr>
<tr>
<td>LEA</td>
<td>Lipid extracted algae</td>
</tr>
<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
</tr>
<tr>
<td>LCI</td>
<td>Life-cycle Inventory</td>
</tr>
<tr>
<td>NER</td>
<td>Net energy ratio</td>
</tr>
<tr>
<td>CES</td>
<td>CO₂ emission saving</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>RED</td>
<td>Renewable Energy Directive</td>
</tr>
<tr>
<td>UFO</td>
<td>Used frying oil</td>
</tr>
<tr>
<td>LUC</td>
<td>Land use change</td>
</tr>
<tr>
<td>PBR</td>
<td>photobioreactor</td>
</tr>
<tr>
<td>HVO</td>
<td>Hydrotreated vegetable oil</td>
</tr>
<tr>
<td>FU</td>
<td>Functional unit</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>NEB</td>
<td>Net energy balance</td>
</tr>
<tr>
<td>CEB</td>
<td>CO₂ emission of biofuel</td>
</tr>
<tr>
<td>CEU</td>
<td>CO₂ emission in upstream of biofuel production</td>
</tr>
<tr>
<td>CEF</td>
<td>CO₂ emission of fossil fuel used in the production of biofuel</td>
</tr>
<tr>
<td>DHA</td>
<td>Docosahexanoic acid</td>
</tr>
<tr>
<td>TAG</td>
<td>Triglyceride</td>
</tr>
<tr>
<td>FFA</td>
<td>Free fatty acid</td>
</tr>
<tr>
<td>BHD</td>
<td>Biohydrogenated diesel</td>
</tr>
</tbody>
</table>

Conflicts of Interest

The authors declare no conflict of interest.

References


© 2014 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/3.0/).