Agriculture **2014**, *4*, 217-230; doi:10.3390/agriculture4030217

OPEN ACCESS

agriculture

ISSN 2077-0472

www.mdpi.com/journal/agriculture

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 CO_2 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 CO_2 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].

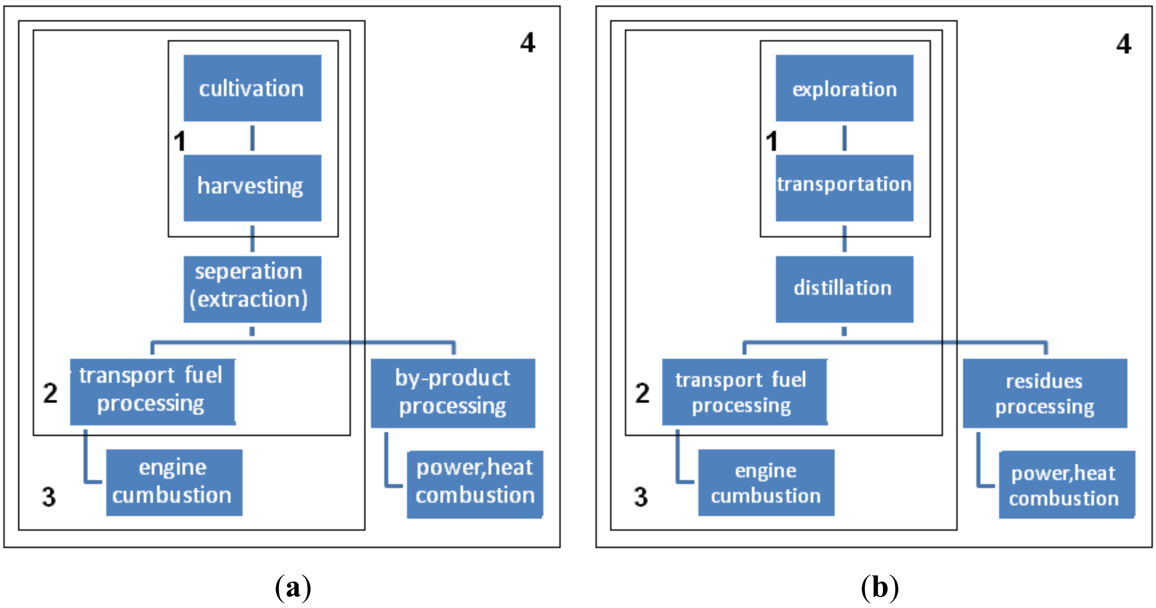
In this paper, the *JCL* demonstration cases implemented in Thailand, India, and West Africa are reviewed and compared with several laboratory works of microalgae, such as *Chlorella*, to further contrast their LCI (life-cycle inventory) of culturing, extracting, producing, and processing. The prospective 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 CO_2 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 1kg 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].

$$\text{NER} = \text{Total energy output/Total energy input}$$

$$\text{NEB} = \text{Total energy output} - \text{Total energy input}$$

2.3. Environmental Balance and GHG Saving

CO_2 was the only green house gas (GHG) considered in this paper, and CEB (CO_2 emission of biofuel) in combustion of biofuel was calculated with either kg or MJ as the functional unit.

$$\text{CEB } (CO_2 \text{ kg/kg}) = \text{mass (kg of biofuel combusted)} \times \text{C content (normalized)} \times 44/12 = 2.86$$

$$\text{CEB } (CO_2 \text{ g/MJ}) = 1000 \times 2.86/\text{energy (MJ producing from 1 kg biofuel)} = 1000 \times 2.86/37.8 = 75.7$$

where 0.78 was used as the carbon content of biodiesel and, assuming all of the carbon in biodiesel was converted to CO_2; 44/12, is the ratio of molecular weight of CO_2 and atomic weight of C. CO_2 emission in the "production stage" is calculated as equivalent CO_2 emission from coal-fired electricity generation (0.83 kg CO_2/KWh), which is much greater than that from natural gas (0.11 kg~0.24 kg·CO_2/KWh) but close to that from wood chips (0.82 kg CO_2/KWh) [7]. The CO_2 emission from coal-fired electricity in China (~1 kg CO_2/KWh) is even higher due to the use of low-grade coal.

CES (CO_2 emission saving) would be used to show the CO_2 emission balance of biofuel and compared to CEF (CO_2 emission of fossil fuel used in the production of biofuel).

$$\text{CES } (\%) = 100 \times [1 - (\text{CEF} + \text{CEB} + \text{CEU})/\text{CEF}]$$

Assuming CEU (CO_2 emission in upstream of biofuel production) to be zero, CEF to be 83.8 g CO_2/MJ fossil fuel, and CEB −75.7 g CO_2/MJ biofuel, the maximum CES is up to 90%, assuming that GEF, GEB and CEU (CO_2 emission upstream of biofuel production) are 83.8 g, 75.7 g and 0 g CO_2/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 m^2 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 m^3/m^2 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 1. Energy balance and yield, net energy ratio (NER), and CO_2 emission saving (CES).

Author	Energy Output/MJ		Energy Input/MJ	NER [1]	CES [2]/%	Plantation	Reference
	JME	By-Product					
Ndong (2009)	1		0.21	4.7	72	Mali/baseline	[5]
Ndong (2009)	1			1.8	11	irrigation/motorized	[5]
Achten (2008)	1		0.886	1.1	77	50%Faming E	[10]
Achten (2008)	1		0.16	6.3	93	17%Faming E	[10]
Prueksakorn (2006)	1		0.88	1.1	72	Thailand	[9]
Prueksakorn (2006)	1	17.88	0.88	21.5	72	Thailand	[9]
Kumar (2012) [2]	37.27		21.83	1.7	54	Irrigated	[7]
Kumar (2012) [2]	37.27		27.6	1.4	40	Rain-fed	[7]
Kumar (2012) [3]	37.27	107.8		1.5–8.6	50–107	Irrigated	[7]
Kumar (2012) [3]	37.27	107.8		1.2–7.0	40–93	Rain-fed	[7]
Pandey (2011)	1		0.578	1.73	23	Five years [4]	[6]

[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_2eq/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 CO_2e/MJ JME. The allocation of emitted CO_2 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 CO_2 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 CO_2/t JME) and rain-fed (1.5 t/ha, Farming energy: 15098 MJ/t JME; Farming emission: 1114 kg CO_2/t JME) scenarios are closely related.

It was found that the utilization of JME saved more energy and emitted less CO_2 (saving 1.2 GJ/ha; emitting 80 kg CO_2/ha per year) than direct use of *JCL* oil (saving 1.0 GJ/ha; 67 kg·CO_2/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 2. Energy input (expense) and greenhouse gas (GHG) emission for producing 1 kg algal oil and energy yield (NER).

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

[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 CO_2 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*, ia 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 CO_2-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%) CO_2 aeration is only 1.5 times and difficult to double compared with air aeration without additional CO_2. 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 CO_2 emission (0.1–4.4 g CO_2e/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 CO_2 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 CO_2 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 CO_2 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

JCL	*Jatropha curcas Linnaeus*
FAME	Fatty Acid Methyl Ester
LEA	Lipid extracted algae
FT	Fischer-Tropsch
LCI	Life-cycle Inventory
NER	Net energy ratio
CES	CO_2 emission saving
GHG	Greenhouse gas
EU	European Union
RED	Renewable Energy Directive
UFO	Used frying oil
LUC	Land use change
PBR	photobioreactor
HVO	Hydrotreated vegetable oil
FU	Functional unit
LCA	Life cycle assesment
CHP	Combined Heat and Power
NEB	Net energy balance
CEB	CO_2 emission of biofuel
CEU	CO_2 emission in upstream of biofuel production
CEF	CO_2 emission of fossil fuel used in the production of biofuel
DHA	Docosahexanoic acid
TAG	Triglyceride
FFA	Free fatty acid
BHD	Biohydrogenated diesel

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Biswas, B.; Scott, P.T.; Gresshoff, P.M. Tree legumes as feedstock for sustainable biofuel production: Opportunities and challenges. *J. Plant Physiol.* **2011**, *168*, 1877–1884.
2. Timilsina, G.R.; Shrestha, A. How much hope should we have for biofuels? *Energy* **2011**, *36*, 2055–2069.
3. Cherubini, F.; Stromman, A.H. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.* **2011**, *102*, 437–451.
4. Kalam, M.A.; Ahamed, J.U.; Masjuki, H.H. Land availability of *Jatropha* production in Malaysia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3999–4007.
5. Ndong, R.; Montrejaud-Vignoles, M.; Saint Girons, O.; Gabrielle, B.; Pirot, R.; Domergue, M.; Sablayrolles, C. Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: A field study. *GCB Bioenergy* **2009**, *1*, 197–210.

6. Pandey, K.K.; Pragya, N.; Sahoo, P.K. Life cycle assessment of small-scale high-input *Jatropha* biodiesel production in India. *Appl. Energy* **2011**, *88*, 4831–4839.
7. Kumar, S.; Singh, J.; Nanoti, S.M.; Garg, M.O. A comprehensive life cycle assessment (LCA) of *Jatropha* biodiesel production in India. *Bioresour. Technol.* **2012**, *110*, 723–729.
8. Basili, M.; Fontini, F. Biofuel from *Jatropha curcas*: Environmental sustainability and option value. *Ecol. Econ.* **2012**, *78*, 1–8.
9. Prueksakorn, K.; Gheewala, S.H. Energy and Greenhouse Gas Implications of Biodiesel Production from *JCL curcas* L. In Proceedings of the 2nd Joint International Conference on "Sustainable Energy and Environment", Bangkok, Thailand, 21–23 November 2006.
10. Achten, W.M.J.; Verchot, L.; Franken, Y.J.; Mathijs, E.; Singh, V.P.; Aerts, R.; Muys, B. *Jatropha* bio-diesel production and use. *Biomass Bioenergy* **2008**, *32*, 1063–1084.
11. Center for Industrial Ecology, Yale University. Life-Cycle Assessment of Jatropha Production in Central India. Available online: http://cie.research.yale.edu/sites/default/files/Jatropha%20LCA%20Spring%202008_0.pdf (accessed on 3 September 2013).
12. Sampattagu, S.; Suttibut, C.; Yucho, S.; Kiatsiriroat, T. Life Cycle Management of JCL Bio-Diesel Production. In Proceedings of the 3rd International Conference on Life Cycle Management, Irchel, Zurich, 27–29 August 2007.
13. Clarens, A.F.; Resurreccion, E.P.; White, M.A.; Colosi, L.M. Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstock's. *Environ. Sci. Technol.* **2010**, *44*, 1813–1819.
14. Hoekman, S.K. Biofuels in the U.S.—Challenges and Opportunities. *Renew. Energy* **2009**, *34*, 14–22.
15. Milledge, J.J. The challenge of Algal Fuel: Economic Processing of the Entire Algal Biomass. *Mater. Eng. Newslett.* **2010**, *1*, 4–6.
16. Wu, W.; Huang, J.; Deng, X. Potential land for plantation of *Jatropha curcas* as feedstocks for biodiesel in China. *Sci. China Ser. D* **2009**, *53*, 120–127.
17. Ou, X.; Zhang, X.; Chang, S.; Guo, Q. Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) People's Republic of China. *Appl. Energy* **2009**, *86*, S197–S208.
18. Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306.
19. Quinn, J.C.; Catton, K.; Wagner, N.; Bradley, T.H. Current large-scale US biofuel potential from microalgae cultivated in photobioreactors. *BioEnergy Res*. **2011**, *5*, 49–60.
20. Jorquera, O.; Kiperstok, A.; Sales, E.A.; Embirucu, M.; Ghirardi, M.L. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresour. Technol.* **2010**, *101*, 1406–1413.
21. Xu, D.; Slade, R.; Bauen, A. The Sustainability of Algae Biofuels: LCA, Environmental and Economic Impacts. In Proceedings of the AquaFUELs Project Final Conference, Imperial College, UK, 30 June 2011.
22. Yanfen, L.; Zehao, H.; Xiaoqian, M. Energy analysis and environmental impacts of microalgal biodiesel in China. *Energy Policy* **2012**, *45*, 142–151.
23. Kalnes, T.; Lupton, S.; Handler, R.M.; Shonnard, D.R.; Blowers, P.; Canter, C.E. Fossil Fuel Consumption and GHG Emissions for Algal Biofuels. In Proceedings of the 2nd International Conference on Algal Biofuels andBioproducts, San Diego, CA, USA, 10–14 June 2012.

24. Batan, L.; Quinn, J.; Willson, I.; Bradley, T. Net energy and greenhouse gasemission evaluation of biodieselderived from microalgae. *Environ. Sci. Technol.* **2010**, *44*, 7975–7980.
25. Lardon, L.; Helias, A.; Sialve, B.; Steyer, P.; Bernard, O. Life-cycle assessment of biodiesel production from microalgae. *Environ. Sci. Technol.* **2009**, *43*, 6475–6481.
26. Vasudevan, V.; Stratton, R.W.; Pearlson, M.N.; Jersey, G.R.; Beyene, A.G.; Weissman, J.C.; Rubino, M.; Hileman, J.I. Environmental performance of algal biofuel technology options. *Environ. Sci. Technol.* **2012**, *46*, 2451–2459.
27. Spolaore, P.; Joannis-Cassan, C.; Duran, E.; Isambert, A. Commercial applications of microalgae. *J. Biosci. Bioeng.* **2006**, *101*, 87–96.
28. Pulz, O.; Gross, W. Valuable products from biotechnology of microalgae. *Appl. Microbiol. Biotechnol.* **2004**, *65*, 635–648.
29. Illman, A.M.; Scragg, A.H.; Shales, S.W. Increase in *Chlorella* strains caloric values when grown in low nitrogen medium. *Enzym. Microb. Technol.* **2000**, *27*, 631–635.
30. Handler, R.M.; Canter, C.E.; Kalnes, T.N.; Lupton, F.S.; Kholiqov, O.; Shonnard, D.R.; Blowers, P. Evaluation of environmental impacts from microalgae cultivation in open-air raceway ponds: Analysis of the prior literature and investigation of wide variance in predicted impacts. *Algal Res.* **2012**, *1*, 83–92.