

Full Length Research Paper

The next generation feedstock of biofuel: *Jatropha* or *Chlorella* as assessed by their life-cycle inventories

Pu Peng^{1*} and Wenguang Zhou^{2*}

¹State Key Laboratory of Catalytic Material and Reaction Engineering, Research Institute of Petroleum Processing, SINOPEC, 18 Xue Yuan Road, Beijing 100083, China.

²Center for Biorefining, Bioproducts and Biosystems Engineering Department, University of Minnesota, 1390 Eckles Ave., Saint Paul, MN 55108, USA.

Received 26 January, 2014; Accepted 14 May, 2014

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) is 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 was 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 are all necessary to meet the requirements of commercial biofuel production.

Key words: Biodiesel, biofuel, *Jatropha*, microalgae, *chlorella*, LCA, LCI.

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 results in a significant reduction in CO₂ emission. The

development of biodiesel (fatty acid methyl ester, FAME) has met with 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

*Corresponding authors. E-mail: pengpu2000@gmail.com and zhouw@umn.edu. Tel: +1-612-867-7173. Fax: +1-612-624-3005.

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through encouraging the production and use of sustainable biofuels. The arable land used for biodiesel production has been 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 has been up to over 2 million tonnes (Mt) and near 10 M t, respectively (Timilsina and Shrestha, 2011). However, 10 Mt is only 3% of diesel consumption in EU and far from the renewable energy directive (RED) 10% target by 2020 in 29 European countries (E27 plus Norway and Switzerland). In order to meet the gap between the 3 and 10% and 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 who would prevail. Economic-crops are able to be planted in marginal lands but the planting of dedicated energy crops often leads to the carbon stock change, known as land use change (LUC) (Laborde, 2011), which sheds doubt on the predicted positive GHG balance (positive CES). In contrast, microalgae are able to be cultivated in ponds or photobioreactor (PBR) located on mudflats or deserts with near zero carbon stock. Meanwhile, other advanced biofuels such as hydrotreated vegetable oil (HVO) (Arvidsson et al., 2011), 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 or offer other technical benefits and be prepared with wider feedstock's.

In Francesco's (Cherubini and Stromman, 2011) comprehensive literature review on biofuel development, it was found that there are 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 *Jatropha curcas Linnaeus* (*JCL*). *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 is 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 one year of growth, but the maximum productivity is after 4 or five years (typical *JCL* yields in the first 5 years are 0.5, 1.5, 3.0, 5.0 and 6.0 t/ha). Its average life span is over 20 years (up to 50 years) (Cherubini and Stromman,

2011; Kalam et al., 2012).

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 life-cycle inventory (LCI) of culturing, extracting, producing and processing. The prospective productivities (annual yield) of both feedstocks were compared and discussed to readdress the exaggerated results often found in the literature.

EXPERIMENTALS

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 in 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 has been constructed using data from the inputs and outputs, and it has given 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.

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, that is, 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 (1kWh=3.6MJ).

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 (Ndong et al., 2009).

Energy balance and fossil fuel saving

The net energy ratio (NER) 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 photobioreactor (PBR) construction and materials, nutrition production, and planting (culturing) operation (primary energy input). NER is also called the energy yield. The net energy balance (NEB) 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 would be larger than one and zero, respectively (Pandey et al., 2011).

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

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

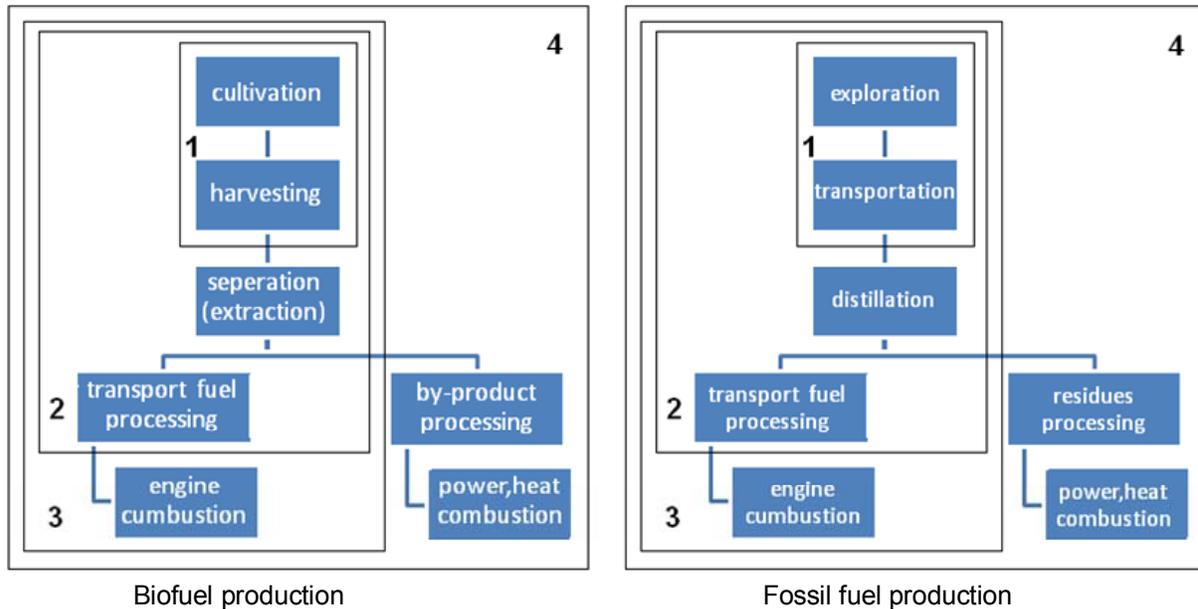


Figure 1. LCI flow model of biofuel and conventional fossil fuel with different boundaries.

Environmental balance and GHG saving

CO₂ was the only green house 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.

CEB (CO₂kg/kg) = mass (kg of biofuel combusted) × C content (normalized) × 44/12 = 2.86

CEB (CO₂g/MJ) = 1000 × 2.86 / energy (MJ producing from 1 kg biofuel) = 1000 × 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 from natural gas (0.11 to 0.24 kg CO₂/KWh) but close to that from wood chips (0.82 kg CO₂/kwh) (Kumar et al., 2012). The CO₂ emission from coal-fired electricity in China (~1 kg CO₂/KWh) is even higher due to the use of low-grade coal.

CO₂ emission saving (CES) was used to show the CO₂ emission balance of biofuel and compare the CO₂ emission of fossil fuel used in the production of biofuel.

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

Assuming CO₂ emission in upstream of biofuel production (CEU) to be zero, and CEF was taken as 83.8 g CO₂/MJ fossil fuel and the CEB was -75.7 g CO₂/MJ biofuel, the maximum CES will be up to 90%, assuming GEF, GEB and CEU (CO₂ emission in upstream of biofuel production) are 83.8, 75.7 and 0 g CO₂/MJ fossil fuel, respectively. In fact, CES is closely 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 becomes negative) depending on the energy consumed in the upstream process and the electricity source of coal, fuel oil or natural gas-fired power station.

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 away from the targets of 5 M ha by 2010 and 13 M ha by 2015 (Ndong et al., 2009). Meanwhile, the prices of *JCL* seed have increased from 0.10 \$/kg in 2005 to 0.34\$/kg in 2011 (Kalam et al., 2012).

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 × 1 m or two trees per m² was utilized. Land preparation 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 (Pandey et al., 2011).

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 consumed in the irrigated mode as compared with rain-fed mode (Kumar et al., 2012).

In West Africa (Mali and Ivory Coast), *JCL* planting was up to 1500 ha in 2007, and at least 2000 ha more in

Table 1. Energy balance and yield (NER) and CO₂ emission saving (CES).

Reference	Energy output/MJ		Energy input/MJ	NER ¹	CES ² /%	Plantation
	JME	By-product				
Ndong et al., (2009)	1		0.21	4.7	72	Mali/baseline
Ndong et al., (2009)	1			1.8	11	irrigation/motorized
Achten et al. (2008)	1		0.886	1.1	77	50%Faming E
Achten et al. (2008)	1		0.16	6.3	93	17%Faming E
Yale University	1		0.88	1.1	72	Thailand
Yale University	1	17.88	0.88	21.5	72	Thailand
Kumar et al. (2012) ²	37.27		21.83	1.7	54	Irrigated
Kumar et al. (2012) ²	37.27		27.6	1.4	40	Rain-fed
Kumar et al. (2012) ³	37.27	107.8		1.5-8.6	50-107	Irrigated
Kumar et al. (2012) ³	37.27	107.8		1.2-7.0	40-93	Rain-fed
Pandey et al. (2011)	1		0.578	1.73	23	Five years ³

¹NER 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. ²Conventional diesel emit 83.8 kg CO₂eq/GJ diesel. ³NER was estimated as a ratio of biodiesel energy and net allocated process energy to biodiesel. ³Averaged by the total yield (energy) of 5 years (3.92 t JME, 161.65 GJ) and NEB=161.65-93.51= 68.14 MJ. Faming E (energy).

2008. Two 5-ha experimental fields with plantation densities of 1111 plants ha⁻¹ were selected with contrasting soil conditions. Ternary fertilizer only was applied during the first three years: 100 kg/ha in 1st year, 150 kg/ha in 2nd year, 200 kg/ha in 3rd year, whereas both 248 kg/ha ternary fertilizer and 201 kg/ha of ammonium nitrate were applied in the 4th year (Pandey et al., 2011).

Productivities of biomass, JME and by-products

The yield hypotheses had a significant impact on the GHG and energy balances of JME. The weight of each fresh fruit and seed is around 10 to 15 and 2 to 4 g, respectively. The annual yield of *JCL* fresh fruit is about 16 t/ha. The yield of seed is widely spread from 0.1 to 10 t/ha (Basili and Fontini, 2012) and an increase of 1 t/ha on 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 on seed production from the baseline of 4 t/ha results 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 shell, are 4, 2, and 0.8 t (dry weight), respectively from the process of *JCL* plantation, and press cake (91.5 kg, dry weight) is obtained when 1 FU (1GJ of JME) is produced (Prueksakorn and Gheewala, 2006).

Kumar et al. (2012) 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 ranges from 21.0 to 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.

Energy balance (net energy use)

The selected JME projects of energy balance expressed in NER (energy yield) and environmental balance expressed in biofuel CO₂ emission factor per GJ energy are shown in Table 1.

Ndong et al. (2009) 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) is 4.7. In other words, 4.7 MJ of energy is produced from 1 MJ of fossil fuel consumed to produce JME. Biofuel production requires direct (electricity, fuels and 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 become only marginal (11%), only one-sixth of the baseline scenario.

In a Thailand demonstration test (Prueksakorn and Gheewala, 2006), the allocation for energy expenses of transesterification, irrigation and fertilization processes was approximately 40% (0.197 GJ for producing steam),

23% (0.205GJ) and 22% (0.198GJ), 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 one time every five 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 energy of 10.289 GJ.

Environmental balance (GHG emission)

Achten et al. (2008) 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 ~77% compared to the GHG emission using fossil diesel. Totally, the production and combustion of JME emits 23.5 g CO₂e/MJ JME. The allocation of CO₂ emitted 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 are 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 is 64% of electricity generation, in which 52% of electricity is generated in coal-fired power plants, whereas the other 12% are allocated from natural gas (11%), oil (1%). The rest are from hydro (23%), nuclear (3%) and renewable materials (10%) (Pandey et al., 2011). In China, coal is the major share of fossil fuel in electricity generation (80%), resulting in more CO₂ emitted.

Sunil⁸ compared energy and environmental balances of irrigated and rain-fed scenarios. Seed annual yields of irrigated (5.9 t/ha, farming energy: 9333MJ/t JME; farming emission: 680kg CO₂/t JME) and rain-fed (1.5 t/ha, farming energy: 15098 MJ/t JME; farming emission: 1114kg CO₂/t JME) scenarios are closely related.

It was found that the utilization of JME saved more energy and emitted less CO₂ (saving 1.2GJ/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 (Center for industrial ecology, Yale University, USA, 2010).

Life cycle costs

It was reported that the total cost of JME without externa-

lities is higher than the current market retail selling price of diesel in Thailand (Sampattagu et al., 2007). The cost allocation is 62.62, 25.27 and 12.12% for agricultural, bio-diesel production and environmental processes, respectively. The highest expenditure is the operation costs in agriculture stage such as fertilizers, insecticide, and electricity for water pumping system, 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 (Clarens et al., 2010). While as a commercially viable option, microalgae will require further improvements in genetic and metabolic engineering to and obtain promising strains and produce higher yield of oil. Moreover, the 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 (Hoekman, 2009). While microalgae are projected as a future feedstock of biodiesel, production cost is much higher than for these terrestrial crops, in the range of US\$2 to \$22 per liter (Timilsina and Shrestha, 2011). In addition, the entire microalgae biomass has to be used to produce biofuel otherwise the yield of biofuel would be too low to be accepted (Milledge, 2010).

Situation in China

It's widely hoped that JME production will offer a newer, more sustainable energy source; but that is 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 in suffering from arable land limitation since then (Timilsina and Shrestha, 2011). Therefore, there has been more effort to search energy crops in China than EU, US, and even Asia countries, such as India and Thailand. However, the climate is not suitable to plant *JCL* on most of land in China. Although Southwest China is considered as a prospective area to plant *JCL*, it has been discovered that both prospective planting area and yield of seed had been overestimated after comprehensive consideration using 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 lands to expand *JCL* areas is only 0.15 M ha by 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 definitely destroy the balance of both energy and environment (NER and CES become minus value) (Wu et al., 2009).

In China, the yield of fresh fruit, dried seed and extracted oil would be less than the countries in the tropic zone, and there is little data from farming sites. The prospective yield of *JCL* seeds and JME are often

Table 2. Energy input (expense) and GHG emission for producing 1 kg algal oil and energy yield (NER).

Reference	Yield ¹ (t/ha)	Lipid %(D W)	Output (MJ)	input (MJ)	NER	CES ² (%)	Cultivation	
							Harvesting	Algal species
Kalnes et al. (2012)		25.0	83.6	85.8	0.97	-2	Dewatering	<i>Nannochloropsis</i>
Kalnes et al. (2012)		25.0	83.6	59.0	1.42	57	HRJ	<i>Nannochloropsis</i>
Batan et al. (2010)	91	42.5	1	0.93	0.93	29	PBR bags	<i>Nannochloropsis</i>
Lardon et al. (2009)	62	17.5	103.8	106.4	0.98		Dry	<i>Chlorella vulgaris</i>
Lardon et al. (2009)	62	17.5	146.8	41.4	3.55		Wet	<i>Chlorella vulgaris</i>
Xu et al. (2011)	128	40.0	37.2	27.5	1.35	41	Tubular	<i>P. tricornutum</i>
Vasudevan et al. (2012)	76	25.0	9.2	32	0.3	-232	Dry extract.	Algae
Vasudevan et al. (2012)	76	25.0	9.2	3.7	2.5	37	Wet extract.	Algae

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

exaggerated and questionable. For instance, the JME yield (5t/ha) and farming (planting) energy (160MJ/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 4t/ha (the JME content is less than 40% of JCL seed). A misleading NER of JME (2.004) even higher than soybean (0.981) was proposed based on a unconfirmed JCL annual yield (5 t/ha) in Hainan province of China which was greatly overestimated and even over the field obtained in the tropic zone (Ou et al., 2009). The reasonable annual yield of JME is 1 to 2 t/ha based on the demonstration test in Thailand (Prueksakorn and Ghewala, 2006), Malaysia (Kalam et al., 2012) and West Africa (Ndong et al., 2009); where, JME content of 30 to 50% is usually accepted.

Comparison with microalgae

It is known that microalgae has attracted the spotlight around the world during past years and was considered as a very hopeful competitor to replace terrestrial plant as feedstock of next generation biofuels. One reason for the superiority of microalgae is that it is unnecessary to use fresh water and arable land in the culturing. Waste, saline, or brackish water and land resources, such as mudflats or deserts, are all usable for the microalgae culturing so that there is no interference in food production as there was for the first generation biofuels (Clarens et al., 2010). Another benefit of microalgae is due to the high expected yield of biomass, which can be as high as over 100 t/ha and oil content as high as 70% of its dry weight in the form of triglycerides (Chisti, 2007). However, these are only speculations based on the excessively optimistic assumptions or laboratory data using minimalistic culturing volume of several milliliters to liters, which largely deviated from the larger scale culturing results either in ponds or PBR. Although *Chlorella*, *Diatom*, *Scenedesmus*, *Tetraselmis*, *Nannochloropsis*

and *Haematococcus pluvialis* have been preferred as hopeful candidates, the real potential of their productivity was not clear until their production was realized at a large scale, resulting to the differences of published biomass and oil (lipid) yield potentials which are as much as 16 times (Quinn et al., 2011).

In this paper, NER was selected to qualify the energy balance and closely related to both the boundaries of LCI and the yield of algal biomass and lipid. Meanwhile CES was selected to qualify the GHG balance. Some of the calculated NER and CES based on published LCA results were summarized in Table 2, and some of them were from laboratory data and extremely exaggerated. The results are dependent on the manner of culturing (pond or PBR), harvesting, biomass yield and lipid content and the boundary. NER for *Nannochloropsis* cultivation process is 4.33 for flat-plate PBR but 7.01 for raceway pond, indicating that both processes were energetically favorable for biomass production (boundary 1) (Jorquera et al., 2010). NER became less than 1 when harvesting stage was included (boundary 2) (except for HRJ or wet harvesting) indicating that dewatering is the most energy consuming process in the upstream (Table 2). The NER is closely dependent on the yield of biomass or lipid and varies as much as six times as reported from different sources (Xu et al., 2011). In order to attain the energy benefit (NER>1), the overestimated LCI data (biomass yield or lipid fraction) were often accepted in the published papers (Chisti, 2007; Yanfen et al., 2012).

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 (Xu et al., 2011).

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 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 \$5,000 to \$100,000 per dry ton of biomass or extracted products (Spolaore et al., 2006). The biomass of microalgae is also used as live feeds in aquaculture, and in waste-water treatment systems with the lower price in the culturing stage (Pulz and Gross, 2004). 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 production 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 to 3000 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. The *Chlorella*, with lower protein content and higher lipid content than *Spirulina*, was recommended to be used as feedstock of 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 rich-CO₂ environments. When low-N nutrients are used in algal cultivation, lipid content increases but the yield of biomass usually decreases (Illman et al., 2000). The improvement of biomass yield with additional (5 to 14%) CO₂ aeration is only 1.5 times and difficult to double as compared with air aeration without additional CO₂. In the lipid fraction, there are not only triglyceride (TAG) and free fatty acids (FFA) but also sterol, terpene and hydrocarbon, 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* (Yanfen et al., 2012).

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 the algal biofuels produced from lipid extracted fraction (lipid extracted algae, LEA) which is difficult to be esterified to form FAME (Kalnes et al., 2012). Even now, the algal biofuel has not been produced or demonstrated in China due to the low algal biomass productivity and the complexity of the algal biomass. This is also the reason that 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. Robert 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 to 4.4 g CO₂e/g microalgae) (Handler et al., 2012).

The difficulties of commercialization

Jatropha

The *JCL* has been successfully planted on a large scale, especially in Asia and Africa where planting areas have been near to 1 M ha, respectively. The seed yield ranges 4 to 5 t/ha in above area but is relatively area and climate dependent. The oil content ranges from 20 to 50% and typically 30 to 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 of biofuel, and 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 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.

On 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 closer to us as the next generation feedstock of biodiesel if there is enough land with proper climate, and we can avoid the CO₂ emission resulting from LUC at the same time.

Microalgae

The cultivation of microalgae even *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* farm 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 of biofuel in the future.

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

The lipid in microalgae should be referred to as bio-crude other than biodiesel. All of bio-crude or biomass has to be processed to produce the sustainable bio-energy instead of biodiesel (FAME) only 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 positive, and CES is also rarely positive if the energy prepared from LEA was not accounted for at the present stage.

Conclusion

The biomass yields of both *JCL* and *Chlorella* per hectare have to be increased further by using the high efficiency irrigation systems for *JCL* plantation and well-designed PBR for *Chlorella* cultivation so as to get economic and environmental benefits. Moreover, it was strongly suggested that not only transesterification or esterification but also Fischer-Tropsch 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. Overall, there is a long way to go for either *Jatropha* or *Chlorella* to become real 2nd generation feedstock at the scale corresponding to 1st generation feedstock.

Conflict of Interests

The author(s) have not declared any conflict of interests.

ACKNOWLEDEMENTS

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

REFERENCES

- Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R (2008). *Jatropha* bio-diesel production and use. *Biomass Bioenergy* 32:1063-84.
- Arvidsson R, Persson S, Fröling M, Svanström M (2011). Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and *Jatropha*. *J. Clean. Prod.* 19:129-37.
- Basili M, Fontini F (2012). Biofuel from *Jatropha curcas*: Environmental sustainability and option value. *Ecol. Econ.* 78:1-8.
- Batan L, Quinn J, Willson I, Bradley T (2010). Net Energy and Greenhouse Gas Emission Evaluation of Biodiesel Derived from Microalgae. *Environ. Sci. Technol.* 44:7975-80.
- Center for Industrial Ecology, Yale University USA (2010).[Internet]. Life-Cycle Assessment of *Jatropha* Production in Central India. Available at: is4ie.org/Content/Documents/Document.ashx?DocId=7763
- Cherubini F, Stromman AH (2011). Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresour. Technol.* 102:437-51.
- Chisti Y (2007). Biodiesel from microalgae. *Biotechnol. Adv.* 25:294-306.
- Clarens AF, Resurreccion EP, White MA, Colosi LM (2010). Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstock's. *Environ. Sci. Technol.* 44:1813-19.
- Handler RM, Canter CE, Kalnes TN, Lupton FS, Kholiqov O, Shonnard DR (2012). 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.* 1:83-92.
- Hoekman SK (2009). Biofuels in the U.S. - Challenges and Opportunities. *Renew. Energy* 34:14-22.
- Illman AM, Scragg AH, Shales SW (2000). Increase in *Chlorella* strains caloric values when grown in low nitrogen medium. *Enzyme Microb. Technol.* 27:631-635.
- Jorquera O, Kiperstok A, Sales EA, Embirucu M, Ghirardi ML (2010). Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresour. Technol.* 101: 1406-1413.
- Kalam MA, Ahamed JU, Masjuki HH (2012). Land availability of *Jatropha* production in Malaysia. *Renew. Sustain. Energy Rev.* 16:3999-4007.
- Kalnes T, Lupton S, Handler RM, Shonnard DR, Blowers P, Canter CE (2012). Fossil Fuel Consumption and GHG Emissions for Algal Biofuels. In: 2nd International Conference on Algal Biofuels and Bioproducts. San Diego, California, June 10-14.
- Kumar S, Singh J, Nanoti SM, Garg MO (2012). A comprehensive life cycle assessment (LCA) of *Jatropha* biodiesel production in India. *Bioresour. Technol.* 110:723-29.
- Laborde D (2011). Assessing the Land Use Change Consequences of European Biofuel policies and its uncertainties. Final report No SI2 580403. The International Food Policy Institute (IFPRI).
- Lardon L, Helias A, Sialve B, Steyer P, Bernard O (2009). Life-Cycle Assessment of Biodiesel Production from Microalgae. *Environ. Sci. Technol.* 43:6475-81.
- Milledge JJ (2010). The challenge of Algal Fuel: Economic Processing of the Entire Algal Biomass. *Mater. Eng. Newsl.* 1(6):4-6.
- Ndong R, Montrejeud-Vignoles M, Saint Girons O, Gabrielle B, Pirot R, Domergue M (2009). Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: a field study. *GCB Bioenergy* 1:197-210.
- Ou X, Zhang X, Chang S, Guo Q (2009). Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) People's Republic of China. *Appl. Energy* 86:S197-208.
- Pandey KK, Pragma N, Sahoo PK (2011). Life cycle assessment of small-scale high-input *Jatropha* biodiesel production in India. *Appl. Energy* 88:4831-39.
- Prueksakorn K, Gheewala SH (2006). Energy and Greenhouse Gas Implications of Biodiesel Production from *JCL curcas* L. In: The 2nd Joint International Conference on "Sustainable Energy and Environment", Bangkok, Thailand, November 21-23. P E-053 (O).
- Pulz O, Gross W (2004). Valuable products from biotechnology of microalgae. *Appl. Microbiol. Biotechnol.* 65:635-648.
- Quinn JC, Catton K, Wagner N, Bradley TH (2011). Current Large-Scale US Biofuel Potential from Microalgae Cultivated in Photobioreactors. *BioEnergy Res.* 5: 49-60.
- Sampattagu S, Suttibut C, Yucho S, Kiatsiriroat T (2007). Life Cycle Management of *JCL* Bio-Diesel Production. In: Thailand. 3rd International Conference on Life Cycle Management, Irchel, Zurich, August 27-29, P326.
- Spolaore P, Joannis-Cassan C, Duran E, Isambert A (2006). Commercial applications of microalgae. *J. Biosci. Bioeng.* 101: 87-96.
- Timilsina GR, Shrestha A (2011). How much hope should we have for biofuels? *Energy* 36:2055-69.
- Vasudevan V, Stratton RW, Pearlson MN, Jersey GR, Beyene AG, Weissman JC (2012). Environmental performance of algal biofuel technology options. *Environ. Sci. Technol.* 46: 2451-59.
- Wu W, Huang J, Deng X (2009). Potential land for plantation of *Jatropha curcas* as feedstocks for biodiesel in China. *Sci. China Ser. D Earth Sci.* 53: 120-27.
- Xu D, Slade R, Bauen A (2011). The Sustainability of Algae Biofuels: LCA, Environmental and Economic Impacts. In: AquaFUELS Project FINAL CONFERENCE. Imperial College, UK, June 30.
- Yanfen L, Zehao H, Xiaoqian M (2012). Energy analysis and environmental impacts of microalgal biodiesel in China. *Energy Policy* 45:142-151.