Bioresource Technology 129 (2013) 72–77

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Life cycle assessment of biodiesel production in China

Sai Liang [a,*], Ming Xu [b,c], Tianzhu Zhang [a]

[a] School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China
[b] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, United States
[c] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, United States

HIGHLIGHTS

- ▶ Various feedstocks had different performances, causing potential problem-shift.
- ▶ Jatropha, castor and waste oil were preferred feedstocks in the short term.
- ▶ Algae were preferred biodiesel feedstocks in the long term.
- ▶ Biodiesel production should consider potential environmental problems.
- ▶ Key processes for technology improvements in biodiesel production were identified.

ARTICLE INFO

Article history:
Received 11 August 2012
Received in revised form 6 November 2012
Accepted 7 November 2012
Available online 16 November 2012

Keywords:
Agriculture
Bioenergy
Biofuel
Input–output analysis
Life cycle assessment

ABSTRACT

This study aims to evaluate energy, economic, and environmental performances of seven categories of biodiesel feedstocks by using the mixed-unit input–output life cycle assessment method. Various feedstocks have different environmental performances, indicating potential environmental problem-shift. Jatropha seed, castor seed, waste cooking oil, and waste extraction oil are preferred feedstocks for biodiesel production in the short term. Positive net energy yields and positive net economic benefits of biodiesel from these four feedstocks are 2.3–52.0% of their life cycle energy demands and 74.1–448.4% of their economic costs, respectively. Algae are preferred in the long term mainly due to their less arable land demands. Special attention should be paid to potential environmental problems accompanying feedstock choice: freshwater use, ecotoxicity potentials, photochemical oxidation potential, acidification potential and eutrophication potential. Moreover, key processes are identified by sensitivity analysis to direct future technology improvements. Finally, supporting measures are proposed to optimize China's biodiesel development.

1. Introduction

Global economic growth in the last couple of decades has been made possible by large-scale consumption of fossil fuels, leading to increasing greenhouse gas (GHG) emissions and global climate changes (Lu and Zhang, 2010). Liquid biofuels are regarded as promising alternatives to fossil fuels (Luque et al., 2010; Ragauskas et al., 2006). Being the global top energy consumer (BP, 2012) and CO_2 emitter (Gregg et al., 2008), China has been promoting liquid biofuel production to reduce GHG emissions while meeting increasing energy demands.

The production of first generation liquid biofuels has caused many problems such as land use change, food price rise, and increased life cycle CO_2 emissions (Sims et al., 2010; Yang et al., 2011). Algae-derived biodiesel can avoid these problems (Yang et al., 2011). Subsequently, algae are regarded as attractive feedstocks for biofuel production (Hu et al., 2008; Zhang et al., 2010). China is facing problems of arable land scarcity (Wang et al., 2012), food security (Fan et al., 2012), and increasing energy demand (Zweig and Ye, 2008). Thus, algae-derived biodiesel is an attractive pathway for China's future biofuel development. Along with popular concern on food security caused by illegal use of gutter oil in China, producing biodiesel from gutter oil is also discussed. Moreover, China is planting jatropha curcas in marginal lands to provide feedstock for biodiesel production. Using jatropha seed and gutter oil to produce biodiesel does not compete with foods and arable land (Kumar et al., 2012). Thus, jatropha curcas and waste oil can also be regarded as potential feedstocks for China's biodiesel development. In general, China has various potential feedstocks for biodiesel production.

Economic feasibility of biodiesel production has been validated (Haas et al., 2006; Araujo et al., 2010; Zhang et al., 2003). Biodiesel production, however, can induce many indirect impacts

---

[*] Corresponding author. Tel.: +86 10 62794144; fax: +86 10 62796956.
E-mail address: liangsai09@gmail.com (S. Liang).

0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.11.037

(Scharlemann and Laurance, 2008). In order to fully capture both direct and indirect impacts, life cycle assessment (LCA) model is popularly applied (ISO, 2006). Current studies on LCA of biodiesel feedstocks mainly focus on limited environmental issues such as energy demands (Malca and Freire, 2011), global warming potential (Malca and Freire, 2011) and water footprint (Yang et al., 2009, 2011). Only focusing on limited environmental impacts may induce the shift of environmental problems (Liang et al., 2012). In addition, the number of feedstocks considered in previous studies is limited. In other words, a systematic study on life cycle comparisons of biodiesel feedstocks considering both a wide range of feedstocks and a wide range of environmental impacts has been seldom conducted. Such a systematic study could identify potential environmental issues in biodiesel production and then provide guidance for future technology improvements.

This study attempted to fill in this vacancy. It analyzed energy, economic and environmental performances of seven categories of China's potential biodiesel feedstocks (comprising soybean, jatropha seed, vegetable seed, castor seed, algae, waste cooking oil and waste extraction oil). Potential environmental problems accompanying each kind of biodiesel feedstock were identified. Results in China could also provide foundations for biodiesel production in other countries.

2. Methodology and data

The mixed-unit input–output life cycle assessment (MUIO-LCA) model was used to conduct the LCA. It extended system boundaries of traditional process-based life cycle assessment model (Hawkins et al., 2007). Detailed descriptions of the MUIO-LCA model can been found in (Hawkins et al., 2007; Liang et al., 2012a,b). Seven categories of biodiesel feedstocks (comprising soybean, jatropha seeds, vegetable seeds, castor seeds, algae, waste cooking oil and waste extraction oil) were considered. These feedstocks are popularly concerned in previous literatures. First, parameters for five production processes were collected: feedstock planting, biomass oil extraction, biodiesel production, materials transportation and biodiesel combustion. Then, production processes were incorporated into the environmentally-extended economic input–output (EEIO) table to construct the MUIO-LCA model. Finally, life cycle environmental impacts of biodiesel production were calculated by the MUIO-LCA model. Detailed calculations can be found in (Liang et al., 2012b).

China produced 0.2 million tonnes of biodiesel in 2007 (RGCECER, 2009). Thus, the function unit in this study was set as 0.2 million tonnes of biodiesel. The construction of the EEIO table and detailed data sources can be found in (Liang et al., 2012b). China's biodiesel was all used for transportation activities to substitute fossil-based diesel that had the same energy value with biodiesel. Co-products (comprising seed cake from biomass oil extraction and glycerol from biodiesel production) were used to substitute related materials, as utilizing co-products can effectively reduce environmental impacts (Hansen et al., 2012). Seed cake from biomass oil extraction was used to substitute organic fertilizers, and glycerol from biodiesel production was used to produce cosmetics. Detailed parameters for these processes were listed in Tables S1 to S5 the Supplementary Information (SI).

3. Results and discussion

3.1. Energy analysis, global warming potential and economic analysis

Net energy yield was equal to energetic value of biodiesel minus life cycle energy use of biodiesel production (Fig. 1). Energy yields of biodiesel from jatropha seeds, vegetable seeds, castor seeds, waste cooking oil and waste extraction oil were larger than their life cycle energy demands. On the contrary, energy yields of biodiesel from soybean and algae were smaller than their life cycle energy demands. Thus, net energy yields of biodiesel from jatropha seeds, vegetable seeds, castor seeds, waste cooking oil and waste extraction oil were positive, while that of biodiesel from soybean and algae were negative. Positive net energy yields of biodiesel from jatropha seeds, vegetable seeds, castor seeds, waste cooking oil and waste extraction oil counted 52.0%, 58.4%, 3.0%, 11.3% and 2.3% of their life cycle energy demands, respectively.

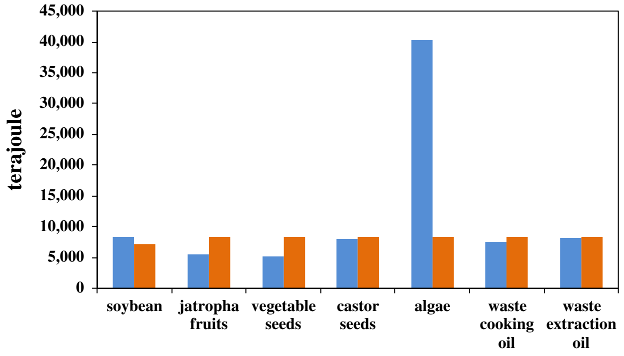


Fig. 1. Energy use and energy yields of biodiesel production. The bar in blue colour indicated life cycle energy use of biodiesel production. The bar in red colour indicated energetic value of biodiesel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Net global warming potential was equal to life cycle global warming potential of biodiesel production minus CO_2 directly captured in feedstock planting (Fig. 2). CO_2 captured in feedstock planting was calculated by feedstock yields multiplied by CO_2 sequestration coefficients (Table S6 in the SI). The planting of vegetables, castor, soybean and jatropha curcas captured more greenhouse gasses (GHG) than life cycle GHG emissions of biodiesel production from these feedstocks. The planting of algae, however, captured less GHG than life cycle GHG emissions of algae-derived biodiesel. Waste cooking oil and waste extraction oil did not have planting stage. Thus, they did not directly capture GHG. Net GHG sequestration of vegetables, castor, soybean and jatropha curcas counted 547.3%, 265.5%, 146.5% and 42.3% of life cycle global warming potential of biodiesel production from these feedstocks, respectively.

Net economic benefit was equal to economic value of both biodiesel and co-products (including seed cake and glycerol) minus the sum of economic value of intermediate inputs into three

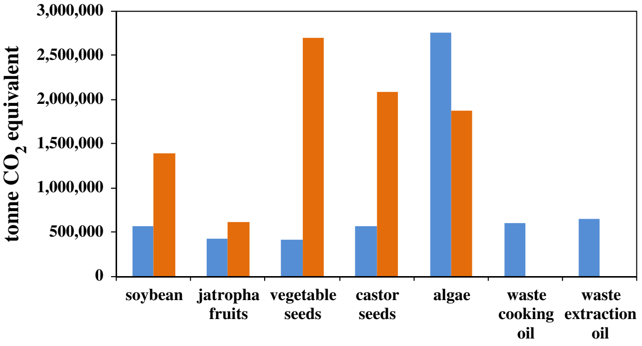


Fig. 2. Global warming potential and CO_2 sequestration of biodiesel production. The bar in blue colour indicated life cycle global warming potential of biodiesel production. The bar in red colour indicated CO_2 directly captured in feedstock planting stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

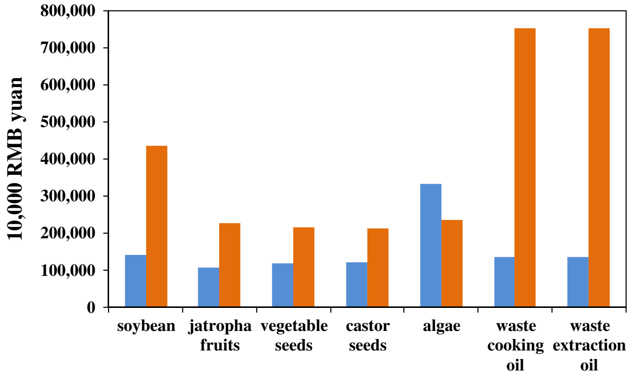


Fig. 3. Economic cost and benefit of biodiesel production. The bar in blue colour indicated the sum of economic value of intermediate inputs into three processes named feedstock planting, oil extraction and biodiesel production. The bar in red colour indicated economic value of both biodiesel and co-products (including seed cake and glycerol). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

processes named feedstock planting, oil extraction and biodiesel production (Fig. 3). Algae-derived biodiesel had negative net economic benefits, counting 29.1% of its economic cost. Biodiesel produced from the other six categories of feedstocks had positive net economic benefits. Positive net economic benefits of waste cooking oil-derived, waste extraction oil-derived and soybean-derived biodiesel were big, counting 448.4%, 448.4% and 207.4% of their economic cost, respectively. On the other hand, positive net economic benefits of jatropha seed-derived, vegetable seed-derived and castor seed-derived biodiesel were relatively small, counting 111.9%, 79.2% and 74.1% of their economic cost, respectively.

3.2. Life cycle environmental impacts

Life cycle environmental impacts of biodiesel production from seven categories of feedstocks were calculated (Table 1). In order to produce 0.2 million tonnes of biodiesel, biodiesel production consumed about 214–268 thousand tonnes of fruits and about 204–234 thousand tonnes of biomass oil from life cycle viewpoint. Waste cooking oil-derived and waste extraction oil-derived biodiesel did not consume fruits and biomass oil, as waste cooking oil and waste extraction oil did not have feedstock planting and oil extraction processes.

Seven categories of biodiesel feedstocks had different environmental performances, indicating potential environmental problem-shift. Algae-derived biodiesel had the largest life cycle energy demands among these feedstocks, while soybean had the largest life cycle freshwater demands. Eight categories of potential impacts are considered. Algae-derived biodiesel had the biggest global warming potential (GWP), photochemical oxidation potential (POCP), acidification potential (AP) and eutrophication potential (EP), while waste cooking oil-derived biodiesel had the biggest human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TETP). Biodiesel from soybean, jatropha seeds, vegetable seeds, castor seeds, algae, waste cooking oil and waste extraction oil discharged 363, 85, 93, 118, 451, 139 and 353 thousand tonnes of solid wastes, respectively, from life cycle viewpoint.

3.3. Sensitivity analysis

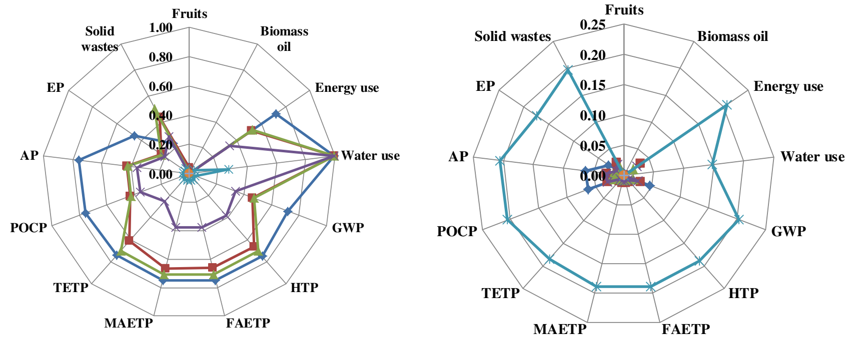
Parameter changes could influence life cycle results. Thus, sensitivity analysis is conducted to analyze the extent of uncertainty of these parameters (Fig. 4). Parameter changes were regarded as technology changes. Subsequently, sensitivity analysis could identify key processes for technology improvements.

Technology improvements in feedstock planting (Fig. 4a, the reduction in parameters for seeds, electricity, freshwater, chemical fertilizer, general purpose machinery, special purpose machinery, electrical machinery and buildings) had big positive effects on life cycle environmental impacts of biodiesel from soybean, jatropha seeds and vegetable seeds, with a reduction by 7–10%. Soybean-derived biodiesel benefited the most from technology improvements in feedstock planting. Technology improvements in oil extraction (Fig. 4b, the reduction in parameters for coal, electricity, general purpose machinery, special purpose machinery, electrical machinery and buildings) affected life cycle environmental impacts of algae-derived biodiesel the most, with environmental impacts reduced by 1.5–2.1%. Technology improvements in biodiesel production (Fig. 4c, the reduction of parameters for electricity, heat power, natural gas, coal, freshwater, chemicals, general purpose machinery, special purpose machinery, electrical machinery and buildings) had big positive effects on environmental impacts reduction of biodiesel from castor seeds, algae, waste cooking oil and waste extraction oil, with a reduction by 5–8%. Efficiency improvements in automobile catalytic converters could reduce emissions from biodiesel combustion. Efficiency improvements in

Table 1
Life cycle environmental impacts of biodiesel production.

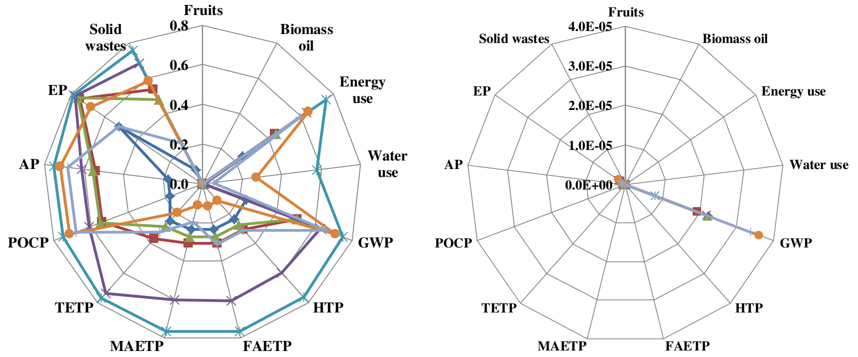
Items	Units	Soybean	Jatropha fruits	Vegetable seeds	Castor seeds	Algae	Waste cooking oil	Waste extraction oil
Fruits	Tonne	214,354	267,682	235,787	219,509	234,184	–	–
Biomass oil	Tonne	204,293	217,397	208,340	219,290	234,184	–	–
Energy	Terajoule	8305	5481	5260	8093	40,276	7485	8142
Freshwater	10,000 tonnes	138,207	102,386	71,679	118,059	4791	1866	9223
GWP	Tonne CO_2-eq.	566,384	430,219	417,447	570,883	2,756,614	602,539	647,602
HTP	Tonne 1,4-dichlorobenzene eq.	11,584,047	5,426,562	5,920,674	8,441,050	14,222,412	24,740,478	8,925,107
FAETP	Tonne 1,4-dichlorobenzene eq.	1,205,481	558,859	615,000	871,386	1,437,457	2,459,580	911,559
MAETP	Tonne 1,4-dichlorobenzene eq.	233,000	108,780	119,084	169,432	284,414	496,285	281,919
TETP	Tonne 1,4-dichlorobenzene eq.	0.226	0.085	0.106	0.141	0.171	0.240	0.142
POCP	Tonne ethylene eq.	152	136	128	163	852	195	204
AP	Tonne SO_2-eq.	4393	3971	3721	4713	24,836	5664	5952
EP	Tonne PO_4-eq.	385	361	353	398	1,177	640	859
Solid wastes	10,000 tonnes	36.3	8.5	9.3	11.8	45.1	13.9	35.3

Notes: The abbreviations GWP, HTP, FAETP, MAETP, TETP, POCP, AP and EP indicated global warming potential, human toxicity potential, freshwater aquatic ecotoxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical oxidation potential, acidification potential, and eutrophication potential, respectively.



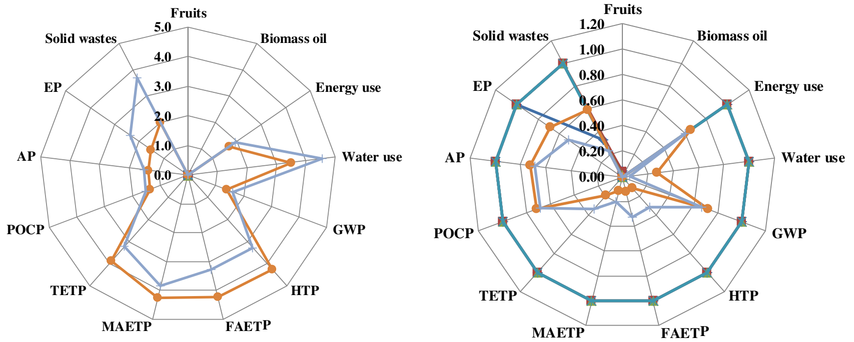
(a) Cultivation technology improves by 10%

(b) Oil extraction technology improves by 10%



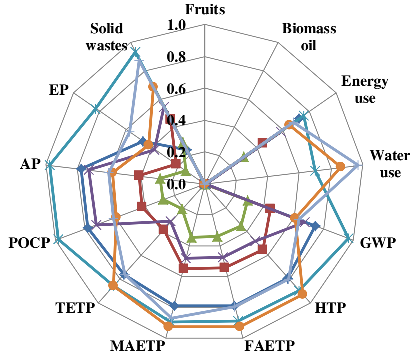
(c) Biodiesel production technology improves by 10%

(d) Removal technology of air emissions from biodiesel combustion improves by 10%



(e) Transportation costs decrease by 10%

(f) All factors in (a) to (e) improve by 10%



(g) Prices of intermediate inputs increase by 10%

Fig. 4. Sensitivity analysis of factors related to life cycle environmental impacts of biodiesel production. (a) Seven colored lines in Fig. (a)–(g) indicated seven categories of feedstocks, as shown in the following: ◆ Soybean; ■ Jatropha seed; ▲ Vegetable seed; ✕ Castor seed; ✳ Algae; ● Waste cooking oil; + Waste extraction oil. (b) The abbreviations GWP, HTP, FAETP, MAETP, TETP, POCP, AP and EP indicated global warming potential, human toxicity potential, freshwater aquatic ecotoxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical oxidation potential, acidification potential, and eutrophication potential, respectively. (c) Fig. (a), for example, showed that if cultivation technology improves by 10%, global warming potential of soybean-derived biodiesel will decrease by 7.2%. Fig. (g) shows that if material prices increase by 10%, global warming potential of jatropha seed-derived biodiesel will increase by 4.4%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

automobile catalytic converters (Fig. 4d, the reduction in parameters for sulfur dioxide, nitrogen oxides, soot, carbon dioxide, methane and dinitrogen oxide) had little effects on environmental impacts of biodiesel production. The reduction of transportation costs (Fig. 4e, the reduction in parameters for fruits transportation and oil transportation) had strong effects on environmental impacts reduction of biodiesel from waste cooking oil (13–43%) and waste extraction oil (15–46%), as transportation occupied a big position in life cycle environmental impacts of biodiesel from waste cooking oil and waste extraction oil. If technology and efficiency improvements in Fig. 4a–e were all implemented, they would have big positive effects on the reduction of life cycle environmental impacts of biodiesel production from all these feedstocks (Fig. 4f). Technology improvements in future work should mainly focus on identified key processes for various feedstocks.

Impacts of material prices on life cycle environmental impacts of biodiesel were also analyzed (Fig. 4g). Material prices had strong impacts on life cycle environmental impacts of soybean-derived, algae-derived, waste cooking oil-derived and waste extraction oil-derived biodiesel. However, impacts of material prices on environmental impacts of jatropha seed-derived, vegetable seed-derived and castor seed-derived biodiesel were smaller.

3.4. Policy implications

Currently, food security is an important issue in China. Soybean and vegetable seeds are food sources. Thus, vegetable seeds and soybean could not be used for biodiesel production in the short term. If food security problem was resolved in the long term, vegetable seed was preferred as one of biodiesel feedstocks. Moreover, technical levels in vegetable planting should be improved to effectively reduce life cycle environmental impacts of vegetable seed-derived biodiesel.

Land use of biofuel is concerned (Campbell and Block, 2010; Gopalakrishnan et al., 2009). China has limited arable lands. Although algae-derived biodiesel had larger life cycle environmental impacts, it had less arable land demands (Clarens et al., 2010; Sander and Murthy, 2010). Currently, algae-derived biodiesel had negative net economic benefits and negative net energy yields. According to previous studies (Clarens et al., 2010; Stephenson et al., 2010), technology improvements could change net energy yield of algae-derived biodiesel from negative into positive. Moreover, algae-derived biodiesel required less freshwater resources. Thus, algae-derived biodiesel could be regarded as a potential pathway in the long term. In addition, technology improvements in oil extraction and biodiesel production processes could reduce life cycle environmental impacts of algae-derived biodiesel most effectively. Chinese governments should provide financial subsidies for algae-derived biodiesel to reduce its economic costs which could further mitigate its life cycle environmental impacts (Fig. 4g). Algae-derived biodiesel, however, had large POCP, AP and EP (Table 1). Promoting algae-derived biodiesel in the long term should especially focus on potential environmental issues of POCP, AP and EP.

China's rapid socioeconomic development is producing more and more waste cooking oil and waste extraction oil. Waste oil did not compete with food production, and properly reusing it can resolve environmental problems. Currently, most of China's waste cooking oil is used for illegal cooking oil or animal feeding, potentially causing human health problems. According to results in this study, using waste cooking oil and waste extraction oil for biodiesel production had positive net energy yields and large positive net economic benefits. Thus, biodiesel production from waste cooking oil and waste extraction oil was regarded as a preferred pathway in China. Waste cooking oil-derived biodiesel, however, had large ecotoxicity potentials (comprising HTP, FAETP, MAETP and TETP). Thus, along with increasing utilization of waste cooking oil in the future, ecotoxicity potentials should also be particularly concerned. Moreover, technology improvements in biodiesel production process could effectively reduce life cycle environmental impacts of waste cooking oil-derived and waste extraction oil-derived biodiesel. Collection systems of waste cooking oil and waste extraction oil should also be improved to reduce their transportation costs, as the reduction of transportation costs could effectively reduce life cycle environmental impacts of biodiesel from waste cooking oil and waste extraction oil (Fig. 4e).

Life cycle environmental impacts of biodiesel from jatropha seeds and castor seeds were small. Net economic benefits and net energy yields of jatropha seed-derived and castor seed-derived biodiesel were positive. Moreover, marginal lands can be used to plant jatropha curcas and castor bean, which did not compete with food production. Thus, jatropha seeds and castor seeds were regarded as preferred feedstocks for biodiesel production in China. Jatropha seed-derived and castor seed-derived biodiesel, however, had larger freshwater demands. Water shortage is a serious problem for China. Thus, freshwater utilization levels of jatropha seed-derived and castor seed-derived biodiesel should be particularly concerned. Moreover, in order to effectively reduce life cycle environmental impacts of jatropha seed-derived and castor seed-derived biodiesel, technology improvements in feedstock plantation and biodiesel production processes should be promoted. In addition, the supply chain of jatropha curcas and castor bean should be optimized (Leão et al., 2011).

China is planning to levy resource tax and environmental tax to protect the natural environment. Resource tax and environmental tax would increase resource prices, which would further increase economic costs of biodiesel production. According to sensitivity analysis for material prices, financial subsidies should be provided to offset increasing economic costs of biodiesel production. This action could further reduce life cycle environmental impacts of biodiesel production.

In general, jatropha seed, castor seed, waste cooking oil and waste extraction oil were preferred feedstocks for biodiesel production in the short term, while algae were preferred feedstocks in the long term. Technical levels of key processes identified by sensitivity analysis should be improved. Moreover, collection systems of waste cooking oil and waste extraction oil should be improved to reduce their transportation costs. Financial subsidies should be provided to offset increasing economic costs, which will further mitigate life cycle environmental impacts. In addition, special attention should be paid to potential environmental problems: freshwater demands and ecotoxicity potentials in the short term, and POCP, AP and EP in the long term.

Findings in this study could provide foundations for biodiesel production in most of the world's countries. The MUIO-LCA model used in this study was based on direct requirement matrix of the EEIO table which reflected technical level of a particular economy. Technical level is the main factor influencing life cycle results of biodiesel production. Parameters for biodiesel production in the MUIO-LCA model are from recent international publications, which can be regarded as representations of current international technical levels.

4. Conclusions

Various feedstocks had different environmental performances. Jatropha seed, castor seed, waste cooking oil and waste extraction oil were preferred feedstocks for biodiesel production in the short term, while algae were preferred feedstocks in the long term. Collection systems of waste cooking oil and waste extraction oil should be improved to reduce their transportation costs. Financial subsidies should be provided to offset increasing costs. Technology development should focus on key processes identified by sensitivity analysis. Moreover, special attention should be paid to potential environmental problems accompanying feedstock selection: freshwater demands, ecotoxicity potentials, photochemical oxidation potential, acidification potential, and eutrophication potential.

Acknowledgements

The authors thank the support from the Major Program of National Philosophy and Social Science Foundation of China under Grant No.11&ZD045. M.X. acknowledges the support from the US National Science Foundation under Grant No. 1132581.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2012.11.037.

References

Wermelinger Sancho Araujo, V.K., Hamacher, S., Scavarda, L.F., 2010. Economic assessment of biodiesel production from waste frying oils. Bioresource Technology 101 (12), 4415–4422.

BP, 2012. BP Statistical Review of World Energy June 2012. BP.

Campbell, J.E., Block, E., 2010. Land-use and alternative bioenergy pathways for waste biomass. Environmental Science and Technology 44 (22), 8665–8669.

Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environmental Science and Technology 44 (5), 1813–1819.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W.J., Zhang, F., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. Journal of Experimental Botany 63 (1), 13–24.

Gopalakrishnan, G., Negri, M.C., Wang, M., Wu, M., Snyder, S.W., Lafreniere, L., 2009. Biofuels, land, and water: a systems approach to sustainability. Environmental Science and Technology 43 (15), 6094–6100.

Gregg, J.S., Andres, R.J., Marland, G., 2008. China: emissions pattern of the world leader in CO_2 emissions from fossil fuel consumption and cement production. Geophysical Research Letters 35 (8), L08806.

Haas, M.J., McAloon, A.J., Yee, W.C., Foglia, T.A., 2006. A process model to estimate biodiesel production costs. Bioresource Technology 97 (4), 671–678.

Hansen, S.B., Olsen, S.I., Ujang, Z., 2012. Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel. Bioresource Technology 104, 358–366.

Hawkins, T., Hendrickson, C., Higgins, C., Matthews, H.S., Suh, S., 2007. A mixed-unit input–output model for environmental life-cycle assessment and material flow analysis. Environmental Science and Technology 41 (3), 1024–1031.

Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M., Darzins, A., 2008. Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. The Plant Journal 54 (4), 621–639.

ISO, 2006. Environmental management – life cycle assessment – principles and framework, International Organization for Standardization.

Kumar, S., Singh, J., Nanoti, S.M., Garg, M.O., 2012. A comprehensive life cycle assessment (LCA) of Jatropha biodiesel production in India. Bioresource Technology 110, 723–729.

Leão, R.R.d.C.C., Hamacher, S., Oliveira, F., 2011. Optimization of biodiesel supply chains based on small farmers: a case study in Brazil. Bioresource Technology 102 (19), 8958–8963.

Liang, S., Zhang, T., Xu, Y., 2012a. Comparisons of four categories of waste recycling in China's paper industry based on physical input–output life-cycle assessment model. Waste Management 32 (3), 603–612.

Liang, S., Xu, M., Zhang, T., 2012b. Unintended consequences of bioethanol feedstock choice in China. Bioresource Technology 125, 312–317.

Lu, W., Zhang, T., 2010. Life-cycle implications of using crop residues for various energy demands in China. Environmental Science and Technology 44 (10), 4026–4032.

Luque, R., Lovett, J.C., Datta, B., Clancy, J., Campelo, J.M., Romero, A.A., 2010. Biodiesel as feasible petrol fuel replacement: a multidisciplinary overview. Energy and Environmental Science 3 (11), 1706–1721.

Malca, J., Freire, F., 2011. Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues. Renewable and Sustainable Energy Reviews 15 (1), 338–351.

Ragauskas, A.J., Williams, C.K., Davison, B.H., Britovsek, G., Cairney, J., Eckert, C.A., Frederick, W.J., Hallett, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R., Tschaplinski, T., 2006. The path forward for biofuels and biomaterials. Science 311 (5760), 484–489.

RGCECER, 2009. 2050 China energy and CO_2 emissions report. Research group on 2050 China energy and CO_2 emissions report. Industrial economic research departments, development research center of the state council; energy research institute, national development and reform commission; institute of nuclear and new energy technology, Tsinghua University.

Sander, K., Murthy, G.S., 2010. Life cycle analysis of algae biodiesel. International Journal of Life Cycle Assessment 15 (7), 704–714.

Scharlemann, J.P.W., Laurance, W.F., 2008. How green are biofuels? Science 319 (5859), 43–44.

Sims, R.E.H., Mabee, W., Saddler, J.N., Taylor, M., 2010. An overview of second generation biofuel technologies. Bioresource Technology 101 (6), 1570–1580.

Stephenson, A.L., Kazamia, E., Dennis, J.S., Howe, C.J., Scott, S.A., Smith, A.G., 2010. Life-cycle assessment of potential algal biodiesel production in the United Kingdom: a comparison of raceways and air-lift tubular bioreactors. Energy and Fuels 24, 4062–4077.

Wang, J., Chen, Y., Shao, X., Zhang, Y., Cao, Y., 2012. Land-use changes and policy dimension driving forces in China: present, trend and future. Land Use Policy 29 (4), 737–749.

Yang, H., Zhou, Y., Liu, J., 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. Energy Policy 37 (5), 1876–1885.

Yang, J., Xu, M., Zhang, X., Hu, Q., Sommerfeld, M., Chen, Y., 2011. Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresource Technology 102 (1), 159–165.

Zhang, Y., Dube, M.A., McLean, D.D., Kates, M., 2003. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. Bioresource Technology 90 (3), 229–240.

Zhang, X., Hu, Q., Sommerfeld, M., Puruhito, E., Chen, Y., 2010. Harvesting algal biomass for biofuels using ultrafiltration membranes. Bioresource Technology 101 (14), 5297–5304.

Zweig, D., Ye, S., 2008. A crisis is looming: China's energy challenge in the eyes of university students. Journal of Contemporary China 17 (55), 273–296.