Bioresource Technology 131 (2013) 139–145

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

# Waste oil derived biofuels in China bring brightness for global GHG mitigation

Sai Liang [a,*], Zhu Liu [b,c,*], Ming Xu [d,e], Tianzhu Zhang [a]

[a] School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China
[b] Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, United States
[e] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, United States

## HIGHLIGHTS

- ▶ Waste oil derived biofuels bring brightness for global GHG mitigation.
- ▶ GHG mitigation potential counted 28.8% and 14.7% of Annex B countries' efforts.
- ▶ Waste oil derived biofuel was an effective way to deal with aviation carbon tax.
- ▶ Supporting measures were discussed to solve bottlenecks.

## ARTICLE INFO

*Article history:*
Received 2 September 2012
Received in revised form 29 November 2012
Accepted 1 December 2012
Available online 12 December 2012

*Keywords:*
Biodiesel
Biofuels
China
Greenhouse gas
Waste oil

## ABSTRACT

This study proposed a novel way for global greenhouse gas reduction through reusing China's waste oil to produce biofuels. Life cycle greenhouse gas mitigation potential of aviation bio-kerosene and biodiesel derived from China's waste oil in 2010 was equivalent to approximately 28.8% and 14.7% of mitigation achievements on fossil-based $CO_2$ emissions by Annex B countries of the Kyoto Protocol in the period of 1990–2008, respectively. China's potential of producing biodiesel from waste oil in 2010 was equivalent to approximately 7.4% of China's fossil-based diesel usage in terms of energy. Potential of aviation bio-kerosene derived from waste oil could provide about 43.5% of China's aviation fuel demand in terms of energy. Sectors key to waste oil generation are identified from both production and consumption perspectives. Measures such as technology innovation, government supervision for waste oil collection and financial subsidies should be introduced to solve bottlenecks.



## 1. Introduction

China has been promoting the development of renewable energy since 2006. China first implemented the Renewable Energy Law in 2006, followed by the Medium and Long Term Renewable Energy Development Plan in 2007. In addition, China made the Eleventh and Twelfth Five-Year Plans for developing renewable energy sources in 2008 and 2012, respectively. Liquid biofuels are important components in these legal initiatives to promote renewable energy. Recently, China has published standards for biodiesel fuel blend in 2010 and technical requirements for biodiesel evaluation in 2011.

China is now experiencing a painful crisis of domestic food security. In addition to poisonous infant milk and dirty food production chains, illegal use of gutter oil has become another pressing issue threatening the health of Chinese consumers (Ramzy, 2011). Mostly illegally used for edible oil or animal feeding, gutter oil is often refined from leftover cooking oil that is either dredged from sewers or directly bought from restaurants. Given its food culture that heavily depends on oil for daily cooking, China generated as much as 2.73 times of gutter oil produced by European Union, the U.S., and Canada combined (Fig. 1). *TIME* reported that about 10% of China's cooking oil is from illegally used gutter oil (Ramzy, 2011) which threatens human health directly (such as causing liver cancer risk (Ramzy, 2011)) or indirectly through food supply chains (Cvengroš and Cvengrošová, 2004; Felizardo et al., 2006).

SkyNRG has succeeded in producing aviation biofuels from waste cooking oil. This represents a possible way for utilising China's gutter oil to achieve a win–win situation for both developing renewable energy and reducing illegal use of gutter oil in cooking.

* Corresponding authors. Tel.: +86 10 62794144; fax: +86 10 62796956.
*E-mail addresses:* liangsai09@gmail.com (S. Liang), liuzhu@iae.ac.cn (Z. Liu).

0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.12.008

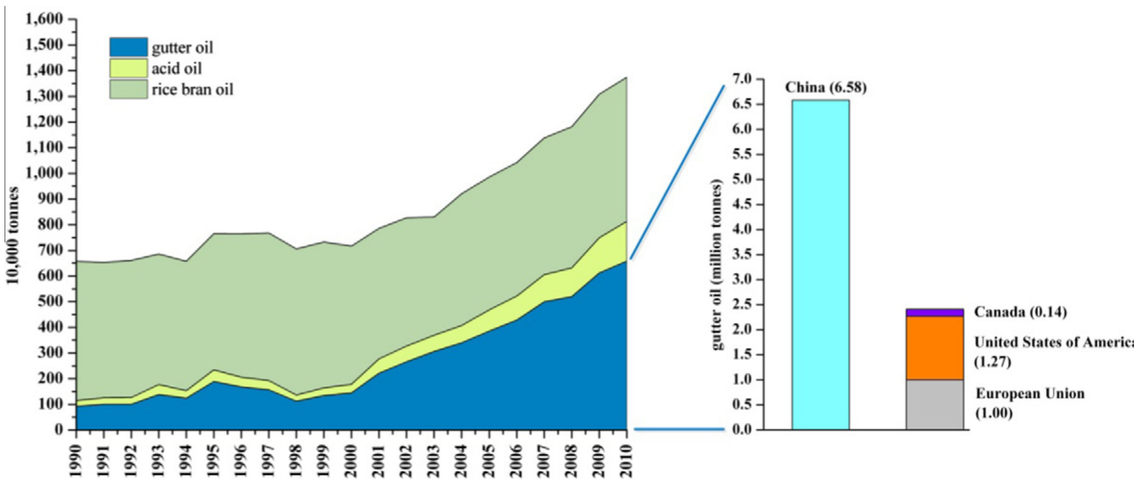


**Fig. 1.** China's potential supply of waste oil in the period of 1990–2010. Potential waste oil of the European Union was from Kulkarni and Dalai (2006), while that of the United States of America and Canada was calculated by their population ESA-UN (2011) multiplied by per capita gutter oil Chhetri et al. (2008).

China has become the world's top energy consumer (BP, 2012) and top $CO_2$ producer (Gregg et al., 2008). Over 20% of global primary energy supply is now consumed by China; yet renewable energy only accounts for less than 8% of China's primary energy supply (BP, 2012). Meanwhile, recycled waste oil – gutter oil and other waste oil – has shown significant potential being one of the main feedstocks for biofuel production (Pinto et al., 2005).

Studies have validated the feasibility of waste oil-derived biofuels (Chua et al., 2010; Kulkarni and Dalai, 2006; Kumaran et al., 2011; Ou et al., 2009; van Kasteren and Nisworo, 2007; Wermelinger Sancho Araujo et al., 2010; Zhang et al., 2003a,b). Previous studies have provided foundations for technology design at micro scale; but cannot fully support policy decisions at macro scale (such as directing future investment and technical development). There still lacks macro-scale research on potential magnitude of producing biofuels from waste oil including gutter oil and other waste oil. This study quantified potential supply of China's waste oil and the potential of waste oil-derived biofuels. It is the first time that the potential magnitudes of China's waste oil and waste oil-derived biofuels at macro scale are investigated. Moreover, this study examines sources and drivers of waste oil generation from both production and consumption perspectives. Waste oil in this study comprises gutter oil, acid oil, and rice bran oil.

## 2. Methodology and data

This study constructed the inventory of waste oil and analysed biofuel potential and relevant environmental benefits. Moreover, sources and drivers of waste oil generation were analysed from both production and consumption perspectives.

### 2.1. Quantifying potential supply of waste oil

Firstly, this study presented the analysis on potential supply of waste oil. The amount of gutter oil is equal to the amount of edible vegetable oil usage multiply with the scrap rate and availability rate. The amount of edible vegetable oil usage is equal to the sum of domestic production and imports less exports. Acid oil is the co-product from the production of edible vegetable oil and is calculated by multiplying the yield of edible vegetable oil with a generation factor. Rice bran oil is extracted from rice bran which is produced by rice processing. It is calculated by multiplying rice yield with a conversion factor. Detailed parameter values and data sources were shown in Supplementary Tables S1–S3.

### 2.2. Calculating biofuel potential from waste oil and relevant environmental benefit

Secondly, this study quantified biofuel potential from waste oil and relevant environmental benefit. Biofuel potential from waste oil is equal to the amount of waste oil multiplying with conversion factors. The difference of life cycle greenhouse gas (GHG) emissions between biofuels and the corresponding fossil-based counterparts is potential GHG offsets by biofuels. Detailed information was in Tables 1 and 2.

### 2.3. Analysing drivers of waste oil generation

This study analysed drivers of waste oil generation from both production and consumption perspectives. The production perspective describes the direct source generating waste oil, while

**Table 1**
Environmental parameters for fossil diesel and waste oil-derived vehicle biodiesel.

| Items | Units | Fossil diesel | Waste oil-derived vehicle biodiesel |
|---|---|---|---|
| Life cycle fossil fuel usage[a] | MJ/tonne[b] | 55,447.6 | 32,190.0 |
| Net energy yield[a] | MJ/tonne | −12,923.6 | 4,699.0 |
| Life cycle greenhouse gas emissions[a] | Tonne $CO_2$ equivalents/tonne | 4.4 | 2.8 |
| Calorific value[c] | MJ/tonne | 42,652 | 37,000 |
| Density[d] | Tonne/cubic metre | 0.840 | 0.840 |

[a] Life cycle fossil fuel usage, net energy yield and life cycle greenhouse gas emissions of fossil diesel and vehicle biodiesel were from Ou et al. (2009). Net energy yield is equal to energy yield minus life cycle fossil fuel usage. Energy yield is equivalent to calorific value of waste oil-derived vehicle biodiesel.
[b] The abbreviation MJ indicated million joules.
[c] Calorific value of fossil diesel was from *China Energy Statistical Yearbook 2011* NBS (1991–2011a), while that of vehicle biodiesel was from van Kasteren & Nisworo's study van Kasteren and Nisworo (2007).
[d] Fossil diesel density was from national standard *GB 19147–2009* SAC (2009). Biodiesel density came from the study of van Kasteren and Nisworo (2007).

**Table 2**
Environmental parameters for fossil aviation kerosene and waste oil-derived aviation bio-kerosene.

| Items | Units | Fossil aviation kerosene | Waste oil-derived aviation bio-kerosene |
|---|---|---|---|
| Life cycle greenhouse gas emissions[a] | Gram $CO_2$ equivalents/MJ | 86.0 | 8.6 |
| Calorific value[b] | MJ/tonne[c] | 43,070 | 44,000 |

[a] Life cycle greenhouse gas (GHG) emissions of fossil aviation kerosene were from The Boeing Company's study Kinder and Rahmes (2009). Life cycle GHG emissions of waste oil-derived aviation bio-kerosene were unavailable in previous studies. Life cycle stages of waste oil-derived aviation bio-kerosene comprised fuel production, transportation and fuel use. According to The Boeing Company's study Kinder and Rahmes (2009), GHG emissions from these three stages counted about 10% of life cycle GHG emissions of fossil aviation kerosene.
[b] Calorific value of fossil aviation kerosene came from *China Energy Statistical Yearbook 2011* NBS (1991–2011a). Calorific value of waste oil-derived aviation bio-kerosene was unavailable in previous studies. It is assumed to be the same as calorific value of camelina-derived aviation bio-kerosene, as shown in The Boeing Company's study Kinder and Rahmes (2009).
[c] The abbreviation MJ indicated million joules.

the consumption perspective illustrates the underlying drivers throughout the whole supply chains.

An input–output based life cycle assessment (IO-LCA) model is constructed to analyse drivers of waste oil generation from both production and consumption perspectives. There are row balances in the IO-LCA model, as expressed by Eq. (1). Detailed descriptions about these mathematical relationships could be found in Miller & Blair's book (Miller and Blair, 2009).

$$W = E(I - A)^{-1}y \quad (1)$$

Column vectors $y$ and $x$ indicate each sector's final demands and total outputs. The matrix W indicates material flows consumed or produced by sectors. The matrix E indicates each sector's magnitude of material flows per unit of its total output. The notation I indicates the identity matrix, and A represents the direct requirement coefficient matrix. The matrix $(I - A)^{-1}$ is named *Leontief inverse matrix* (Miller and Blair, 2009). Material flows from the production perspective and that from the consumption perspective are calculated by Eqs. 2 and 3.

$$\text{The production perspective} = E\hat{x} \quad (2)$$

$$\text{The consumption perspective} = E(I - A)^{-1}\hat{y} \quad (3)$$

There are also large transactions between residents and production (Miller and Blair, 2009) as well as between capital and production (Minx et al., 2011). Thus, traditional monetary input–output table (MIOT) is closed with respect to residents and capital. Residents and capital are treated as two activities of intermediate delivery matrix of MIOT, as shown in Table 3. Key sectors from the production and consumption perspectives are identified by using the hierarchical cluster analysis (HCA) method. Details about the HCA method can be found in previous studies (Liang et al., 2012c; Liang et al., 2012d).

Chinese 2007 monetary input–output table (MIOT) with 135 economic sectors (NBS, 2009) was used to construct input–output based life cycle assessment model. Waste oil was treated as physical multiplier of the MIOT. In Chinese 2007 MIOT, there is a column named "others" in final demands. This column is regarded as statistical error (Liang et al., 2013; 2012b; Liang and Zhang, 2011b; Peters et al., 2007). It is subtracted from final demands, and the MIOT is rebalanced according to its row and column balances. Moreover, Chinese 2007 MIOT is closed with respect to residents and capital (Table 3). Elements except for that from traditional 2007 MIOT are obtained from *2007 Fund Flow Statement* (physical transaction) of *China Statistical Yearbook 2010* (NBS, 1991–2011b). Finally, Chinese 2007 MIOT has 137 socio-economic activities (Table 4).

Waste oil is attributed by monitoring socio-economic activities where waste oil is produced (Liang and Zhang, 2011a). Acid oil is attributed to *Vegetable oil and forage*, and rice bran oil is attributed to *Grain mill products*. Gutter oil is from waste edible vegetable oil usage. It is attributed to 6 categories of socio-economic activities named *Convenient food*, *Liquid milk and dairy products*, *Spices and fermentation products*, *Other food manufacturing*, *Eating and drinking places* and *Residents*. Percentage of edible vegetable oil usage by each of these activities in total edible vegetable oil usage is calculated using transaction data between *Vegetable oil and forage* and these 6 categories of socio-economic activities from Chinese 2007 MIOT. Then, the magnitude of gutter oil produced by each of these activities is calculated by their percentage for edible vegetable oil usage multiplied by total gutter oil.

## 3. Results and discussion

### 3.1. Inventory analysis of potential supply of waste oil

Three categories of waste oil in China could be used for biofuel production: gutter oil, acid oil, and rice bran oil. China produced 13.74 million tonnes (Mt) of waste oil in 2010, including 6.58 Mt

**Table 3**
Closing monetary input–output table with respect to residents and capital.

| Inputs/ Outputs | Traditional economic sectors | Residents | Capital | Government consumption | Stock increments | Net exports | Total outputs |
|---|---|---|---|---|---|---|---|
| Traditional economic sectors | Intermediate delivery matrix of traditional MIOT | Residential consumption of traditional MIOT | Gross domestic fixed capital formation of traditional MIOT | Corresponding elements from traditional MIOT | | | Row sum |
| Residents | Labourers' remuneration of traditional MIOT | Zero | Capital gains of residents | Social welfare and government subsidy | Zero | Net foreign labourers' remuneration | Row sum |
| Capital | Depreciation of fixed assets of traditional MIOT | Household saving | Zero | Government saving | Zero | Net Foreign saving | Row sum |
| Other value added | Net taxes on production and operating surplus of traditional MIOT | Calculated by column balance | Calculated by column balance | | | | |
| Total inputs | Equal to total outputs | | | | | | |

**Table 4**
Final classification of economic sectors of Chinese input–output based life cycle assessment model.

| No. | Socio-economic activities | No. | Socio-economic activities |
|---|---|---|---|
| 1 | Crop cultivation | 70 | Chemical engineering, wood and non-metallic processing equipment |
| 2 | Forestry | 71 | Agriculture, forestry, animal husbandry and fishing machinery |
| 3 | Livestock and livestock products | 72 | Other special equipment |
| 4 | Fishery | 73 | Railroad transport equipment |
| 5 | Technical services for agriculture, forestry, livestock and fishing | 74 | Motor vehicles |
| 6 | Coal mining and processing | 75 | Ship building |
| 7 | Crude petroleum products and Natural gas products | 76 | Other transport machinery |
| 8 | Ferrous ore mining | 77 | Generators |
| 9 | Non-ferrous ore mining | 78 | Power transmission, distribution and control equipment |
| 10 | Non-metal minerals and other mining | 79 | Cable and electrical materials |
| 11 | Grain mill products | 80 | Household appliances |
| 12 | Feeding stuff production and processing | 81 | Other electric machinery and equipment |
| 13 | Vegetable oil and forage | 82 | Communication equipment |
| 14 | Sugar refining | 83 | Radar and broadcasting equipment |
| 15 | Slaughtering and meat processing | 84 | Electronic computer |
| 16 | Prepared fish and seafood | 85 | Electronic element and device |
| 17 | Other food processing | 86 | Household audio-visual equipment |
| 18 | Convenient food | 87 | Other electronic equipment |
| 19 | Liquid milk and dairy products | 88 | Instruments, metres and other measuring equipment |
| 20 | Spices and fermentation products | 89 | Cultural and office equipment |
| 21 | Other food manufacturing | 90 | Arts and crafts products and other manufacturing products |
| 22 | Wines, spirits and liquors | 91 | Scrap and waste |
| 23 | Non-alcoholic beverage | 92 | Electricity and heat power |
| 24 | Tobacco products | 93 | Gas production and supply |
| 25 | Cotton textiles | 94 | Water production and supply |
| 26 | woollen textiles | 95 | Construction |
| 27 | Hemp textiles | 96 | Railway transport |
| 28 | Other textiles not elsewhere classified | 97 | Highway transport |
| 29 | Knitted mills | 98 | Domestic public transport |
| 30 | Wearing apparel | 99 | Water transport |
| 31 | Leather, furs, down and related products | 100 | Air transport |
| 32 | Sawmills, fibreboard, and products of wood, bamboo, cane, palm, straw, etc. | 101 | Pipeline transport |
| 33 | Furniture | 102 | Handling and other transport |
| 34 | Paper and products | 103 | Warehousing |
| 35 | Printing and record medium reproduction | 104 | Post |
| 36 | Cultural goods, toys, sporting and athletic and recreation products | 105 | Telecommunication |
| 37 | Petroleum refining and nuclear fuel | 106 | Computer services |
| 38 | Coking | 107 | Software |
| 39 | Raw chemical materials | 108 | Wholesale and retail trade |
| 40 | Chemical fertilisers | 109 | Hotels |
| 41 | Chemical pesticides | 110 | Eating and drinking places |
| 42 | Chemicals for painting, dying and others | 111 | Finance |
| 43 | Synthetic chemicals | 112 | Insurance |
| 44 | Chemicals for special usages | 113 | Real estate |
| 45 | Chemical products for daily use | 114 | Leasehold |
| 46 | Medical and pharmaceutical products | 115 | Business services |
| 47 | Chemical fibres | 116 | Tourism |
| 48 | Rubber products | 117 | Scientific research and experiment |
| 49 | Plastic products | 118 | Special technical services |
| 50 | Cement, lime and plaster | 119 | Science & technology exchange and promotion services |
| 51 | Cement and plaster products | 120 | Geological prospecting |
| 52 | Brick, tile, stone and other building materials | 121 | Water conservancy |
| 53 | Glass and glass products | 122 | Environmental management |
| 54 | Ceramic | 123 | Public infrastructure management |
| 55 | Fireproof products | 124 | Resident services |
| 56 | Other non-metallic mineral products | 125 | Other services |
| 57 | Iron-smelting | 126 | Educational services |
| 58 | Steel-smelting | 127 | Health services |
| 59 | Steel-processing | 128 | Social security |
| 60 | Alloy iron smelting | 129 | Social welfare |
| 61 | Nonferrous metal smelting | 130 | News press |
| 62 | Nonferrous metal processing | 131 | Radio, television, film and audio–video |
| 63 | Metal products | 132 | Culture and arts |
| 64 | Boiler, engines and turbine | 133 | Sports |
| 65 | Metalworking machinery | 134 | Recreational services |
| 66 | Lifting transport equipment | 135 | Public administration and social organization |
| 67 | Pump, valve, compressor and similar machineries | 136 | Residents |
| 68 | Other general machinery | 137 | Capital |
| 69 | Mining, metallurgy and construction equipment | | |

of gutter oil, 1.55 Mt of acid oil, and 5.61 Mt of rice bran oil (Fig. 1 and Supplementary Table S1). After a two-decade increase, China's waste oil production in 2010 doubled the 1990 level. In particular, the production of gutter oil has sharply increased since 2000, probably due to increasing demand of edible vegetable oil as a result of improved life standard in China (NBS, 2011).

In 2010, China produced 6.58 Mt of gutter oil, roughly 2.73 times the total gutter oil production of European Union (EU), the U.S., and Canada (Fig. 1). In addition to the world's largest $CO_2$ producer, China now is also the world's largest gutter oil producer, posing a promising opportunity for producing biofuels using waste oil.

### 3.2. Biofuel potential and relevant environmental benefits

Waste oil can be used to produce both biodiesel and aviation bio-kerosene. China's waste oil in 2010 could potentially produce 12.49 Mt of biodiesel (Fig. 2), nearly two thirds of the global biodiesel production or 7.4% of China's fossil-based diesel consumption in 2010 (Fig. 4), and reduce 12.87 Mtce of GHG emissions from its life cycle (Fig. 3). Although the GHG reduction potential was equal to only 0.2% of China's total $CO_2$ emissions in 2010 (Guan et al., 2012), it was equivalent to 14.7% of mitigation achievements on fossil-based $CO_2$ emissions by the Kyoto Protocol Annex B countries during the period of 1990–2008 (Fig. 3).

As an alternative, China's waste oil could also produce 6.52 Mt of aviation bio-kerosene and 3.03 Mt of co-product biodiesel in 2010 (Fig. 2). Potential aviation bio-kerosene and co-product biodiesel could substitute 43.5% and 1.8% of China's fossil-based aviation kerosene and diesel in 2010, respectively (Fig. 4). Potential aviation bio-kerosene from waste oil in 2010 could meet 87.0% of mixture need of aviation fuel at the ratio of 50–50. Waste oil-derived aviation bio-kerosene and co-product biodiesel in 2010 could potentially reduce 22.19 million tonne $CO_2$ equivalents (Mtce) and 3.12 Mtce of GHG emissions, respectively (Fig. 3), equivalent to 54.5% of total $CO_2$ emission from China's aviation transportation in 2010. Moreover, it equalled to about 28.8% of mitigation achievements of the Kyoto Protocol Annex B countries during the period of 1990–2008 (Fig. 3).

### 3.3. Drivers of waste oil generation

Drivers of waste oil generation in China were analysed from both production and consumption perspectives. The production perspective describes the direct source producing waste oil, while the consumption perspective reflects underlying drivers throughout supply chains.

From the production perspective, eight categories of activities were direct sources producing waste oil (Fig. 5): grain mill products producing rice bran oil; vegetable oil and forage producing acid oil; and food manufacturing, eating and drinking services and residents producing gutter oil. From the consumption perspective, seven categories of activities were main underlying drivers of waste oil generation throughout supply chains (Fig. 5): knitted mills, wearing apparel, electronic computer, educational services, health services, public administration and residents. These seven categories of activities except for residents did not directly produce waste oil. However, their contribution accumulated throughout supply chains was big.

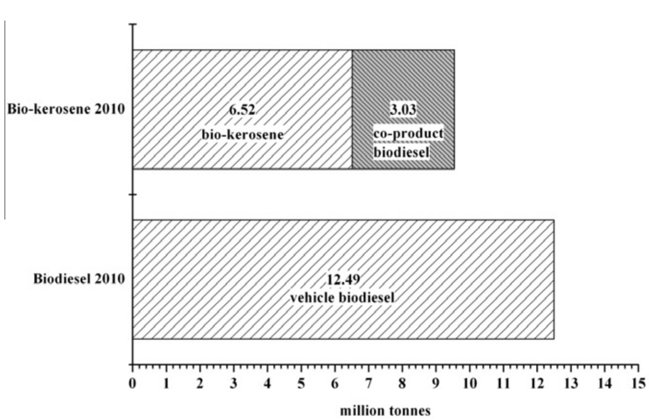


**Fig. 2.** China's biofuel potential in 2010.

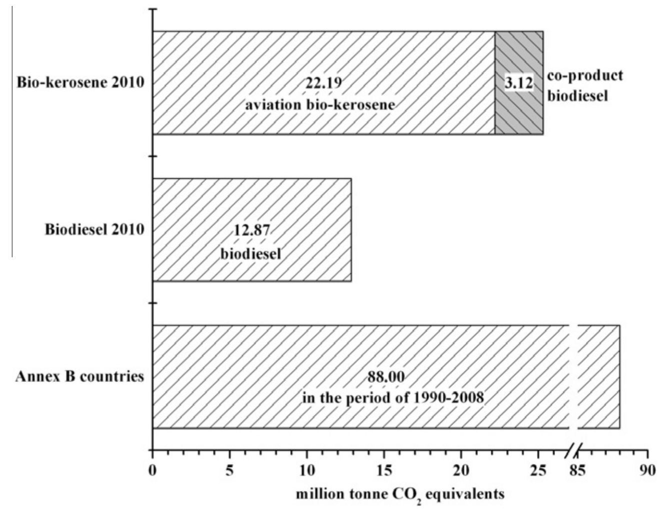


**Fig. 3.** Life cycle greenhouse gas mitigation potential of China's waste oil-derived biofuels in 2010.

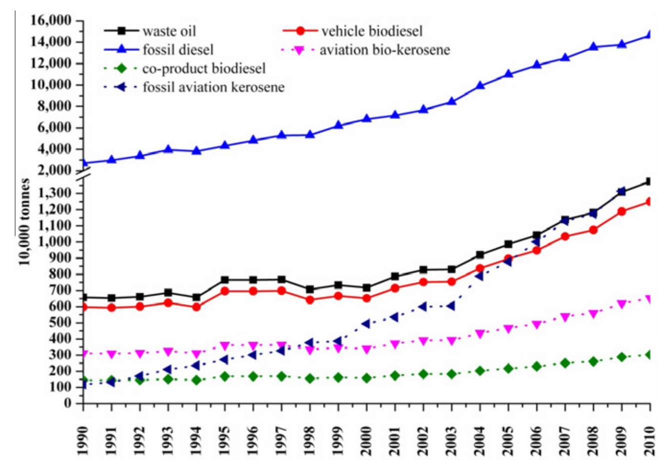


**Fig. 4.** Comparisons of fossil-based fuels with waste oil-derived biofuels in China. The dotted lines indicate the alternative way to using waste oil for vehicle biodiesel. Vehicle biodiesel means using biodiesel produced from waste oil for road transportation. Aviation bio-kerosene means using bio-kerosene produced from waste oil for air transportation, and co-product biodiesel is the co-product from the production of aviation bio-kerosene.

### 3.4. Policy implications

The potential of China's waste oil-derived biodiesel in 2010 already exceeded the demand of biodiesel in China given its 2–5% fuel blend mandate (SAC, 2010). But the potential of waste oil-derived biodiesel is so large that, even if China increases the biodiesel portion in the blend mandate up to 10% or 20%, it still can meet 74.1% or 37.0% of vehicle biodiesel demand, respectively. In addition, waste oil-derived bio-kerosene is also potentially an effective way to mitigate the increasing cost due to EU's newly established aviation carbon tax. Results showed that GHG mitigation potential of waste oil-derived bio-kerosene in China could save approximately 39.1% of the aviation carbon tax that Chinese airlines are supposedly paying.

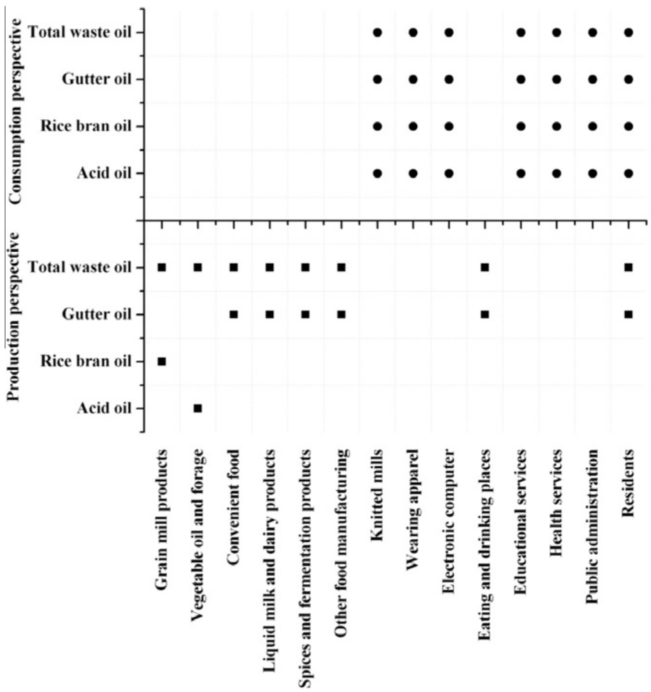


**Fig. 5.** Drivers of China's waste oil generation from both production and consumption perspectives.

Most encouraging of all, China is conducting pilots for vehicle biodiesel and aviation bio-kerosene production from waste oil, such as Qingdao City in Shandong Province. However, there are two bottlenecks for waste oil-derived biofuel: feedstock collection and production technology.

China's waste oil is mostly used for illegal purpose due to attractive economic profit, causing feedstock shortage for waste oil-derived biofuels. Solving this problem requires improvements on government supervision for legal collection of waste oil. Electrical inspect system for waste oil should be established, which can immediately supervise the flows of waste oil and reduce the opportunities for illegal collection. This action is feasible and China has been launching pilots in Shanghai and Beijing in recent years. In addition, illegal collection of waste oil usually has more economic profit than legal collection, as the investment in machinery and equipment for legal collection is much larger than that for illegal collection. Thus, governments should provide financial subsidies for legal collection of waste oil to increase the price of waste oil, which can make legal collection more competitive than illegal collection.

China's biofuel production is just in initial stage, and there are many gaps on production technologies between China and other countries such as the U.S., Canada, EU and Brazil. For instance, China's current conversion factor for waste oil-derived biodiesel is 90.9%, which is much lower than that (97%) of Canada (Zhang et al., 2003a). Thus, technology innovation and technology import are key issues and should be highly encouraged by financial incentives from Chinese governments. Moreover, economic profit of biodiesel has few advantages over that of fossil-based diesel (BEC, 2008), which may largely reduce the competitiveness of waste oil-derived biodiesel. Thus, Chinese governments should provide financial subsidy for waste oil-derived biodiesel and promulgate mandatory orders to use biodiesel in road transportation. In addition, nearly half of China's waste oil is gutter oil. The composition of gutter oil is more complex than foreign waste cooking oil. In order to use gutter oil as raw material for aviation bio-kerosene production, many pre-treatment processes such as filtration and extraction are needed to remove impurities of gutter oil. Those pre-treatment processes will increase economic costs of gutter oil-derived aviation bio-kerosene. Thus, financial subsidy should be provided to the production of gutter oil-derived aviation bio-kerosene. This measure could promote the production of gutter oil-derived aviation bio-kerosene. Besides biofuel potential of waste oil, potential environmental problem shifting in biofuel production should also be considered in policy decisions (Liang et al., in 2013; 2012b).

Using waste oil to produce biofuels belongs to end-of-pipe treatment. Source control of waste oil should also be concerned to reduce the generation magnitude of waste oil. For source control of waste oil, not only technical levels of 8 categories of key socio-economic activities identified from the production perspective should be improved, but also that of 6 categories of key activities identified from the consumption perspective should be optimised. This calls for the structure optimization of government consumption expenditure, inventory increments and international trades. This can efficiently control waste oil generation from the viewpoint of supply chains.

In general, producing biofuels from waste oil is an efficient way of improving food security and mitigating climate change impacts. Mitigating anthropogenic GHG emissions plays an important role in curbing human induced climate changes. Twenty years after the agreement of Kyoto Protocol, the world is still struggling for globally increasing GHG emissions. China's large waste oil potential brings brightness to meet China's increasing energy demand and reducing its soaring GHG emissions. This indicates a promising breakthrough for global anthropogenic GHG mitigation in the Post-Kyoto period. For source control of waste oil generation, technical levels of key sectors identified from both production and consumption perspectives should be improved. The increasing production of waste oil is a growing problem all around the world (Felizardo et al., 2006). Being the world's largest developing country and top reservoir of gutter oil, China's results can provide guidance for biofuel production from waste oil in other countries.

### 3.5. Uncertainty and recommendations

Uncertainties of results mainly came from parameters used for calculation. Currently, biofuel production in China is just in the initial stage and related parameters are mostly unavailable. These parameters used in this study were from published biofuel literatures and Chinese biofuel production companies, and they were regarded to be representative for current technical levels. The accuracy of parameters could be improved in future accompanying the rapid development of waste oil-derived biofuels.

In future studies, standard database for waste oil-derived biofuels should be established in China to provide more accurate parameters for scientific studies and industrial scale production. Moreover, studies on pre-treatment processes of gutter oil should be conducted to clear the road of producing aviation bio-kerosene from waste oil in future.

## 4. Conclusions

Life cycle GHG mitigation potential of aviation bio-kerosene and biodiesel derived from China's waste oil in 2010 was equivalent to approximately 28.8% and 14.7% of mitigation achievements on fossil-based $CO_2$ emissions by Annex B countries of the Kyoto Protocol in the period of 1990–2008, respectively. China's potential of producing biodiesel from waste oil in 2010 was equivalent to approximately 7.4% of China's fossil-based diesel usage. Potential of aviation bio-kerosene derived from waste oil could provide about 43.5% of China's aviation fuel demand. For source control of waste oil generation, key sectors were identified from both production and consumption perspectives.

## Acknowledgements

M.X. was supported by the U.S. National Science Foundation under Grant No. 1132581. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## 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.2012.12.008.

## References

BEC, 2008. Biodiesel: Economic cost analysis of biodiesel. BEC (http://www.bioenergy.cn).
BP, 2012. BP Statistical Review of World Energy June 2012. BP.
Chhetri, A., Watts, K., Islam, M., 2008. Waste cooking oil as an alternate feedstock for biodiesel production. Energies 1 (1), 3–18.
Chua, C., Lee, H., Low, J., 2010. Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore. The International Journal of Life Cycle Assessment 15 (4), 417–423.
Cvengroš, J., Cvengrošová, Z., 2004. Used frying oils and fats and their utilization in the production of methyl esters of higher fatty acids. Biomass and Bioenergy 27 (2), 173–181.
ESA-UN. 2011. World Population Prospects: The 2010 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat.
Felizardo, P., Neiva Correia, M.J., Raposo, I., Mendes, J.F., Berkemeier, R., Bordado, J.M., 2006. Production of biodiesel from waste frying oils. Waste Management 26 (5), 487–494.
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.
Guan, D., Liu, Z., Geng, Y., Lindner, S., Hubacek, K., 2012. The gigatonne gap in China's carbon dioxide inventories. Nature Climate Change 2 (9), 672–675.
Kinder, J.D., Rahmes, T. 2009. Evaluation of Bio-Derived Synthetic Paraffinic Kerosene (Bio-SPK). Sustainable Biofuels Research & Technology Program, The Boeing Company.
Kulkarni, M.G., Dalai, A.K., 2006. Waste cooking oil-an economical source for biodiesel: a review. Industrial & Engineering Chemistry Research 45 (9), 2901–2913.
Kumaran, P., Mazlini, N., Hussein, I., Nazrain, M., Khairul, M., 2011. Technical feasibility studies for Langkawi WCO (waste cooking oil) derived-biodiesel. Energy 36 (3), 1386–1393.
Liang, S., Xu, M., Zhang, T., 2013. Life cycle assessment of biodiesel production in China. Bioresource Technology 129, 72–77..
Liang, S., Xu, M., Zhang, T., 2012b. Unintended consequences of bioethanol feedstock choice in China. Bioresource Technology 125, 312–317.
Liang, S., Zhang, T., 2011a. Urban metabolism in china achieving dematerialization and decarbonization in Suzhou. Journal of Industrial Ecology 15 (3), 420–434.
Liang, S., Zhang, T., 2011b. What is driving $CO_2$ emissions in a typical manufacturing center of South China? The case of Jiangsu Province. Energy Policy 39 (11), 7078–7083.
Liang, S., Zhang, T., Jia, X., 2012c. Clustering economic sectors in China on a life cycle basis to achieve environmental sustainability. Frontiers of Environmental Science & Engineering, online. http://dx.doi.org/10.1007/s11783-012-0402-2.
Liang, S., Zhang, T., Wang, Y., Jia, X., 2012d. Sustainable urban materials management for air pollutants mitigation based on urban physical input–output model. Energy 42 (1), 387–392.
Miller, R.E., Blair, P.D., 2009. Input–output analysis: foundations and extensions, second ed. Cambridge University Press, Cambridge, UK.
Minx, J.C., Baiocchi, G., Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2011. A "carbonizing dragon": China's fast growing $Co_2$ emissions revisited. Environmental Science & Technology 45 (21), 9144–9153.
NBS, 2009. National Bureau of Statistics of China 2007. Input–Output Tables of China. China Statistics Press, Beijing.
NBS, 1991–2011a. National Bureau of Statistics of China. China Energy Statistical Yearbooks 1991–2011. China Statistics Press, Beijing.
NBS, 2011. National Bureau of Statistics of China. China Industry Economy Statistical Yearbook 2011. China Statistics Press, Beijing.
NBS, 1991–2011b. National Bureau of Statistics of China. China Statistical Yearbooks 1991–2011. China Statistics Press, Beijing.
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. Applied Energy 86 (1), S197–S208.
Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2007. China's growing $Co_2$ emissions: a race between increasing consumption and efficiency gains. Environmental Science & Technology 41 (17), 5939–5944.
Pinto, A.C., Guarieiro, L.L.N., Rezende, M.J.C., Ribeiro, N.M., Torres, E.A., Lopes, W.A., Pereira, P.A.D.P., Andrade, J.B.D., 2005. Biodiesel: an overview. Journal of the Brazilian Chemical Society 16, 1313–1330.
Ramzy, A., 2011. China Cracks Down on "Gutter Oil", a Substance Even Worse Than its Name. TIME, Hong Kong, China.
SAC, 2009. Automobile Diesel Fuels GB 19147–2009. Standardization Administration of China, Beijing.
SAC, 2010. Biodiesel Fuel Blend B5 GB/T 25199–2010. Standardization Administration of China, Beijing.
van Kasteren, J.M.N., Nisworo, A.P., 2007. A process model to estimate the cost of industrial scale biodiesel production from waste cooking oil by supercritical transesterification. Resources, Conservation and Recycling 50 (4), 442–458.
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.
Zhang, Y., Dubé, M.A., McLean, D.D., Kates, M., 2003a. Biodiesel production from waste cooking oil: 1. Process design and technological assessment. Bioresource Technology 89 (1), 1–16.
Zhang, Y., Dubé, M.A., McLean, D.D., Kates, M., 2003b. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. Bioresource Technology 90 (3), 229–240.