Science of the Total Environment 637–638 (2018) 1230–1240

Contents lists available at ScienceDirect

Science of the Total Environment

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

Preliminary economic assessment of the use of waste frying oils for biodiesel production in Beirut, Lebanon

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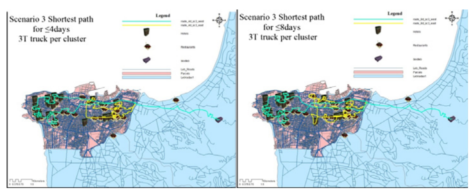
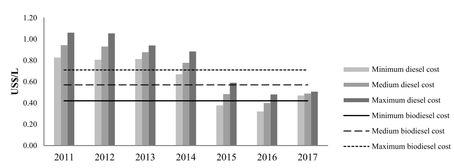
HIGHLIGHTS

- Restaurant and hotel enterprises revealed interest in WFOs supply chain participation.
- Quality biodiesel of 99.4% yield is produced via a one-step base catalyzed transesterification.
- The average of 81 scenarios of the total cost for the production of biodiesel from WFOs is US$/L 0.57 (CI = 0.42–0.71).
- Competitive petroleum diesel prices render the biodiesel production from WFOs an economically non-viable option.
- Biodiesel production from WFOs is a profitable option upon enforcement of low WFOs' acquisition costs.

GRAPHICAL ABSTRACT



Routing systems for the clustering scenario in Beirut at the different collection periods



Biodiesel costs compared with the Lebanese market price of diesel fuel

ARTICLE INFO

Article history:
Received 23 November 2017
Received in revised form 16 April 2018
Accepted 30 April 2018
Available online 15 May 2018

Editor: Simon Pollard

Keywords:
Biodiesel production
Waste frying oils
Economic assessment
Lebanon

ABSTRACT

In this study, a method for assessing the costs of biodiesel production from waste frying oils in Beirut, Lebanon, was investigated with the aim of developing an economic evaluation of this alternative. A hundred restaurant and hotel enterprises in Beirut were surveyed for promoting them in participating in the biodiesel supply chain, and for data collection on waste frying oils generation, disposal methods and frequency, and acquisition cost. Also, waste frying oils were collected and converted into biodiesel using a one-step base catalyzed transesterification process. Physicochemical characteristics of the produced biodiesel were conforming to international standards. Data produced from laboratory scale conversion of waste frying oils to biodiesel, as well as data collected from the only biodiesel plant in Lebanon was used to determine the production cost of biodiesel. Geographic Information System was used to propose a real-time vehicle routing model to establish the logistics costs associated with waste frying oils collection. Comparing scenarios of the configuration collection network of waste frying oils, and using medium-duty commercial vehicles for collection, a logistics cost of US$/L 0.08 was optimally reached. For the calculation of the total cost of biodiesel production, the minimum, average, and maximum values for the non-fixed cost variables were considered emerging 81 scenarios for possible biodiesel costs. These were compared with information on the commercialization of diesel in Lebanon for the years 2011 through 2017. Although competitive with petroleum diesel for years 2011 to 2014, the total biodiesel cost presented less tolerance to declining diesel prices in the recent years. Sensitivity analysis demonstrated that the acquisition cost of waste frying oils is the key factor affecting the overall cost of biodiesel production.

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https://doi.org/10.1016/j.scitotenv.2018.04.421

The results of this study validate the economic feasibility of waste frying oils' biodiesel production in the studied urban area upon enforcement of low waste frying oils' acquisition costs, and can help spur food service enterprises to become suppliers of biodiesel production feedstock and support a healthy development of the biodiesel industry in Lebanon.

1. Introduction

More and more countries around the world are turning towards renewable energies to use as resources. Research has confirmed the wisdom of these efforts, as many studies have shown that an increased use of intermittent renewable energy sources can reduce carbon emissions (Lund, 2007; Nelson, 2012; Solomon et al., 2014). Of these intermittent renewable energy sources, biomass is the most frequent form (McKendry, 2002; Uthman and Abdulkareem, 2014) and can be converted to other utilizable forms of energy like biofuels. And, among these biofuels, biodiesel is one of the leading potential alternatives to petroleum (Tan et al., 2011; Veiga et al., 2014).

The American Society for Testing and Materials (ASTM) defines biodiesel as monoalkyl esters of long chain fatty acids derived from a renewable lipid feedstock, such as vegetable oil or animal fat (ASTM D6751-12, 2014). Biodiesel has similar characteristics to fossil diesel fuel but with the added advantages of being non-toxic, readily biodegradable, and cleaner-burning than petroleum diesel (Noshadi et al., 2011; Wan Nor Nadyaini and Nor Aishah, 2011; Abuhabaya et al., 2013). Furthermore, biodiesel significantly diminishes the emission of harmful air pollutants including carbon monoxide, unburned hydrocarbons, particulate matter, and sulfur dioxide (OSWER, 2004). However, the biggest obstacle to biodiesel's commercialization is its high cost. Biodiesel produced from vegetable oil or animal fat is usually 10 to 50% more expensive than petroleum-based diesel fuel (Santori et al., 2012).

Nevertheless, cheaper biodiesel alternatives to raw vegetable oils have appeared, notably waste frying oils (WFOs), biodiesel feedstock that can efficiently reduce raw material charge (Shibasaki-Kitakawa et al., 2011). Even though the trade price of waste oils has recently risen in developing countries, WFOs remain lower-cost feedstocks, making biodiesel production more competitive with petroleum-based diesel fuel (Uzun et al., 2012). WFOs viability has been helped by the increased consumption of growing population in developing countries that produce ever-larger amounts of WFOs (CIA, 2011) and make the WFOs alternative especially attractive. Besides its economic appeal for decreasing reliance on imports of petroleum-based diesel and limited fuel resources, the use of WFOs in biodiesel production also contributes to reducing the amounts of WFOs being dumped into landfills and sewers (Sabudak and Yildiz, 2010).

Literature on biodiesel has focused on the optimization of biodiesel production processes from waste frying oil which involve the transesterification of oils by a short chain alcohol in the presence of a suitable catalyst (Fernando et al., 2007; Maceiras et al., 2009; Alves et al., 2013; Al-Hamamre and Yamin, 2014). Dias et al. (2008) compared the performance of different homogeneous alkali catalysts during the transesterification of waste and virgin oils. Sabudak and Yildiz (2010) added to Dias's work by performing a two-step acid-base catalyzed transesterification and comparing biodiesel yields. Uzun et al. (2012) determined the optimized reaction parameters by carrying out an alkali-catalyzed transesterification of WFOs under various conditions, permitting the investigation of the effects of catalyst type, catalyst concentration, reaction time, methanol/ethanol molar ratio, reaction temperature, and purification type on biodiesel yields.

On another note, many studies have analyzed the economic feasibility of producing biodiesel from WFOs. In South Africa, large-scale biodiesel productions were investigated based on a 2% blend with conventional diesel (Moodley, 2006). Small-scale, on-farm studies examined the potential of using biodiesel as an alternative local fuel (Pienaar and Brent, 2012). Patle et al. (2014) analyzed trade-offs between profit and heat duty, and profit and organic waste generated in two biodiesel production processes. They deduced that the profit improves with the increase in heat duty, and that the profit increase is accompanied by larger amounts of organic waste, the main contributor to these increases being the waste cooking oil flow rate. Araujo et al. (2010) proposed a method to evaluate the costs of biodiesel production from WFOs with the goal of assessing the economic feasibility of such an alternative. The method they used embraced a logistics perspective which proved to be relevant to the total biodiesel production cost. Valizadeh et al. (2014) proposed a method for improving the economic performance of biofuel supply chain in Malaysia and recommended that by incorporating uncertainties including feedstock demand, the biodiesel supply chain would be optimized. Mosarof et al. (2015), assessed the cost of biodiesel produced from palm oil by including the feedstock price, installation, operation, and maintenance costs of the biodiesel production plants, and by-products credit and concluded that economic prospects for the produced biodiesel are not yet promising due to factors such as production cost and fuel economy. Chanthawong and Dhakal (2016) contributed to the liquid biofuels' market analysis in illustrating import-export dynamics in Southeast Asian Countries in terms of policies and challenges.

This study aims at assessing the economic feasibility of biodiesel production from WFOs in the capital of Lebanon, Beirut, and uses data produced from laboratory scale conversion of WFOs to biodiesel, as well as data collected from the only biodiesel plant in Lebanon to determine the production cost of biodiesel. Data from 100 restaurants and hotels in Beirut aiming at evaluating WFOs generation and potential contribution of the food enterprises to the biodiesel supply chain was equally analyzed. This study presents an initial assessment of the economic feasibility of the implementation of biodiesel production at a large scale in Lebanon which was not addressed previously. Furthermore, the study proposes vehicle routing model scenarios to determine logistics network for the profitable reuse of WFOs in Beirut. The assessment of the economic feasibility of biodiesel production from WFOs allows a better understanding of cost interactions and acts as an initial ground for multiple actors such as government and WFOs and biodiesel producers, to jointly implement the recycling logistics system of WFOs in Beirut as well as in other cities.

2. Methodology

The study involved laboratory-scale biodiesel production, field research through visits, interviews, and the distribution of a structured questionnaire for data collection purposes from main WFOs producers including restaurants and hotels enterprises. The study also entailed the development of a vehicle routing model scenarios to determine logistics network for the profitable reuse of waste frying oil in Beirut.

2.1. WFOs collection

Fast food restaurants and hotels being the main sources of WFOs in Lebanon were chosen as the population. The sample included small, medium, large and chain restaurants and hotels in Lebanon's capital and most crowded city, Beirut. 36% of the enterprises had no >100 seats and 25% served >200 dinners per day. The types of food facilities ranged between ethnic, fast food, casual dining and fine dining. Structured questionnaires were carried out with the different restaurants and hotels to obtain information concerning how long is the oil used before it is disposed of, how much WFOs are generated, and for how much it is sold. In parallel, other interviews were performed with WFOs collection companies based in Lebanon and responsible for collecting and exporting the used oils for recycling outside Lebanon. All corresponding visits delivered entry data for the form of collection of the oil, the capacity and cost of the collecting vehicles, and the time taken to achieve the rounds. The only company that produces biodiesel from WFOs, currently operating in Lebanon was also interrogated. This last step produced information about large-scale production costs, including general expenses, equipment, manufacturing costs and fixed capital. The different restaurants and hotels visited were mapped and georeferenced through a Geographical Information System (GIS). The location of the only biodiesel company in the country was also added to the map, thus helping develop a vehicle routing model that finds the best WFOs transportation sequence to the operating plant, minimizing the impedance and optimizing the logistics cost.

2.1.1. Data collection

This paper opts for restaurant and hotel enterprises as the focuses for two reasons. First, the amount of WFOs produced by restaurants and hotels is much larger than that of families, giving a much more observable sample. Second, restaurants and hotels dispose of the WFOs in a more marketing approach. For these reasons, studying such subjects is more suitable to coordinate and manage a supply chain that helps in the establishment of the logistics cost and the WFOs acquisition cost. The capital of Lebanon, Beirut, was selected as the survey area since it holds a large number of restaurants and hotels. Over 70 restaurants and 30 hotels were surveyed. The return rate of the questionnaire was 87%. Descriptive statistics and graphics analysis were used to describe the basic features of the collected data including the quantity of vegetable oil consumed, WFOs disposal frequencies and methods, the willingness of the restaurants and hotels owners to cooperate in the WFOs supply chain, and the acquisition cost of WFOs. They formed the basis of the subsequent quantitative analysis for the assessment of the economic profitability of biodiesel production from WFOs in the study city, Beirut.

2.1.2. Questionnaire design

As a mechanism for obtaining information and opinion on WFOs commercialization and their potential use in biodiesel production, a structured questionnaire was designed to survey restaurants and hotels in the area of Beirut (Table S1 in Supplementary information). The designed questionnaire adopted in this study included questions regarding the generation and disposal of WFOs, the recycling approach and motives and the potential of the surveyed enterprises in participating in the WFOs supply chain for the production of biodiesel. The questionnaire covered basic information related to the seats number, the type of food served, the number of dinners per day, the types, amounts and costs of vegetable oil used, the period during which a batch of vegetable oil is used before disposal, the quantities and sale prices of WFOs produced, the methods of WFOs disposal, the awareness of WFOs recycling through biodiesel production, and the willingness to participate in the WFOs supply chain for biodiesel production. The questionnaire was also a mean to obtain WFOs samples in order to assess their biodiesel yield in the lab. The return rate of the sample collection was 22%. The physical appearance of the WFOs was examined at the time of the collection in order to confirm the information provided by the enterprises' owners towards the periods of use of the WFOs before they are discarded, and differentiate between minimally used batches versus more exhausted ones.

2.2. Biodiesel production

2.2.1. Reagents and chemicals

The reagents used during the synthesis and purification procedures were: methanol 99% (Fischer Scientific), potassium hydroxide capsules 95% (KOH, Aldrich), sulfuric acid 99% (H_2SO_4, Aldrich), anhydrous magnesium sulfate 70% ($MgSO_4$, Aldrich) and anhydrous sodium sulfate 99% (Na_2SO_4, Aldrich).

2.2.2. WFOs sampling and preparation

WFOs' sampling was conducted during the summer season over a period of 2 months extending from mid-June until mid-August. Samples were collected in 0.5 L amber glass bottles and were subsequently randomly mixed to prepare the oil feedstocks for biodiesel production. All WFOs batches were produced from the mixture of at least three different supply sources including WFOs of different quality (WFOs discarded after a maximum of 4 days of use and those used for a longer period, ranging between 5 and 8 days). A total of 21 batches were reconstituted and used for the biodiesel production.

2.2.3. Pretreatment and Transesterification

The prepared WFOs mixtures were first filtered (Whatman GF/A 90 mm Ø filter paper) to remove food residues. Most of the water was initially removed by gravity separation and the oil was then heated at 105–110 °C to remove any additional water until constant sample weight is reached. Next, the quality of WFOs mixture samples was examined by testing the acid values. For mixtures of WFOs containing a level of free fatty acids (FFAs) lower than 5% (0.94% to 3.56%), biodiesel synthesis was carried out via a one-step base catalyzed transesterification, following a modified method used by Dias et al. (2008). A defined amount of methanol (6:1 methanol/oil molar ratio) was pre-mixed with the KOH catalyst at a 0.75% of oil mass. The mixture of methanol and catalyst was then added to 200 g of WFOs preheated in a reactor at the reaction temperature (60 °C). The reactor consisted on a 1 L flat-bottom flask equipped with a magnetic stirrer. The reaction time was 1 h under stirring at 600 rpm.

For FFAs content higher than 5% (6.73%) which consisted of only 5% of the mixed WFOs samples mixed, the synthesis method was different. On these samples—which were of a visually poor quality and contained oil that had been used continually for a month, acid-catalyzed esterification was first carried out to ensure the conversion of FFAs to methyl esters. In this case a method by Inman (1945) was adopted. Briefly, methanol (77% of the weight of oil) and sulfuric acid (0.75% of the weight of oil) were added to the oil while stirring took place at 69 °C for 1 h. After neutralization, methanol (6:1 methanol/oil molar ratio) premixed with KOH (1.25% of the weight of oil) was added, and the mixture was stirred for an additional hour at 50 °C. The oil phase was analyzed and new FFAs average values of 2.7% were obtained. Since the fraction of oil mixtures with acid value higher than 5% was minimal (5% of the total oil mixtures prepared), it was disregarded from the study analysis and cost assessment of the biodiesel production was only based on the one step base catalyzed transesterification. This was deemed reasonable, as an initial step of acid esterification would erroneously increase the overall cost of the production and is unnecessary when considering the option of further decreasing the oil FFA content through mixing it with additional amount of oil of low acid values. Samples of mixed WFOs were prepared in duplicates for the transesterification reactions. For each sample, the experimental errors were determined for the different reaction parameters including reaction temperature and weight of used chemicals. An experimental error of <0.5% was obtained.

2.2.4. Purification

At the end of the transesterification reaction, products were left to settle in a decantation funnel for 1 h to ensure the separation of the mixture into two layers. The upper layer contained methyl esters, and the lower one consisted of glycerin, remaining catalyst, excess methanol, soaps formed and some drawn methyl esters. Lower concentrations of glycerin, catalyst and methanol were in the upper methyl ester phase.

The upper phase was washed firstly with an acid solution (0.2% H_2SO_4) and then repeatedly with distilled water (ratio of 1:1), until the pH of the washing water was the same as the distilled water. To remove unreacted glycerides and water, 2 g of magnesium sulfate ($MgSO_4$) were added at 35 °C for 45 min (Felizardo et al., 2006). Biodiesel was later dried over anhydrous sodium sulfate (Na_2SO_4) for 1 h under room temperature, and then filtered under reduced vacuum in order to obtain the purified biodiesel.

2.2.5. Biodiesel quality characterization

The characteristics of the final biodiesel product were determined according to the ASTM D 6751 and EN 14214 standard test methods, which include the acid value (ASTM D664), kinematic viscosity (ASTM D445), density (ASTM D4052), flash point (ASTM D93), and methyl ester content (EN 14103). Biodiesel samples were prepared in DCM. FAMEs concentration in biodiesel was determined according to the EN 14103:2011 method using an internal standard. The analysis was performed on a Trace Ultragas chromatogram equipped with a flame ionization detector and an HP-INNOWAX capillary column (30 m × 250 μm × 0.25 μm). The flow rate of helium carrier gas was 1 mL/min. The split flow rate was equal to 100 mL/min, the inlet temperature was held at 320 °C and the flame temperature was 250 °C. The sample injection volume was 1 μL. The oven temperature program was as follows: start at 60 °C (2 min), ramp at 10 °C/min to 200 °C (0 min), ramp at 5 °C/min to 240 °C (7 min).

2.3. Assessment of economic feasibility of biodiesel production

To assess the production feasibility of biodiesel from WFOs, several cost categories were investigated. These were: acquisition cost of the WFOs depending on source, logistics cost incurred in the WFOs collection, inputs cost counting the different reagents and chemicals used for the production of biodiesel as determined through the laboratory scale transesterification reactions, production costs considering general expenses, equipment and fixed capital at the scale of plant capacity as per the data provided by the only biodiesel plant in Lebanon, and finally labor and taxes costs.

3. Results and discussion

3.1. Production

Product yield is defined as mass percentage of final product transesterified and purified relative to the initial mass of WFOs introduced into transesterification. For the mixtures of WFOs containing a level of FFAs higher than 5%, the acid-base transesterification resulted in a final yield of biodiesel ranging between 19.1 and 35% (w/w). Much higher yields were obtained in the case of the one-step base catalyzed transesterification and ranged between 96.9 and 99.4% (w/w). Considering the very low yield and negligible fraction of the oil mixtures with FFA levels higher than 5%, this fraction was not included in any further analysis and only the one-step base catalyzed transesterification was considered in the assessment of biodiesel production cost.

3.2. Characterization of biodiesel

The physico-chemical properties of the biodiesel samples produced through a one-step base catalyzed transesterification were determined and are presented in Table 1. Triplicate analysis was performed in each case and the average results were reported. All reported parameters are in accordance with ASTM D6751 and EN 14214 standards except for the acid value. The latter exceeds the limits. In fact, 85% of the biodiesel samples showed an acid value ranging between 0.1 and 0.4 mg KOH/g, and

Table 1
Physical and chemical properties of the biodiesel produced from WFOs.

Property	Value	Limits (EN 14214)	Limits (ASTM D6751)
Acid value (mg KOH/g)	0.1–0.65	0.5	0.5
Kinematic viscosity at 40 °C (mm^2/s)	4.21–4.78	3.5–5.0	–
Density at 15 °C (g/cm^3)	0.886–0.891	0.860–0.900	0.860–0.900
Flash point (°C)	165–178	–	130
Water content (% w/w)	0.02–0.04	0.05	–
Potassium content (mg/kg)	1.7–3.9	–	5
Sulfated ash (%)	0.006–0.017	0.02	0.02
Ester content of FAME (% w/w)	96.9–99.4	96.5	96.5

95% of these samples exhibited acid values between 0.1 and 0.25 mg KOH/g. The remaining 15% recorded an acid value slightly higher than 0.5 mg KOH/g (0.55 to 0.65 mg KOH/g).

The produced biodiesel characteristics agree with the Standard Specifications for Biodiesel Fuel. High levels of free fatty acids will influence fuel aging (Felizardo et al., 2006; Predojevic, 2008) and affect biodiesel stability (Dias et al., 2008). 85% of the samples showed an acid value lower than the limit, with values ranging from 0.1 to 0.4 mg KOH/g. For all analyzed samples, flash point was much higher than the minimum standard limit. Values ranged from 165 to 178 °C. These high values indicate the recovery of excess methanol and safety in handling and storage (Srivastava and Verma, 2008; Encinar et al., 2007). High yields of FAME (96.9%–99.4%) obtained prevent carbon deposition that lead to negative impacts on fuel injector performance allowing fuel atomization and distribution in the engine (Meher et al., 2006). FAME yields are very much related to the viscosity and density which serve as indicators of the completeness of the transesterification reaction and which are in compliance with the ASTM and European Biodiesel Standard (De Filippis et al., 2005; Felizardo et al., 2006).

3.3. Analysis of the questionnaire

Data generated from the questionnaire was gathered for a typical working week. Among the surveyed facilities, the average weekly generation of WFOs was 70 kg/week/restaurant (variance = 45.832). Fig. 1a describes the quantity of edible oils consumed per week by the surveyed restaurants and hotels. It indicates that 43% of all enterprises use >90 kg/week/restaurant of edible oil of different types. Fig. 1b presents the disposal method of WFOs by the different surveyed restaurants and hotel enterprises. Among the facilities, 9% disposed of WFOs once per day. The largest amount (79%) of enterprises disposed of the WFOs by a frequency of 1–4 days, while 18% of the facilities changed their frying oil with a fresh one every 5–8 days. The survey showed that WFOs recycling was quite high, whereby 87% of the facilities sell the used oil for economic benefits with little or no knowledge of its fate. The main buyers were independent venders, companies that export WFOs for biodiesel production outside Lebanon, or the biodiesel production plant currently operating in Lebanon (Fig. 1c). After putting a slight effort into providing the restaurants and hotels facilities with an understanding about the significance and the motives behind recycling WFOs for biodiesel production, a total of 76% of restaurants and hotels enterprises expressed willingness to cooperate with biodiesel manufacturers (Fig. 1d). The willingness rate was accompanied with two main cooperation demands, summarized in a door-to-door collection service and a sensible WFOs selling price.

3.4. Formation of the logistics costs

Logistics cost is of relevance to the total biodiesel production cost. WFOs need to be collected from the various supply sources that are geographically widespread, requiring planned collection. The cost of collection of WFOs from restaurants and hotels and its delivery to the biodiesel production plant should be embraced since the results

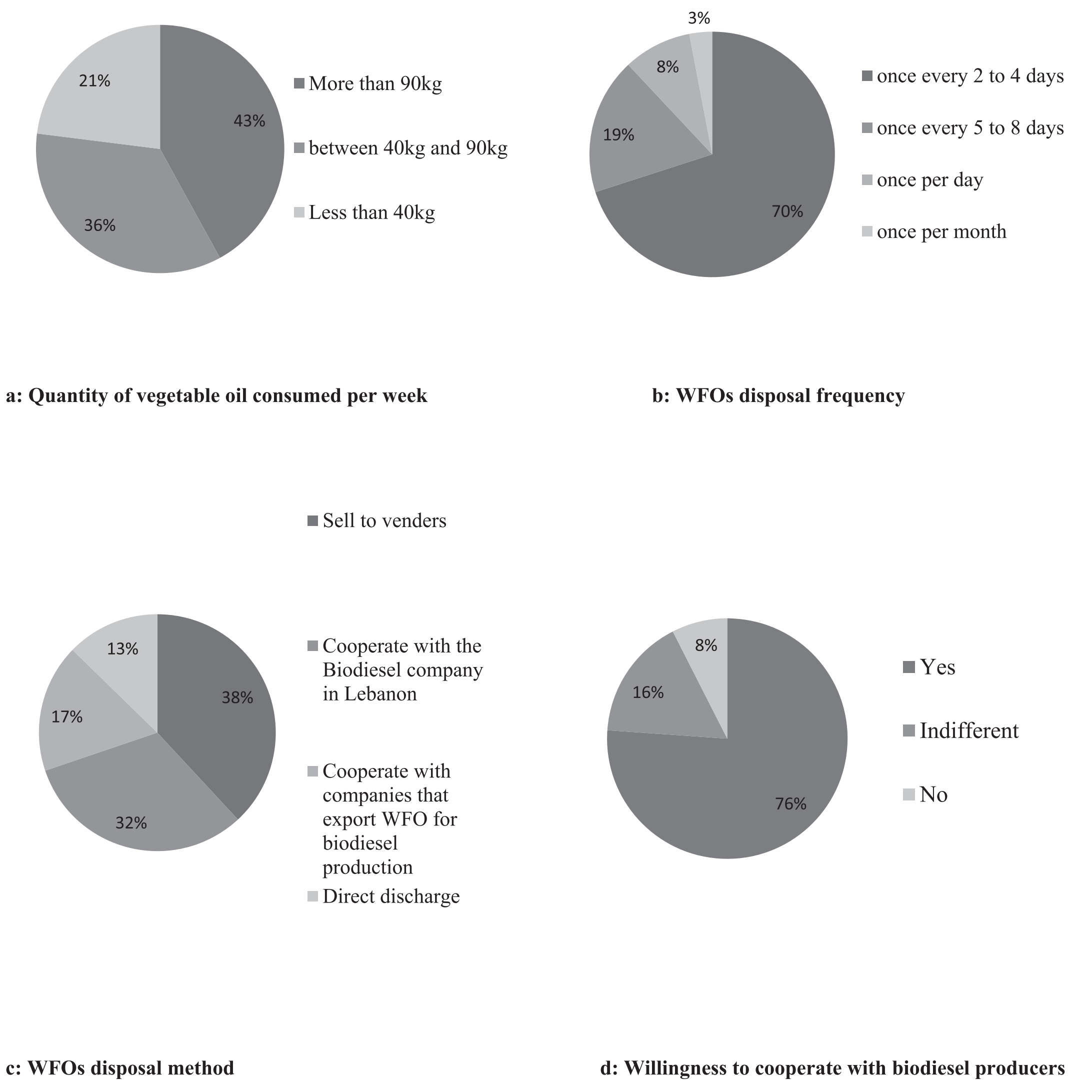

Fig. 1. Questionnaire data per typical working week.

obtained partially demonstrate the economic viability of biodiesel production from WFOs. To determine the logistics cost, different routing scenarios were developed, tested and compared based on the information acquired from the survey. The logistics cost per liter was calculated as the ratio of the total collection cost to the total volume of oil collected.

Upon conducting the survey in 100 restaurants and hotels in Beirut city, two major categories were strongly noted among the enterprises. 79% of the enterprises renew the frying oil they use every 4 days or less, while 19% of the enterprises replace the frying oil they use with fresh vegetable oil every 5 to 8 days. A very limited number of hotels change the frying oil used once every month. Since the amount of oil disposed of counted for only 0.03% of the total volume of oil, these corresponding hotels were no longer reckoned as collection points for the transportation design.

The assumptions for truck fuel was given a fixed cost of fleet of 0.2 $/km. The average driving speed for trucks in the city was set at 40 km/h and the fixed cost per vehicle adopted was $ 7.76/h, justifying the labor cost of the driver (owner of the truck) and his assistant. The regular working time for the driver and his assistant was calculated at 10 h including the unloading time at the biodiesel production plant and the lunch-break. Justifiable over-times (traffic, unexpected events like accidents, and need for repair) were given an hourly rate of $ 8.7. Each enterprise was estimated to be visited once during a collection event and every visit calls for 10 min between the collections of WFOs and receipts.

To decide for the truck capacity, the total amount of WFOs from the hotels and restaurants were added accounting for a weight of 2 kg for each empty 20 L-container (Table 2).

A stationary collection system designed to gather WFOs stocks twice every 8 days. This system created separate collection times/routes/clusters for hotels and restaurants with similar WFOs disposal periods whereby the truck travels to and from the biodiesel production plant

Table 2
Determination of vehicle capacity based on the suggested collection scenarios.

Parameters	Scenario 1		Scenario 2			Scenario 3			
WFOs collection	≤4 days	≤8 days	≤4 days	≤8 days		≤4 days		≤8 days	
Clusters	–	–	–	–		East	West	East	West
Amount of oil to collect (kg)	3851	4553	3851	3851	744	2423	1950	2632	2311
Weight of empty gallons (kg)	426	504	426	426	82	268	216	290	256
Total weight (kg)	4277	5057	4277	4277	826	2691	2166	2922	2567
Vehicle capacity (t)	6	6	5	5	1	3	3	3	3
Number of vehicles	1		2			2			

when fully loaded from the multiple collection points. The first collection was scheduled on day 4 of the 8 day period and was geared to amass the WFOs from enterprises that changed the frying oil every 4 days or less; the second collection was planned for 4 days after the first collection to collect the WFOs generated from all restaurants and hotels including those that renew their oil every 4 days or less, having generated new stocks of WFOs.

Three scenarios were adopted, in which collection points were organized according to the categories discussed above and for which a routing system was created (available in Supplementary information). Scenario 1 describes the collection of the WFOs twice every 8 days from the restaurants and hotels by the same truck of 6 t capacity (Fig. S1a). Scenario 2 defines the collection of WFOs by 1 vehicle of 5 t for the first collection and by two trucks of 5 t and 1 t capacity respectively during the second collection (Fig. S1b). Having observed that the different collection points could be easily separated into zones, Scenario 3 was chosen to proceed with the clustering technique which represents two different regions of Beirut: East zone and West zone. Each zone will be visited by a vehicle of 3 t each collection day (Fig. S2c).

Real distances were then generated on GIS which allowed the acquisition of the total travelling time, the cost per distance travelled, the driver's salary per operational day and the total cost per year for each scenario (Table 3).

The development and testing of the different scenarios for vehicle routing permitted the comparison between these to determine the realistic WFOs collection routine with optimized logistics cost attached.

Logistics cost per liter is the ratio of the total collection cost to the total volume of oil collected twice every 8 days. The data corresponds to the collection for a typical year. The results show that the logistics cost for Scenarios 1 and 3 are similar. The increased distance in Scenario 3 is compensated by the total cost as the driver does not work for extra hours. Therefore, no extra fees beyond the 10 working hours are charged. Furthermore, the number of hours that the driver would need to satisfy in the event of driving a 6 t vehicle, is 5 to 8 h beyond the 10 working hours. Such a scenario is not favored considering the appropriate and ethical working hours limit of any worker on one hand, and the means of being able to cover all the restaurants and hotels enterprises within opening hours on the other hand. In Scenario 2 the same vehicle of 5 t goes through the same routing system during the two collections. All the restaurants and hotels enterprises that change the frying oil every 5 to 8 days were grouped to be visited by a 1 t capacity vehicle. With this alternative, the logistics cost increased to 0.09 $/L of WFOs collected. Compared to the two other scenarios, scenario 3 presents results which show that the oil collected per vehicle is specially convenient to the maximum capacity of the vehicle (3 t), much as the number of hours consumed that is within the 10 h working period, which demands no extra fee from the production plant. Therefore, clustering seems to optimize the commutation between cost and vehicle capacity. Taking scenario 3 into consideration, a possible variation in the agreement upon the amounts of WFOs supplied should be recognized. The offers are flexible enough to accommodate a variation of 25% accounting for tourism, seasonal flows, and holidays. A logistics cost increase to 0.10 $/L of WFOs collected follows a decrease of 25% of the quantity of the WFOs offered (6654 L every 8 days). That is mostly due to the shortage in the vehicles capacity filling. Whereas, in the case of an increase of 25% (13,820 L every 8 days), the logistics cost drops to 0.06 $/L of WFOs collected and the weight surcharge can be filled into the 3 t vehicles when well distributed.

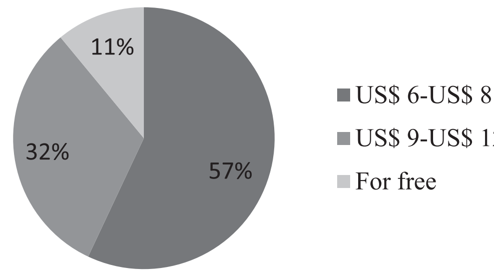

Fig. 2. WFOs acquisition cost per 20 L WFOs.

3.5. Calculation of total cost

The final cost of large-scale biodiesel production from WFOs factors in the cost of acquiring the WFOs, the logistics cost incurred in WFOs collection, the cost of the different reagents and chemicals used for the production of biodiesel, production costs that include general expenses, equipment and fixed capital at the scale of a plant capacity, and finally labor and taxes costs. Logistics costs related to the distribution of the produced biodiesel to retail outlets were not included in the overall biodiesel costs as the studied biodiesel plant uses the ex-works method for the distribution of the end product.

3.5.1. Acquisition cost of WFOs

Large scale biodiesel production industries encounter some difficulties concerning raw material, among which is the unreliability of supplies (Pan et al., 2010; Zhang et al., 2012). Findings in the field, state that the solution to this problem is to improve WFOs supply chain coordination and reduce the cost of WFOs supply (Zhang et al., 2009).

Fig. 2 presents the acquisition cost of 20 L of WFOs (standard volume of the commonly used liquid storage container is 20 L). The average acquisition price of 1 L of WFO was found to be US$ 0.35 with a standard deviation of 0.05.

Table 3
Total logistics cost per year for the different scenarios generated.

Parameters	Scenario 1		Scenario 2			Scenario 3			
	Generation of WFO ≤ 4 days	Generation of WFO ≤ 8 days	Generation of WFO ≤ 4 days	Generation of WFO ≤ 8 days		Generation of WFO ≤ 4 days		Generation of WFO ≤ 8 days	
Cluster	–	–	–	–	–	East zone	West zone	East zone	West zone
Number of enterprises	64	79	64	64	15	31	33	38	41
Vehicle capacity (t)	6	6	5	5	1	3	3	3	3
Total distance travelled (km)	61.20	66.51	61.20	61.20	40.58	38.85	44.25	45.20	48.21
Total travelling time (h)	15.41	18.09	15.41	15.41	6.56	8.24	8.72	9.59	10.18
Fixed fleet cost per distance ($/km)	12.24	13.30	12.24	12.24	8.12	7.77	8.85	9.04	9.64
Driver's salary per operational day ($/day)	113.77	137.08	113.77	113.77	66.70	66.70	66.70	66.70	68.27
Total cost per operational day ($/day)	126.01	150.38	126.01	126.01	74.82	74.47	75.55	75.74	77.91
Total cost including maintenance ($/year)	35,172.28		37,795.60			36,600.75			
Logistics cost ($/L)	0.08		0.09			0.08			

Table 4
Total fixed and varied costs for biodiesel production from WFOs.

	Logistics	Acquisition	Production	Methanol	Catalyst	Labor	Taxes	Glycerin + FA
Minimum cost (US$/L)	0.06	0.30	0.15	0.11	0.00083	0.12	0.10	−0.40
Medium cost (US$/L)	0.08	0.35	0.20	0.12				
Maximum cost (US$/L)	0.10	0.40	0.25	0.13				

3.5.2. Capital, manufacturing and chemicals' cost

The present cost will take into account the capital cost, the equipment cost including material for WFOs transesterification and biodiesel purification, the maintenance cost, and the cost of production loss. It will be called production cost. Plant capacity is an important factor affecting production processes as well as the catalyst choice. Marchetti and Errazu (2008) studied a biodiesel plant of 36,036 t/year capacity that uses an acid catalyst pretreatment process before the alkali base transesterification. The production cost of such a plant turned out to be 0.31 US$/L. On the other hand, Bender (1999) studied a much larger biodiesel production plant (one that employs an alkali-catalyst), of 115,000 t/year capacity. The production cost there turned out to be 0.10 US$/L. In the present study, the production procedure for collected WFO did not need any acid catalyst pretreatment. Therefore, additional equipment costs related to acid transesterification were omitted. The choice of alkali catalyst was validated by the Lebanese biodiesel production plant we interviewed. This biodiesel production plant is a medium scale plant of 4000 t/year capacity whose average production cost per liter of biodiesel is 0.20 US$/L (standard deviation = 0.05 US$/L).

For the tansesterification process to be established, the inputs adopted were the WFOs, alcohol and catalyst. For 100% biodiesel produced the technical coefficients of the different inputs to the production procedure were considered. Methanol was adopted at 20% consumption by volume and the catalyst, at 0.75% consumption by mass.

The methanol cost is based on the purchase price provided by the Lebanese biodiesel plant. The resulting average price was US$/L 0.60 with a standard deviation of 0.05. The catalyst cost adopted in the research was US$/L 0.11 with a standard deviation of 0.01. Therefore, involving the acquisition of methanol and catalyst, for each biodiesel liter produced, there is an average cost of US$ 0.12 (standard deviation = 0.01 US$/L) and US$ 0.00083.

3.5.3. Labor cost and utility and taxes costs

For the 4000 t/year biodiesel plant operating in Lebanon, a total of 6 operators including 5 technical operators and 1 chemical operator, are employed. Since the production process is continuous and fully automated, it requires less supervision and therefore, the labor cost remains the same even when the plant capacity increases. The production plant consists of six total operators. Five technical operators are paid a total monthly salary of US$ 2500 and one chemical operator is satisfied a salary of US$/month 2000. Based on the operators' monthly salaries, the study found that for each biodiesel liter produced, there is a labor cost of US$/L 0.12.

Utility and taxes costs include value-added tax, city tax, security tax, electricity costs and insurance which add a total of US$/L 0.10 biodiesel produced. The source for this information was also the biodiesel plant.

3.5.4. Glycerin and FAEs credit

Glycerin is generated as a co-product of the transesterification reaction. It has many applications in the pharmaceutical, food and chemical industries (Dhar and Kirtania, 2010). The process used to purify crude glycerin is composed of methanol removal, neutralization, distillation and bleaching (Van Gerpen et al., 2004; Xiao et al., 2013). The income from the sale of glycerin was considered in the calculation of the total cost and provided by the biodiesel production plant. A high total value of US$/L 0.10 of glycerin produced is what is currently marketed by the biodiesel plant to different companies. The glycerin acidification process separates the crude glycerin into three layers of FAEs on the top, glycerin rich layer in the middle and inorganic salts at the bottom (Hájek and Skopal, 2010; Tianfeng et al., 2013). Fatty acids' esters (FAEs) are a high priced product that can be used as lubricant of tablets (Aoshima et al., 2005). According to the biodiesel plant, the net benefit from FAEs produced by the purification of glycerin is US$/L 0.30.

3.5.5. Biodiesel cost calculation and analysis

The main variables for the calculation of the cost of biodiesel from WFOs are the inputs used in the process of biodiesel production, taxes, and the logistics costs. The income from glycerin and FAEs is also considered in this calculation. As the values for most of the variables can vary, the calculation was done based on all possible combinations of the three different values for the logistics, WFOs acquisition, biodiesel production and methanol costs, yielding $3^4 = 81$ scenarios. The three values used for each variable represent a minimum, average and maximum cost based on the numbers obtained above. The optimum logistics values obtained for the clustered scenario were considered as the logistics costs. As the labor, taxes and the glycerin costs are assumed fixed and the catalyzer cost is not significant in the total cost composition, variations of these variables were not considered in the biodiesel total cost analysis. The minimum, average and maximum values of the variables used in the establishment of the cost of biodiesel are summarized in Table 4.

Fig. 3 presents the results for the total biodiesel cost obtained from the different 81 generated scenarios. The average biodiesel cost of the different scenarios is US$/L 0.57. The cost can drop to US$/L 0.42 in the best case scenario and rise to US$/L 0.71 in the worst case scenario. Mohammadshirazi et al. (2014) reported a total cost of US$/L 1.2 for biodiesel produced from WFOs. The high share of costs was mainly due to the great expense of WFOs (US$/L 0.66) and the human labor payments (US$/L 0.33). Lee et al. (2011) conducted the economic analysis of three continuous biodiesel processes with production capacity of 40,000 t/year and including a conventional alkali-catalyzed process using waste vegetable oil. Also, an alkali-catalyzed process of WFOs of a 40,000 t/year of biodiesel produced a total biodiesel cost of US$/L

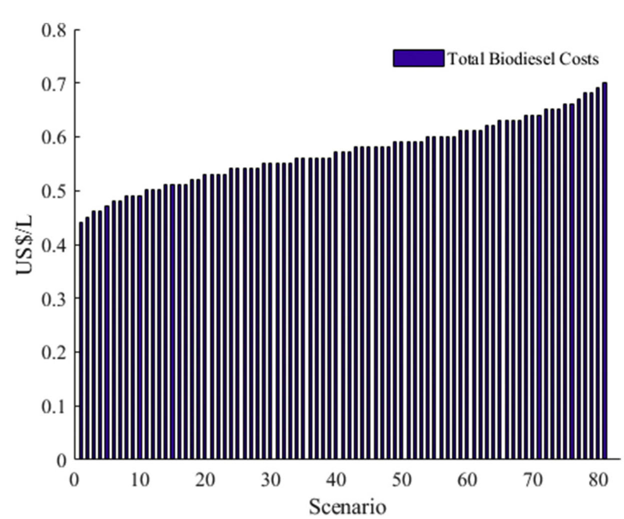

Fig. 3. Total biodiesel cost.

Table 5
Influence of input parameter variation on biodiesel cost.

Varied input	Logistics (US$/L)	Acquisition (US$/L)	Production (US$/L)	Methanol (US$/L)	Input variation (%)[a]	Simulated biodiesel cost (US$/L)	Biodiesel cost variation (%)[b]	Relative sensitivity ζ[c]
Logistics	**0.08**	0.35	0.2	0.12		0.57		0.14
	0.06	0.35	0.2	0.12	−25	0.55	−3.5	
	0.1	0.35	0.2	0.12	25	0.59	3.5	
Acquisition	0.08	**0.35**	0.2	0.12		0.57		0.61
	0.08	**0.3**	0.2	0.12	−14.3	0.52	−8.8	
	0.08	**0.4**	0.2	0.12	14.3	0.62	8.8	
Production	0.08	0.35	**0.2**	0.12		0.57		0.35
	0.08	0.35	**0.15**	0.12	−25	0.52	−8.8	
	0.08	0.35	**0.25**	0.12	25	0.62	8.8	
Methanol	0.08	0.35	0.2	**0.12**		0.57		0.21
	0.08	0.35	0.2	**0.11**	−8.3	0.56	−1.8	
	0.08	0.35	0.2	**0.13**	8.3	0.58	1.8	

Bold: Examining variability, one input parameter at a time.
[a] Percent difference between the new input value and the value used for the base simulation, the latter being 0.08, 0.35, 0.2 and 0.12 for logistics, acquisition, production and methanol costs, respectively.
[b] Percent difference between the simulated biodiesel cost using the new input value and the biodiesel cost obtained in the base simulation (0.57083 $/L).
[c] Relative sensitivity = $\zeta = (\Delta Y / Y) / (\Delta X / X)$ where Y is the sensitivity index value (simulated biodiesel cost) and X is the input parameter value that is varied.

0.76 including glycerol credit and revenues from biodiesel sales. Glisic et al. (2016) performed a techno-economic analysis of biodiesel production from WFOs using, among other assessed production technologies, the homogeneous alkali catalyzed process. They reported a cost of 0.63 US$/L of produced biodiesel at process capacities of 100,000 t/year. Similarly, Patle and Ahmad (2014) conducted a techno-economic analysis of an alkali catalyzed biodiesel production of waste palm oil and concluded that the process profitability increases with the increase in production capacity. The present study's lower average total biodiesel cost could be attributed to the low WFOs expenses and labor cost as well as the revenue from biodiesel production co-products.

3.5.6. Sensitivity analysis

A sensitivity analysis was performed in order to define the impact of key parameters on biodiesel cost variation. Important variables included logistics cost, WFOs acquisition cost, production cost and methanol cost.

The absolute values of the relative sensitivity $|\zeta|$ were found to be 0.61, 0.35, 0.21 and 0.14 for the WFOs acquisition cost, production cost, methanol cost and logistics cost, respectively (Table 5). That is to say that the model is the most sensitive to the WFOs' acquisition cost followed by the production cost, almost equally least sensitive to the logistics cost and the methanol cost, nearly 2.5 times more sensitive to the production cost than to the logistics cost and nearly 2 times more sensitive to the WFOs acquisition cost than to the production cost.

3.5.7. Long-term economic assessment of biodiesel

The study's resulting costs can be compared with the Lebanese market price of diesel fuel. Fig. 4 presents break-even lines for biodiesel minimum, average, and maximum costs, in relation to the minimum, average, and maximum prices of marketed diesel in Lebanon in years 2011 to 2017. For the years 2011, 2012, and 2013 biodiesel costs are lower than the minimum commercialized diesel for the respective years which demonstrates that transesterified WFOs could be an economically-sustainable fuel alternative to common diesels. Within the 81 scenarios, only 4 resulted in a cost higher than the minimum diesel fuel price for the year 2014. However, for the years 2015 through 2017, the average cost of biodiesel production is no longer competitive with the average petroleum diesel prices. In years 2015 and 2017, whereby diesel prices hovered at 0.48 US$/L, only the minimum biodiesel cost calculated in this study is in general competitive. This minimum cost is lower than the maximum tolerance for biodiesel viability in comparison with the minimum diesel cost in 2015 and minimum and average costs in 2016. This makes the viability of biodiesel as alternative fuel highly dependent on the actual cost of diesel commercialization.

Therefore, government's intervention in the promotion of social and economic changes is vital to ensure the viability of biodiesel production from WFOs in Lebanon. Sufficient government enforcement and support leading to a significant reduction in overall WFOs acquisition cost to which the global biodiesel production is mostly sensitive can lead to the success and stability of the biodiesel production for the long term. This can be attained by adopting different measures that commit

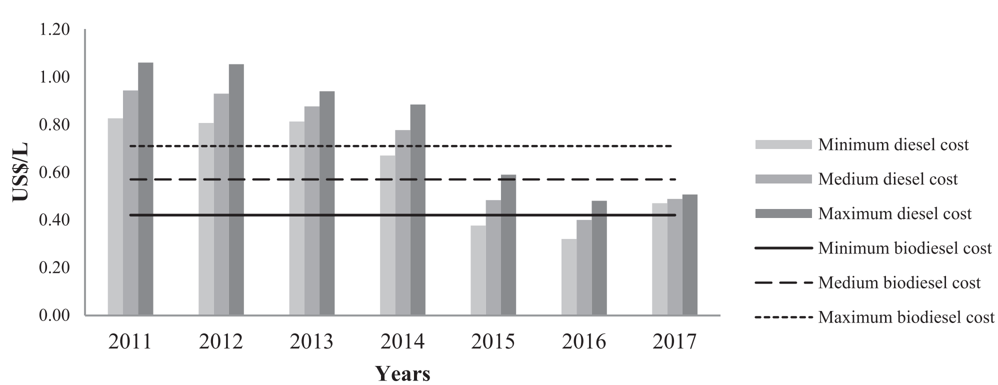

Fig. 4. Variation of diesel oil cost in Lebanon.

the government towards biodiesel industries. In this context, adequate government official policies will be critical in areas such as developing capital grants for biodiesel producers and increasing fuel levy rebates (Steenberghen and López, 2008). Governmental measures would include encouraging restaurants and hotels to participate in the biodiesel supply chain, by implementing positive actions. Among these, the connection of relevant laws about WFOs with relevant laws related to renewable energy could be considered (Saldago, 2006; Wiesenthal, 2009). Through firm directives, WFOs recycling could also be incorporated into the tax incentive system and into the health assessment, class assessment, and honor assessment of the restaurants and enterprises promoting competition (Wong et al., 1996; Schulte et al., 2004).

3.6. Environmental and net energy benefit analysis

Aside from solving significant disposal problems, proper utilization and management of WFOs as raw material for biodiesel production reduce greenhouse gas emissions from engines. Substituting conventional petroleum diesel with biodiesel or its blends reduces particulate matter (PM) emissions by up to 75% (Von Wedel, 1999; Kado and Kuzmicky, 2003). Total hydrocarbon emissions reductions of 70% were supported by EPA and a number of other studies (Last et al., 1995; EPA, 2002; Nwafor, 2004; Alam et al., 2006). A carbon monoxide (CO) emission reduction of almost 50% with biodiesel with respect to conventional diesel fuel is reported (Peterson and Reece, 1996; Krahl et al., 2003). Also, biodiesel reduces net CO_2 emissions by 78.45% compared to petroleum diesel (Sheehan et al., 2000). To be a viable substitute for a fossil fuel, biodiesel should not only be economically competitive with petroleum diesel but also to have superior environmental benefits over it and provide a net energy gain over the energy sources used to produce it. Therefore, the energy requirements for the key steps in producing biodiesel and petroleum diesel were compared. Primary energy needed for the production of petroleum diesel by fractional distillation and for refining crude oil are 1.113 and 0.0650 MJ/MJ diesel respectively (Sheehan et al., 2000), resulting in a total energy input of 1.178 MJ/MJ diesel. For biodiesel production from WFOs in Lebanon, primary energy inputs are WFOs, methanol, KOH, human labor, electricity and machinery (including land). Total energy equivalent per liter biodiesel was obtained by multiplying energy equivalent of input by the quantity needed per unit volume of biodiesel (L) (Table 6). Total energy equivalent (MJ/L) was then converted to primary energy used to produce 1 MJ of biodiesel; using energy equivalent of Biodiesel produced which is 37.25 MJ/L (Kitani and Jungbluth, 1999). Total energy input for biodiesel production is 0.867 MJ/MJ Biodiesel. The slightly lower energy equivalent of biodiesel counter to that of petroleum diesel reflects a lower demand for process energy across the production of biodiesel from WFOs, making biodiesel more energy efficient than petroleum diesel. Also, a total energy input and energy output of biodiesel production are calculated as 32.274 and 44.614 MJ/L which show that biodiesel production results in a positive net energy balance. The energy output-input ratio is 1.38 whereby, for each MJ of energy consumed to produce biodiesel, 1.38 MJ of energy is obtained. The energy output-input ratio was obtained by the following equation

$$\frac{\text{Total output Energy equivalent per liter of biodiesel (MJ/L)}}{\text{Total input Energy equivalent per liter of biodiesel (MJ/L)}}.$$

Hence, biodiesel provides sufficient economical and environmental benefits to merit investment by NGOs and governmental agencies.

4. Conclusion

The study proposed vehicle routing model scenarios to determine logistics network for the profitable reuse of WFOs in Beirut and generated integrated total biodiesel cost. Despite being an economically-sustainable fuel alternative for the years 2011 through 2014, the viability of biodiesel production from WFOs doesn't apply to the years 2015 to present. The economic sensitivity assessment of biodiesel production from WFOs allowed a better understanding of cost interactions and showed that biodiesel production cost is economically competitive with fossil diesel when a subsidy policy on WFOs acquisition cost is implemented by the government. Benefit analysis showed that biodiesel presents superior environmental benefits over petroleum diesel and its production provides a net energy gain. Accordingly, by interacting with local authorities and creating a more covered supply chain coordination system, it would be possible to successfully reuse WFOs for the production of biodiesel on a national scale for the long term, and reduce the environmental damages caused by their disposal.

Acknowledgment

This research was supported by the American University of Beirut's Research Board (award number 102544; project number 21112).

Table 6
Total energy use for biodiesel production.

	Energy production	Unit energy	Quantity per unit volume of biodiesel (L)	Energy equivalent (MJ/unit)	Total energy equivalent per liter of biodiesel (MJ/L)	Total energy equivalent per energy equivalent of 1 L of biodiesel (MJ/MJ biodiesel)
Inputs	Human labor	h	0.556	1.96[a]	1.090	0.029
	WFOs	L	1	23.16[a]	23.160	0.622
	Methanol	L	0.271	26.60[b]	7.209	0.194
	KOH	g	0.0075	19.87[c]	0.149	0.004
	Electricity	kWh	0.013	11.93[a]	0.155	0.004
	Machinery	h	0.009	57.78[d]	0.520	0.014
Total					32.274	0.867
Outputs	Biodiesel	L	1	37.25[e]	37.250	1
	Glycerin	L	0.12	25.30[f]	3.036	0.082
	Methanol	L	0.11	26.60[b]	2.926	0.079
	Soap	L	0.019	42.105[g]	0.80	0.021
	Glycerides	L	0.009	66.87[g]	0.602	0.016
Total					44.614	1.198

[a] Source: Mohammadshirazi et al. (2014).
[b] Source: Singh and Mittal (1992).
[c] Source: Al-Zuhair et al. (2012).
[d] Source: Huo et al. (2008).
[e] Source: Kitani and Jungbluth (1999).
[f] Source: Sheehan et al. (2000) and Krohn and Fripp (2012).
[g] Source: Reusch (1999).

Appendix A. Supplementary data

Questionnaire and different routing systems generated on GIS are available in Supplementary information. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.04.421.

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