Arab J Sci Eng (2015) 40:583–594
DOI 10.1007/s13369-014-1452-5

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Pangium edule Reinw: A Promising Non-edible Oil Feedstock for Biodiesel Production

A. E. Atabani · Irfan Anjum Badruddin ·
H. H. Masjuki · W. T. Chong · Keat Teong Lee

Received: 5 May 2014 / Accepted: 30 September 2014 / Published online: 10 December 2014

Abstract Biodiesel production from non-edible feedstocks is currently drawing much attention due to legitimate concerns about the effects of using edible oil for fuel. *Pangium edule* Reinw is a non-edible feedstock. *Pangium* is a tall tree native to the Micronesia, Melanesia and the mangrove swamps of South-East Asia. In this study, biodiesel production and characterization from *P. edule* oil was reported. The seeds were obtained from Bogor, Indonesia. The oil was found to have an acid value of 19.62 mg KOH/g oil. Therefore, a two-step acid–base-catalysed transesterification was used to produce biodiesel. This was followed by evaluating the physical and chemical properties of biodiesel and its blends with diesel. It has been found that the determined properties of *P. edule* methyl ester indicate that the oil can be considered as a future biodiesel source. The most remarkable feature of *P. edule* is its cloud, pour and cold filter plugging points. This biodiesel yielded cloud, pour and cold filter plugging points of −6, −4 and −8 °C, respectively. This indicates the viability of using this biodiesel in cold countries. Therefore, it is suggested that more research should be conducted on *P. edule* for future biodiesel production.

Keywords Biodiesel · Non-edible oils · *Pangium edule* Reinw · Blending · Physical and chemical properties

Abbreviations

CCMO	Crude *Croton megalocarpus* L. oil
CIME	*Calophyllum inophyllum* methyl ester
CMOO	Crude *Moringa oleifera* L. oil
CN	Cetane number
COME	Coconut methyl ester
CPEO	Crude *Pangium edule oil*
CPO	Crude palm oil
CSO	Crude soybean oil
EPEO	Esterified *Pangium edule* oil
IV	Iodine value
JCME	*Jatropha curcas* methyl ester
MOME	*Moringa oleifera* methyl ester
PME	Palm oil methyl ester
PEME	*Pangium edule* methyl ester
SN	Saponification number
SME	Soybean methyl ester

1 Introduction

The fossil fuel burning has caused a tremendous destruction to the environment that led to focussing on the use of biodiesel as a substitute for petroleum-based diesel fuel. The need for looking an alternate to diesel has been further amplified by the threat of diminishing fossil fuel reserves and dependency on foreign energy sources [1–4]. Biodiesel is considered as a sustainable, non-toxic, biodegradable, alternative and clean fuel as it does not contain any sulphur, aromatic hydrocarbons, metals, crude oil residues and con-

A. E. Atabani (✉)
Department of Mechanical Engineering, Faculty of Engineering,
Erciyes University, 38039 Kayseri, Turkey
e-mail: a_atabani2@msn.com

A. E. Atabani · I. A. Badruddin · H. H. Masjuki · W. T. Chong
Department of Mechanical Engineering, Faculty of Engineering,
University of Malaya, 50603 Kuala Lumpur, Malaysia

A. E. Atabani
Erciyes Teknopark A.Ş, Yeni Mahalle Aşıkveysel Bulvarı
Erciyes Teknopark, Tekno 3 Binası 2, Kat No: 28, 38039
Melikgazi, Kayseri, Turkey

K. T. Lee
School of Chemical Engineering, Universiti Sains Malaysia (USM),
Engineering Campus, Seri Ampangan, 14300 Nibong Tebal,
Pulau Pinang, Malaysia

tributes a minimal amount of net greenhouse gases to the atmosphere. Therefore, it can be employed in current diesel engines without major modifications of the engines. Biodiesel is defined as mono-alkyl esters of long-chain fatty acids derived from renewable lipid feedstocks, such as vegetables oil or animal fats, and alcohols through transesterification reaction with or without a catalyst. Globally, there are more than 350 oil-bearing crops identified as potential sources for biodiesel production. Historical research has focussed towards biodiesel production from edible oils (such as rapeseed, palm, coconut and sunflower oils) rather than non-edible oils (such as *Jatropha curcas*, *Calophyllum inophyllum* and *Pongamia pinnata* oils) [1–10]. Current statistics suggests that more than 95 % of the world biodiesel is produced from edible oils such as rapeseed (84 %), sunflower oil (13 %), palm oil (1 %), soybean oil and others (2 %). This is because of the fact that edible oils have high yield of biodiesel, and they are easy to be processed (transesterified) due to their low free fatty acids. However, their use raises many concerns such as food versus fuel crisis and major environmental problems such as serious destruction of vital soil resources, deforestation and usage of much of the available arable land. Moreover, in the last ten years the prices of vegetable oil plants have increased dramatically which will affect the economic viability of biodiesel industry [3,11]. Production of biodiesel from non-edible feedstocks such as *Jatropha curcas, Calophyllum inophyllum, Moringa oleifera, Croton megalocarpus, Cerbera odollam, Terminalia (Terminalia belerica Ronx.), Madhuca indica (mahua), Pongamia pinnata (karanja), Guizotia abyssinica L., Hevea brasiliensis (rubber seed) and Azadirachta indica (neem)* is considered as a potential alternative to biodiesel production from edible oils [2,3,8,10,12–18]. *Pangium edule* Reinw oil is one of the possible alternative oil crops for biodiesel production.

1.1 Objective of this Study

To the best of the author's knowledge, no detailed study on the possibility of *P. edule* Reinw oil as a potential non-edible oil feedstock for biodiesel production has been reported in the literature except [19]. Nofiarl et al. [19] have recently reported the production of biodiesel from *P. edule* Reinw. The authors have testified some important properties such as kinematic viscosity, density, acid number, iodine number and saponification number. However, some other important properties such as cloud point, pour point, cold filter plugging point, oxidation stability and calorific value were not presented. Moreover, the crude oil characteristics and fatty acid compositions were not reported in that study. Additionally, the study did not present any properties of *P. edule* Reinw methyl ester and its blends with diesel.

Therefore, the purpose of this work is to produce biodiesel from *P. edule* oil using homogeneous acid catalyst (H_2SO_4) and alkaline catalyst (KOH) followed by a detailed study of physical and chemical properties and fatty acid compositions of the produced biodiesel (PEME). The physical and chemical properties of (PEME–diesel) blends of 5, 10, 15 and 20 % were also studied. The success of this study could yield a promising and massive new raw material for biodiesel production on a large scale. Moreover, a comparison with other feedstocks has been presented in this study for better understanding and evaluation of this feedstock.

1.2 Botanical Description and Distribution of *Pangium edule* (PE)

Pangium edule is a tall tree belongs to *Flacourtiaceae* family. It is known as football fruit, Kepayang and Sis nut. It is a tropical tree that is native to the Micronesia, Melanesia and the mangrove swamps of South-East Asia (Indonesia, Malaysia and Papua New Guinea). Figure 1 shows the distribution of *P. edule* tree around the world and *P. edule* tree, fruit and seeds [20]. The tree can grow very tall (often over 40 m, with a sparse crown spreading perhaps 50 m in diameter). The tree prefers slightly acidic soil with a little shade. The tree has large, glossy, heart-shaped leaves that are conspicuously veined and long-stemmed. The flowers are large and greenish; the sexes are separate. The fruit is oval and about the size of a large husked coconut, brown and rough-surfaced. The exterior colour of the fruits is brown. The outside skin is rough to touch. The inner skin (rind) is pale yellow to white, around an inch thick. The mature fruit is edible; however, the seeds of this tree are poisonous, mostly because of the presence of cyanogenic glucosides [21–23].

2 Materials and Methods

2.1 Materials and Chemicals

The seeds of *P. edule* were supplied from Bogor, Indonesia, through personal communication. Other chemicals such as methanol, H_2SO_4, KOH and Na_2SO_4 were purchased from local market. Qualitative filter paper (filters Fioroni) of 150 mm size was supplied from (Metta Karuna Enterprise, Malaysia).

2.2 Crude Oil Extraction

The kernels of the *P. edule* fruits were obtained manually and cleaned before being dried overnight in an oven at 353 K. A moderate temperature for the drying of the *P. edule* kernels

Fig. 1 Distribution of *P. edule* around the world and *P. edule* tree, fruit and seeds [20]

was used to prevent possible decomposition or oxidation of the kernels at higher temperature (>373 K) at which the properties of the extracted oil could be affected. The dried *P. edule* kernels were then ground to fine particles using food processor and then dried for the second time in the oven to remove excess moisture. The oil extraction process was carried out using Soxhlet apparatus using n-hexane as a solvent, and the duration of each extraction process was set at approximately 4 h under temperature of 343 K (reflux temperature of the solvent). *P. edule* oil was obtained after separating the mixture of solvent and oil using rotary evaporator. The resultant *P. edule* oil was decanted mechanically to remove impurities and other components (glycosides) that may be present in the oil.

2.3 Apparatus for Biodiesel Production

In this study, a small-scale (1L) Jacketed glass batch reactor (Brand: Favorit) consisting of reflux condenser to recover methanol, overhead mechanical stirrer (IKA EUROSTAR digital), circulating water bath, hoses, refrigerator and sampling outlet was used to produce biodiesel from crude *P. edule* oil (CPEO). Figure 2 shows the experimental set-up used to perform biodiesel production.

2.4 Determination of Physical and Chemical Properties of CPEO, PEME and PEME–Diesel Blends

The important physical and chemical properties such as viscosity, density, calorific value, cloud point, pour point and cold filter plugging point of crude *P. edule* oil (CPEO), *P. edule* methyl ester (PEME) as well as its blends with diesel are determined and presented in this study. Table 1 shows the apparatus used in this study to measure to perform this analysis beside the country of manufacture of all equipment [10,24,25].

Fig. 2 Experimental set-up used to perform biodiesel production. (*1*) 1L Jacketed glass batch reactor (Brand: Favorit); (*2*) reflux condenser; (*3*) overhead mechanical stirrer (IKA EUROSTAR digital); (*4*) circulating water bath; (*5*) hoses; (*6*) Refrigerator

2.5 Determination of Saponification Number, Iodine Value, and Cetane Number of (PEME)

The cetane number (CN), iodine value (IV) and saponification number (SN) of PEME were determined empirically using the following equations [26–28]:

$$SN = SUM\left(\frac{560 \times A_i}{MW_i}\right) \tag{1}$$

$$IV = SUM\left(\frac{254 \times D \times A_i}{MW_i}\right) \tag{2}$$

$$CN = \left(46.3 + \left(\frac{5458}{SN}\right) - (0.225 \times IV)\right) \tag{3}$$

where A_i is the percentage of each component, D is the number of double bond, and MW_i is the molecular mass of each component.

2.6 Biodiesel Production Method from Crude *Pangium edule* Oil (CPEO)

The high acid value of crude *P. edule* oil (CPEO) (19.62 mg KOH/g oil) prevents the use of *alkaline-catalysed process*. Thus, a two-step process (acid–base catalyst) was used to reduce the high acid value of *P. edule* oil in the first stage and then to methyl ester in the second stage. Figure 3 shows the adopted methodology to produce biodiesel from CPEO.

Table 1 Summary of the apparatus used to measure the properties [10,24,25]

No.	Property	Equipment	Manufacturer	Test method
1	Kinematic viscosity	SVM 3000 Stabinger Viscometer	(Anton Paar, UK)	ASTM D445
2	Density	SVM 3000	(Anton Paar, UK)	ASTM D1298
3	Oxidation stability	873 Rancimat	(Metrohm, Switzerland)	EN ISO 14112
4	Flash point	Fully automatic Pensky-martens flash point -NPM 440	(Norma lab, France)	ASTM D93
5	Cloud and pour point	Fully automated cloud and pour point tester-NTE 450	(Norma lab, France)	ASTM D2500, ASTM D97
6	Cold filter plugging point	Fully automated cold filter plugging point tester-NTL 450	(Norma lab, France)	ASTM D 6371
7	Caloric value	C2000 basic calorimeter	(IKA, UK)	ASTM D240
8	Viscosity index	SVM 3000	(Anton Paar, UK)	N/A
9	Refractive index	RM 40 Refractometer	(Mettler Toledo, Switzerland)	N/A
10	Transmission	Spekol 1500	(Analytical Jena, Germany)	N/A
11	Absorbance	Spekol 1500	(Analytical Jena, Germany)	N/A

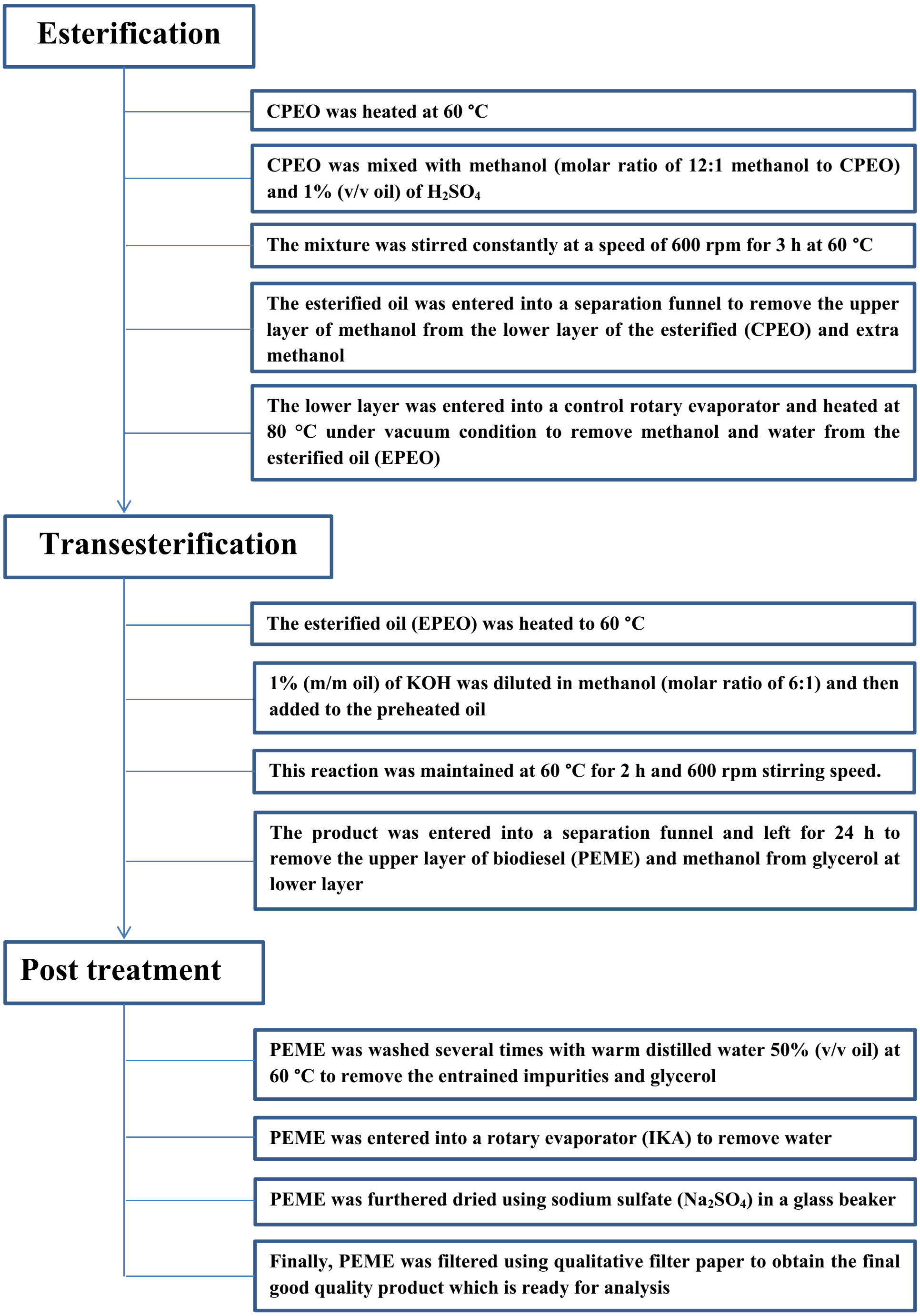

Fig. 3 Detailed flow chart of biodiesel production process of PEME

CPEO was heated at 60 °C

CPEO was mixed with methanol (molar ratio of 12:1 methanol to CPEO) and 1% (v/v oil) of H_2SO_4

The mixture was stirred constantly at a speed of 600 rpm for 3 h at 60 °C

The esterified oil was entered into a separation funnel to remove the upper layer of methanol from the lower layer of the esterified (CPEO) and extra methanol

The lower layer was entered into a control rotary evaporator and heated at 80 °C under vacuum condition to remove methanol and water from the esterified oil (EPEO)

The esterified oil (EPEO) was heated to 60 °C

1% (m/m oil) of KOH was diluted in methanol (molar ratio of 6:1) and then added to the preheated oil

This reaction was maintained at 60 °C for 2 h and 600 rpm stirring speed.

The product was entered into a separation funnel and left for 24 h to remove the upper layer of biodiesel (PEME) and methanol from glycerol at lower layer

PEME was washed several times with warm distilled water 50% (v/v oil) at 60 °C to remove the entrained impurities and glycerol

PEME was entered into a rotary evaporator (IKA) to remove water

PEME was furthered dried using sodium sulfate (Na_2SO_4) in a glass beaker

Finally, PEME was filtered using qualitative filter paper to obtain the final good quality product which is ready for analysis

The next section gives a detailed description of biodiesel production processes.

2.6.1 Acid Esterification Process

In this process, crude *P. edule* oil (CPEO) was entered at room temperature into the reactor and heated to 60 °C. CPEO was firstly mixed with methanol (molar ratio of 12:1 methanol to CPEO). This was followed by adding sulphuric acid (H_2SO_4 95−97 %) to the mixture drop by drop using a connected pipe to the reactor. The amount of H_2SO_4 catalyst added for the reaction was 1 % (v/v oil). During the reaction, the mixture was stirred constantly at a speed of 600 rpm for 3 h at 60 °C.

The esterified *P. edule* oil (EPEO) was then removed from the reactor and entered into a separation funnel and left for 15 min to remove the upper layer which includes methanol from the lower layer of EPEO and extra methanol. The lower layer was entered into a control rotary evaporator (IKA) and heated at 80 °C under vacuum condition to remove methanol and water from the esterified oil.

2.6.2 Alkaline Transesterification Process

In this process, EPEO was entered at room temperature into the reactor and heated to 60 °C. Then, 1 % (m/m oil) of potassium hydroxide (KOH 99 % pure) was diluted in methanol (molar ratio of 6:1) and then added to the preheated EPEO. This reaction was maintained at 60 °C for 2 h and 600 rpm stirring speed. The product was then removed from the reactor and entered into a separation funnel and left for 24 h to remove the upper layer of *P. edule* methyl ester (PEME) and methanol from glycerol at lower layer.

2.6.3 Post-treatment Process

In this process, the methyl ester was washed several times with warm distilled water 50 % (v/v oil) at 60 °C to remove the entrained impurities and glycerol. This process was repeated several times until the pH of distilled water became neutral. The lower layer was discarded and upper layer was entered into a rotary evaporator (IKA) to remove water. This was followed by further drying using sodium sulphate (Na_2SO_4) in a glass beaker. Lastly, the produced biodiesel was filtered using qualitative filter paper to obtain the final good quality product which is ready for testing.

2.7 The Gas Chromatography (GC) Method of *Pangium edule* Methyl Ester (PEME)

The fatty acid compositions (FAC) profile of *P. edule* methyl ester (PEME) was tested using gas chromatography (GC) (Shidmadzu, Japan) equipped with a flame ionization detector and a BPX70 capillary column of 30 m × 0.25 μm × 0.32 mm. The analysis was done using an optimized in-house GC method for analysis of total fatty acid composition in various oils and fats. 1 μL of PEME sample was injected into gas chromatography. An initial temperature of 140 °C was held for 2 min, which was then increased at the rate of 8 °C per minute until 165, 2 °C per minute until 192 °C and finally 8 °C per minute to 220 °C. The column was held at the final temperature for another 5 min. The oven, injector and the detector ports were set at 140, 240 and 260 °C, respectively. The carrier gas was helium with column flow rate of 1.10 $mL\,min^{-1}$ at a 50:1 split ratio. Table 2 shows the summary of GC operating conditions.

Table 2 GC operating conditions

Property	Specifications
Carrier gas	Helium
Linear velocity	24.4 cm/s
Flow rate	1.10 mL/min (column flow)
Detector temperature	260.0 °C
Column head pressure	56.9 kPa
Column dimension	BPX 70, 30.0 m × 0.25 μ m × 0.32 mm ID
Injector column oven	240.0 °C
Temperature ramp	140.0 °C (hold for 2 min)
	8 °C/min 165.0 °C
	2 °C/min 192.0 °C
	8 °C/min 220.0°C (hold for 5 min)

2.8 Biodiesel–Diesel Blending

Blending of PEME with diesel was done to examine the effect on some physical and chemical properties such as kinematic viscosity, density, cloud point, pour point, cold filter plugging point, flash point, oxidation stability, viscosity index and calorific value.

In this study, *P. edule* methyl ester was blended with diesel at four blends of 5, 10, 15 and 20 % by volume blends in a glass beaker at room temperature using a magnetic stirrer (model: IKA® C-MAG HS 7) at 1,500 rpm for 20 min and shaker (model: IKA® KS 130 basic) at 450 rpm for 1 h to ensure the homogeneity of the blends.

The polynomial curve fitting method was used in this study to estimate the properties of the blends. This method is an attempt to describe the relationship between variable X as a function of available data and a response Y, which seeks to find a smooth curve that best fits the data. Mathematically, a polynomial of order k in X is expressed in the following form:

$$\mathrm{Y} = \mathrm{C}_0 + \mathrm{C}_1 X + \mathrm{C}_2 X^2 + \cdots\cdots\cdots + \mathrm{C}_\mathrm{k} X^k \tag{4}$$

3 Results and Discussion

3.1 Properties of Crude *Pangium edule* Oil (CPEO)

Table 3 shows the physical and chemical properties of crude *P. edule* oil (CPEO) beside a detailed comparison with some edible and non-edible feedstocks such as palm (CPO), soybean (CSO), *Croton megalocarpus* (CCMO) and *Moringa oleifera* (CMOO) [24]. The primary evaluation of feedstock characteristics influence the biodiesel production process selection and final properties of biodiesel [24].

From this table, it can be seen that CPEO possessed the lowest kinematic viscosity of 27.175 mm^2/s compared to CPO, CSO, CCMO and CMOO. However, CPEO and CPO possess the lowest oxidation stabilities (0.08 h) among other oils. The measured acid value of CPEO of (19.62 mg KOH/g oil) is higher compared to CCMO and CMOO. Density of

Table 3 Properties of crude *P. edule* oil (CPEO)

No	Property	Unit	CPEO	CPO[a]	CSO[a]	CMOO[a]	CCMO[a]
1	Kinematic viscosity at 40 °C	mm^2/s	27.175	41.932	31.739	43.4680	29.8440
2	Kinematic viscosity at 100 °C	mm^2/s	6.6407	8.496	7.6295	9.0256	7.2891
3	Dynamic viscosity at 40 °C	mpa.s	24.393	37.731	28.796	38.9970	27.1570
4	Viscosity index (VI)	–	216.20	185.0	223.2	195.20	224.20
5	Cloud point (CP)	°C	−6	N/D	N/D	N/D	N/D
6	Pour point (PP)	°C	−10	N/D	N/D	N/D	N/D
7	Density at 40 °C	kg/m^3	897.6	899.8	907.3	897.1	910.0
8	Calorific value	kJ/kg	39,523	39,867	39,579	39,762	39,331
9	Oxidation stability	h at 110 °C	0.08	0.08	6.09	41.75	0.14
10	Acid value	mgKOH/goil	19.62	N/D	N/D	8.62	12.07
11	Refractive index	*N*	1.4683	1.4642	1.4725	1.4661	1.4741
12	Transmission	–	86.1	63.2	65.2	69.2	87.5
13	Absorbance	Abs	0.064	0.199	0.186	0.16	0.058

[a] [24]

CPEO (0.8976 kg/m^3) is lower than CPO, CSO and CCMO but slightly higher than CMOO. Viscosity index of CPEO (216.2) is higher than that of CPO (185.0) and CMOO (195.2) but lower than that of CSO of (223.2) and CCMO of (224.2). The calorific value of CPEO of 39,523 kJ/kg is higher than that of CCMO but lower than CPO, CSO and CMOO [24].

3.2 Fatty Acid Composition of *Pangium edule* Methyl Ester (PEME)

Table 4 shows the results of fatty acid composition of PEME beside a comparison with some edible and non-edible feedstocks such as palm, *Calophyllum inophyllum*, *Jatropha curcas* and coconut [28–30]. The results showed that the saturated fatty acids of PEME represent only 12.6 % of the total fatty acids. However, monounsaturated and polyunsaturated fatty acids represent 45.6 and 41.8 %, respectively, with total unsaturation level of 87.4 %. It was also observed that oleic acid (cis-9-octadecenoic) and linoleic acid (cis-9-cis-12 octadecadienoic) are the most dominant fatty acids in PEME with 45.2 and 39.3 %, respectively. The obtained results are similar to other non-edible biodiesel feedstocks which are dominated by unsaturated fatty acids such as JCME (unsaturation level 77.4 %), CIME (unsaturation level 72.65 %). In contrast, edible biodiesel feedstocks such as COME are mainly dominated by saturated fatty acid (91.8 %), while PME is comprised of 49.1 % saturated fatty acids and 42 % monounsaturated fatty acids, respectively.

3.3 Properties of *Pangium edule* Methyl Ester (PEME)

Table 5 shows the physical and chemical properties of *P. edule* methyl ester (PEME) beside a detailed comparison with some edible and non-edible biodiesel feedstocks such as palm (PME), soybean (SME), *Calophyllum inophyllum* (CIME), *Croton megalocarpus* (CMME) and *Moringa oleifera* (MOME) [25]. The next section will discuss some of the most important findings of this study supported with a comparison with the literature.

3.3.1 Kinematic Viscosity

Kinematic viscosity is the resistance of liquid to flow. It refers to the thickness of the oil and is determined by measuring the amount of time taken for a given measure of oil to pass through an orifice of a specified size [17,24]. Viscosity affects operation of the fuel injection equipment and spray atomization, mainly at low temperatures when the increase in viscosity affects the fluidity of the fuel. This can ultimately lead to the formation of engine deposits [3,24,31]. The difference in viscosity between the crude oil and biodiesel can be used as an indication to monitor biodiesel production. Kinematic viscosity has been included in biodiesel standards (1.9–6.0 mm^2/s in ASTM D6751 and 3.5–5.0 mm^2/s in EN 14214). An upper limit on viscosity ensures that fuel will flow readily during cold starting, and a minimum limit is often specified to avoid the possibility of a serious power loss at high temperatures.

The results from Table 5 show that the kinematic viscosity of PEME is 5.2296 mm^2/s compared to 27.175 mm^2/s of CPEO (Table 2). This indicates that the obtained result agrees with the limit specified by ASTM D6751 but slightly higher than that of EN 14214. Moreover, a comparison with the results from literature showed that the viscosity of PEME is lower than CIME (5.5377 mm^2/s) but higher than PME (4.6889 mm^2/s), SME (4.3745 mm^2/s) and MOME (5.0735 mm^2/s), respectively [25].

Table 4 Fatty acid composition of PEME

No	Fatty acid	Molecular weight	Structure	Systematic name	Formula	PEME	JCME[a]	CIME[b]	COME[c]	PME[c]
1	Caprylic	144	8:0	Octanoic	$C_8H_{16}O_2$	0	0	0	6.3	0
2	Capric	172	10:0	Decanoic	$C_{10}H_{20}O_2$	0	0	0	6.0	0
3	Lauric	200	12:0	Dodecanoic	$C_{12}H_{24}O_2$	0	0.1	0	49.2	0.2
4	Myristic	228	14:0	Tetradecanoic	$C_{14}H_{28}O_2$	0.1	0.1	0	18.5	0.5
5	Palmitic	256	16:0	Hexadecanoic	$C_{16}H_{32}O_2$	8.3	14.6	12.01	9.1	43.4
6	Palmitoleic	254	16.1	Hexadec-9-enoic	$C_{16}H_{30}O_2$	0.1	0.6	0	0	0.1
7	Stearic	284	18:0	Octadecanoic	$C_{18}H_{36}O_2$	4.0	7.6	12.95	2.7	4.6
8	Oleic	282	18:1	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	45.2	44.6	34.09	6.5	41.9
9	Linoleic	280	18:2	cis-9-cis-12 Octadecadienoic	$C_{18}H_{32}O_2$	39.3	31.9	38.26	1.7	8.6
10	Linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	2.5	0.3	0.3	0	0.3
11	Arachidic	312	20:0	Eicosanoic	$C_{20}H_{40}O_2$	0.2	0.3	0	0	0.3
12	Gondoic	310	20:1	11- Eicosenoic	$C_{20}H_{38}O_2$	0.3	0	0	0	0
13	Behenic	340	22:0	Docosanoic acid	$C_{22}H_{44}O_2$	0	0	0	0	0.1
Saturated fatty acids						**12.6**	**22.7**	**24.96**	**91.8**	**49.1**
Monounsaturated fatty acids						**45.6**	**45.2**	**34.09**	**6.5**	**42**
Polyunsaturated fatty acids						**41.8**	**32.2**	**38.56**	**1.7**	**8.9**
Total sum						**100**	**100**	**97.61**	**100**	**100**

[a] [28]
[b] [29]
[c] [30]

Table 5 Physical and chemical properties of *Pangium edule* methyl ester (PEME)

No.	Property	Unit	PEME	PME[c]	SME[c]	CIME[c]	MOME[c]	ASTM D6751	DIN 14214
1	Kinematic viscosity at 40 °C	mm^2/s	5.2296	4.6889	4.3745	5.5377	5.0735	1.9–6.0	3.5–5.0
2	Kinematic viscosity at 100 °C	mm^2/s	1.9651	1.7921	1.764	1.998	1.9108	N/A	N/A
3	Dynamic viscosity at 40 °C	mpa.s	4.5551	4.0284	3.8014	4.8599	4.3618	N/A	N/A
4	Viscosity index (VI)	–	211.8	203.6	257.8	183.2	206.7	N/A	N/A
5	Cloud point (CP)	°C	−6	13	1	12	21	Report	Report
6	Pour point (PP)	°C	−4	15	1	13	19	Report	Report
7	Cold filter plugging point (CFPP)	°C	−8	12	−3	11	18	Report	Report
8	Density	kg/m^3	871.0[a]	859.1[a]	869.0[a]	877.6[a]	859.7[a]	880	860–900
9	Calorific value	kJ/kg	39,625	40,009	39,976	39,513	40,115	N/A	35,000[b]
10	Oxidation stability	h at 110 °C	0.57	23.56	4.08	6.12	12.64	3 h (min)	6 (min)
11	Cetane number	–	47	–	–	–	–	47 (min)	–
12	Iodine value	g I/100 g	119	–	–	–	–	120 (max)	–
13	Saponification number	–	201	–	–	–	–	–	–
14	Refractive index (RI) at 25 °C	N/A	1.4551	1.4468	1.4553	1.4574	1.4494	–	–
15	Transmission at WL 656.1	%T	69.2	89.1	92	87.7	90	–	–
16	Absorbance at WL 656.1	Abs	0.160	0.05	0.037	0.057	0.046	–	–

[a] at 40 °C
[b] DIN 14213
[c] [25]

3.3.2 Density

The density of a material or liquid is defined as its mass per unit volume [17,24]. Generally, biodiesel has higher density than diesel. This means that volumetrically operating fuel pumps will inject greater mass of biodiesel than conventional diesel fuel [32]. The results from Table 5 show that the density of PEME is 0.8710 kg/m^3 compared to 0.8976 kg/m^3 of CPEO. This finding is also lower to that of CIME (0.8776 kg/m^3) but higher than that of SME (0.869 kg/m^3)

and of PME (0.8591 kg/m$^{3)}$ and of MOME (0.8597 kg/m^3) [25].

3.3.3 *Cloud Point and Pour Point*

The cloud point is the temperature at which the product just shows a cloud or haze of wax crystals when it is cooled under standard test conditions. Pour point is the temperature at which the amount of wax out of solution is sufficient to gel the fuel [3, 17]. The results from Table 5 show that PEME possesses a very good of cloud and pour point profile of −6 and −4 °C, respectively. These results are much lower than PME (13 and 15 °C), SME (1 and 1 °C) CIME (12 and 13 °C) and MOME (21 and 19 °C) [25].

3.3.4 *Oxidation Stability*

Oxidation stability is an indication of the degree of oxidation, potential reactivity with air, and can determine the need for antioxidants. Oxidation occurs due to the presence of unsaturated fatty acid chains and the double bond in the parent molecule, which immediately react with the oxygen as soon as it is being exposed to air [3]. Moreover, some other factors such as heat, light, traces of metal and peroxides can also influence the oxidation stability of biodiesel [24]. The results from Table 5 show that PEME possesses a very poor oxidation stability of only 0.57 h compare to PME (23.56 h), SME (4.08 h), CIME (6.12 h) and MOME (6.12 h) [25]. This result is lower than the limit (minimum 3 h) specified by ASTM D6751 and EN 14214 (minimum 6 h). Therefore, mixing of antioxidants with biodiesel is important to improve the oxidation stability of PEME. Moreover, blending with diesel is another option to improve this property as will be seen in the nest section.

3.3.5 *Calorific Value*

The caloric value of crude oils is generally lower than biodiesel. As can be seen from Tables 3 and 5, the calorific value of PEME (39,625 kJ/kg) is slightly higher than that of CPEO (39,523 kJ/kg). The comparison with literature shows that the calorific value of PEME is slightly higher than that of CIME (39,513 kJ/kg) but lower than that of PME (40,009 kJ/kg), SME (39,976 kJ/kg) and MOME (40,115 kJ/kg) [25].

3.4 Physical and chemical Properties of PEME–Diesel Blends

The effect of blending PEME and conventional petroleum-derived diesel fuel on kinematic viscosity, density, calorific value, oxidation stability and viscosity index was also investigated. Table 6 shows the obtained results of physical and chemical properties of PEME–diesel blends of 5, 10, 15 and

Table 6 Physical and chemical properties of diesel, *Pangium edule* methyl ester (PEME) and PEME–diesel blends

No.	Property	Unit	Diesel	B_5	ASTM D975	B_{10}	B_{15}	B_{20}	ASTM D7467	PEME	ASTM D6751	DIN 14214
1	Kinematic viscosity at 40 °C	mm^2/s	3.2333	3.2759	1.9–4.1	3.3467	3.4481	3.5278	1.9–4.1	5.2296	1.9–6.0	3.5–5.0
2	Kinematic viscosity at 100 °C	mm^2/s	1.2446	1.3008	N/A	1.3234	1.3234	1.3571	N/A	1.9651	N/A	N/A
3	Dynamic viscosity at 40 °C	mpa.s	2.6996	2.747	N/A	2.8126	2.9038	2.9746	N/A	4.5551	N/A	N/A
4	Viscosity index (VI)	N/A	90	134.6	N/A	137.1	143.5	149.9	N/A	211.8	N/A	N/A
5	Cloud point (CP)	°C	8	7	Report	8	6	6	Report	−6	Report	Report
6	Pour Point (PP)	°C	0	0	Report	0	0	−3	Report	−4	Report	Report
7	Cold filter plugging point	°C	8	8	Report	7	8	8	Report	−8	Report	Report
8	Flash point	°C	68.5	73.5	52 min	74.5	76.5	79.5	52 min	N/D	120 min	120 min
9	Density	kg/m^3	827.2[a]	838.5[a]	N/A	840.4[a]	842.2[a]	843.2[a]	N/A	871.0[a]	880	860–900
10	Calorific value	kJ/kg	45,272	44,907	N/A	44,634	44,412	44,082	N/A	39,625	N/A	35,000[b]
11	Oxidation stability	h at 110 °C	N/D	75.38	N/A	37.03	23.27	20.13	6 (min)	0.57	3 h (min)	6 h (min)

[a] at 40 °C

[b] DIN 14213

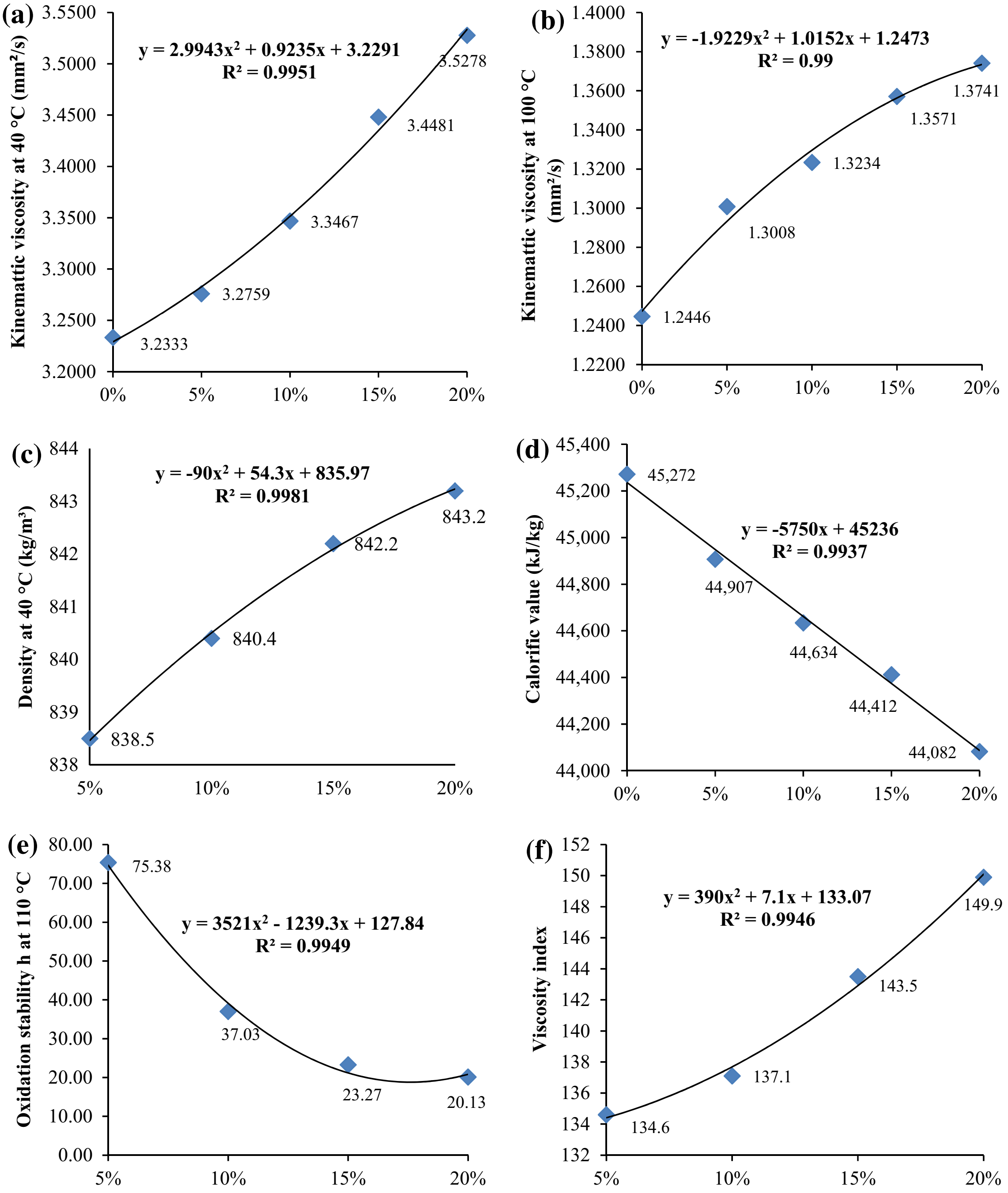

Fig. 4 Effect of blending PEME and diesel on kinematic viscosity, density, calorific value, oxidation stability and viscosity index: **a** kinematic viscosity 40 °C; **b** kinematic viscosity 100 °C; **c** density 40 °C; **d** calorific value; **e** oxidation stability; **f** viscosity index

20 %, respectively, beside a comparison with ASTM D6751 and EN 14214 specifications for (B_{100}), ASTM D975 specifications for diesel fuel and blends up to 5 % by volume (B_5) and ASTM D7467 for blends ($B_6 - B_{20}$).

Blending with diesel improves kinematic viscosity, density, oxidation stability and calorific value of PEME. However, cloud and pour point increase slightly.

The following Fig. 4a–f presents the derived equations which allow predicting the kinematic viscosity, density, calorific value, oxidation stability and viscosity index of the blends based on the percentage of *P. edule* methyl ester (PEME) (in the range of 0–20 % blends) as follow:

4 Conclusion

Nowadays production of biodiesel from non-edible feedstocks is gaining more attention than in the past. *P. edule* (PE) is an example of these promising non-edible feedstocks. This study aims to investigate the possibility of biodiesel production from *P. edule* oil. A two-step acid–base-catalysed transesterification process has been used to produce biodiesel from this feedstock. *P. edule* methyl ester (PEME) was produced using H_2SO_4 as acid catalyst in the first process followed by KOH as an alkaline catalyst in the second process. This was followed by an investigation of some important physical and chemical properties of the produced biodiesel such as viscosity, density, calorific value, iodine value, acid value, saponification number and cetane number. Moreover, the properties of (PEME–diesel) blends (5, 10, 15 and 20 %) were also determined. It has been found that almost all these properties fell within the recommended biodiesel ASTM and EN standards. However, *P. edule* methyl ester possesses a very poor oxidation stability of only (0.57 h). Blending of *P. edule* methyl ester (PEME) with diesel has improved the oxidation stability of PEME remarkably.

The most significant feature of PEME is its cloud, pour point and cold filter plugging points. It has been found that PEME possesses a cloud point of $-6\,^{\circ}$C, pour point of $-4\,^{\circ}$C and cold filter plugging point of $8\,^{\circ}$C. This shows out the viability of using PEME especially in cold countries. This indicates that this oil can be considered as a future biodiesel source. Therefore, the authors recommend conducting further studies on this feedstock for biodiesel production in terms of biodiesel optimization, engine performance and emissions testing.

Acknowledgments The authors would like to acknowledge for the Ministry of Higher Education of Malaysia and The University of Malaya, Kuala Lumpur, Malaysia, for the financial support under UM.C/HIR/MOHE/ENG/06 (D000006-16001) and ER026-2011A.

References

1. Kafuku, G.; Mbarawa, M.: Biodiesel production from *Croton megalocarpus* oil and its process optimization. Fuel **89**(9), 2556–2560 (2010)
2. No, S.Y.: Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: a review. Renew. Sustain. Energy Rev. **15**(1), 131–149 (2011)
3. Atabani, A.E.; Silitonga, A.S.; Badruddin, I.A.; Mahlia, T.M.I.; Masjuki, H.H.; Mekhilef, S.: A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew. Sustain. Energy Rev. **16**(4), 2070–2093 (2012)
4. Singh, S.P.; Singh, D.: Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. Renew. Sustain. Energy Rev. **14**(1), 200–216 (2010)
5. Silitonga, A.S.; Atabani, A.E.; Mahlia, T.M.I.; Masjuki, H.H.; Badruddin, I.A.; Mekhilef, S.: A review on prospect of Jatropha curcas for biodiesel in Indonesia. Renew. Sustain. Energy Rev. **15**, 3733–3756 (2011)
6. Demirbas, A.: Biodiesel production from vegetable oils via catalytic and non-catalytic supercritical methanol transesterification methods. Prog. Energy Combust. Sci. **31**(5-6), 466–487 (2005)
7. Demirbas, A.: Biofuels: Securing the Planet's Future Energy Needs. Springer, London (2009)
8. Kumar, A.; Sharma, S.: Potential non-edible oil resources as biodiesel feedstock: an Indian perspective. Renew. Sustain. Energy Rev. **15**(4), 1791–1800 (2011)
9. Moser, B.R.; Vaughn, S.F.: Coriander seed oil methyl esters as biodiesel fuel: unique fatty acid composition and excellent oxidative stability. Biomass Bioenergy **34**(4), 550–558 (2010)
10. Atabani, A.E.; Mofijur, M.; Masjuki, H.H.; Badruddin, I.A.; Kalam, M.A.; Chong, W.T.: Effect of *Croton megalocarpus*, *Calophyllum inophyllum*, *Moringa oleifera*, palm and coconut biodiesel–diesel blending on their physico-chemical properties. Ind. Crops Prod. **60**, 130–137 (2014)
11. Gui, M.M.; Lee, K.T.; Bhatia, S.: Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy **33**(11), 1646–1653 (2008)
12. Balat, M.: Potential alternatives to edible oils for biodiesel production: a review of current work. Energy Convers. Manag. **52**(2), 1479–1492 (2011)
13. Chakraborty, M.; Baruah, D.C.; Konwer, D.: Investigation of terminalia (terminalia belerica Robx) seed oil as perspective biodiesel source for North-East India. Fuel Process. **90**(12), 1435–1441 (2009)
14. Rashid, U.; Anwar, F.; Moser, B.R.; Knothe, G.: *Moringa oleifera oil*: a possible source of biodiesel. Bioresour. Technol. **99**(17), 8175–8179 (2008)
15. Kansedo, J.; Lee, K.T.; Bhatia, S.: *Cerbera odollam* (sea mango) oil as a promising non-edible feedstock for biodiesel production. Fuel **88**(6), 1148–1150 (2009)
16. Sarin, R.; Sharma, M.; Khan, A.A.: Studies on *Guizotia abyssinica* L. oil: biodiesel synthesis and process optimization. Bioresour. Technol. **100**(18), 4187–4192 (2009)
17. Atabani, A.E.; Silitonga, A.S.; Ong, H.C.; Mahlia, T.M.I.; Masjuki, H.H.; Badruddin, I.A.; Fayaz, H.: Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew. Sustain. Energy Rev. **18**, 211–245 (2013)
18. Atabani, A.E.; da Silva César, A.: Calophyllum inophyllum L.—a prospective non-edible biodiesel feedstock. Study of biodiesel production, properties, fatty acid composition, blending and engine performance. Renew. Sustain. Energy Rev. **37**, 644–655 (2014)
19. Nofiarl, K.A.; Nurdin, H.: The biodiesel characteristic of kepayang oil (*Pangium edule* reinw.). ARPN J. Agric. Biol. Sci. **8**(3), 241–244 (2013)
20. Discover Life. 2013 [cited 2014 5th May]; Available from: http://www.discoverlife.org/mp/20m?map=Pangium+edule
21. University of Guam. *Panguim Edule*. 2012 [cited 2014 25th April]; Available from: http://university.uog.edu/cals/people/POG/pangium.html
22. Andarwulan, N.; Fardiaz, S.; Apriyantono, A.; Hariyadi, P.; Shetty, K.: Mobilization of primary metabolites and phenolics during natural fermentation in seeds of *Pangium edule* Reinw. Process Biochem. **35**(1-2), 197–204 (1999)
23. The Archieves of The Rare Fruit Council of Australia. The football fruit. 2013 [cited 2014 4th May]; Available from: http://rfcarchives.org.au/Next/Fruits/Pangium/Pangium11-97.htm
24. Atabani, A.E.; Mahlia, T.M.I.; Anjum Badruddin, I.; Masjuki, H.H.; Chong, W.T.; Lee, K.T.: Investigation of physical and chemical properties of potential edible and non-edible feedstocks for biodiesel production, a comparative analysis. Renew. Sustain. Energy Rev. **21**(0), 749–755 (2013)
25. Atabani, A.E.; Mahlia, T.M.I.; Masjuki, H.H.; Badruddin, Irfan Anjum; Yussof, Hafizuddin Wan; Chong, W.T.; Lee, Keat Teong: A comparative evaluation of physical and chemical properties of biodiesel synthesized from edible and non-edible oils and study on the effect of biodiesel blending. Energy **58**, 296–304 (2013)

26. Devan, P.K.; Mahalakshmi, N.V.: Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. Fuel Process. Technol. **90**(4), 513–519 (2009)
27. Mohibbe Azam, M.; Waris, A.; Nahar, N.M.: Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass Bioenergy **29**(4), 293–302 (2005)
28. Mofijur, M.; Masjuki, H.H.; Kalam, M.A.; Atabani, A.E.: Evaluation of biodiesel blending, engine performance and emissions characteristics of *Jatropha curcas* methyl ester: Malaysian perspective. Energy **55**, 879–887 (2013)
29. Sahoo, P.K.; Das, L.M.; Babu, M.K.G.; Naik, S.N.: Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel **86**(3), 448–454 (2007)
30. Sanford, S.D., White, J.M., Shah, P.S., Wee, C., Valverde, M.A., Meier, G.R.: Feedstock and Biodiesel Characteristics. 2011 [cited 2014 4th May]; Available from: http://www.regfuel.com/pdfs/Feedstock%20and%20Biodiesel%20Characteristics%20Report.pdf.
31. Knothe, G.: Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel Process. Technol. **86**(10), 1059–1070 (2005)
32. Giakoumis, E.G.: A statistical investigation of biodiesel physical and chemical properties, and their correlation with the degree of unsaturation. Renew. Energy **50**, 858–878 (2013)