



An evaluation of *Moringa peregrina* seeds as a source for bio-fuel



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ABSTRACT

Moringa peregrina leaves and pods are known for their medicinal and nutritional values. In this paper, *M. peregrina* seeds had been investigated for the first time as a potential source for bio-fuel. Physical characterization revealed that *M. peregrina* seed is composed of about 59% kernel and 41% husk. The kernel was found to contain about 38% of oil. Higher heating values of 18.21, 20.65 and 39.99 MJ/kg were obtained for *M. peregrina* seed husk, *M. peregrina* seed oil cake and *M. peregrina* seed oil respectively. Thermochemical characteristics and thermal behavior of *M. peregrina* seed husk and *M. peregrina* seed oil cake in an inert atmosphere of N₂ were studied. The initial results showed that *M. peregrina* seed husk and *M. peregrina* seed oil cake could potentially produce energy through thermochemical conversion processes. Low iodine value (67.73 g I₂/100 g oil) and high saponification value (187.53 mg KOH/g oil) were reported for *M. peregrina* seed oil. Thus, a high cetane number (60.16) was reported for *M. peregrina* seed-oil-based biodiesel. *M. peregrina* seed oil was found to contain very low free fatty acids (0.35%), rendering its conversion into biodiesel possible in one step by alkaline catalyst. A high fraction of unsaturated fatty acids was observed in *M. peregrina* seed oil (81.24%) while 76.92% of *M. peregrina* seed oil was contributed by monounsaturated fatty acids with oleic acid as the major component (72.19%). Therefore, high thermo-oxidative stability was observed in *M. peregrina* seed oil. However, its significant fraction of long-chain fatty acids (C20:0 + C20:1 + C22:0) (6.76%) may affect the cold flow properties of the derived biodiesel. We concluded from this study that *M. peregrina* is a potential source for both bio-fuel and food.

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1. Introduction

Moringa is a small genus for mono-generic family called Moringaceae. It includes thirteen species of shrubs and trees originating in Asia and Africa that have been distributed in many other tropics lately. All these species are known for their uses as medicine, food and water purifying agents (Padayachee and Bajinath, 2012). *Moringa oleifera* and *Moringa peregrina* are the best known and

utilized species (Lalas et al., 2012). *M. oleifera* has been investigated for its fast growth, high nutritional attributes, and utilization as a livestock fodder crop. It can be grown as a crop on marginal lands with high temperatures and low water availability, where cultivation of other agricultural crops is difficult (Nouman et al., 2014). It can be cultivated under tropical dry forest conditions, when phosphorus and potassium are available in the soil. *Moringa* maintains a high biomass yield over time with up to 24 tons ha⁻¹ year⁻¹ of total dry matter (DM) yield and crude protein (CP) content in fresh leaves varying from 193 to 264 g kg⁻¹ DM (Mendieta-Araica, 2011). A study conducted in Tanzania has reported *M. oleifera* as a superior source of vegetable oil with 1 ton ha⁻¹ year⁻¹ of oil yield to be used as a renewable fuel (Kibazohi and Sangwan, 2011). Two cultivars of *M. oleifera* from Tanzania and India are found promising for oil production (580 kg ha⁻¹) in the Arid Chaco ecosystem of Northern Western Argentina (Ayerza, 2011), indicating possible cultivation of this plant in other parts of the world where climates are similar.

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In Sudan, *Moringa* is cultivated in many areas in different Sudanese states. In the state of Khartoum, the tree is cultivated in many farms by different individuals and agricultural companies. The tree parts (leaf, seed, bark, pods) are of economic importance and available in local markets. Meanwhile, cultivation of *Moringa* in Sudan as a perennial crop by small-scale farmers is promising for sustainable development. This is because, *Moringa*, like any other perennial crop, continues to produce for a number of years and it has the added advantage of not requiring annual clearance of new forest lands.

M. peregrina is native to the region extending from the Dead Sea to Southern Arabia and northern Somalia (Olson, 2002). In the past, *M. peregrina* was both an indigenous and a cultivated tree in Sudan (Jahn et al., 1986). It is a very fast growing tree or shrub that can reach 3–10 m in height after 10 months of plantation time (Padayachee and Baijnath, 2012). According to germination experiments conducted by Goma and Picó (2011), *M. peregrina* seeds have short germination time and high seedling growth rate. Moreover, planting trials in Sudan revealed that *M. peregrina* grew fast from both seeds and cutting and both of them could be used for multiplication in a nursery (Munyanziza and Yongabi, 2007). Trees of *M. peregrina* bear 20–40 cm-long seed pods, each containing 8–15 un-winged seeds (Afsharypuor et al., 2010). A single tree may produce up to 1000 pods per year (Munyanziza and Yongabi, 2007). *M. peregrina* leaf is an excellent source of protein, minerals and essential amino acids (Osman and Abohassan, 2012). Moreover, the seed kernel has high oil content in the range of 42–54% (Afsharypuor et al., 2010). The refined oil has a yellowish color which is odorless and none sticking (Zaghloul et al., 2010). As a result, *Moringa* oil can be potentially used for different industrial applications such as in cosmetics (Kleiman et al., 2008), lubricants (Sharma et al., 2009) and biodiesel (Mofijur et al., 2014; Rashid et al., 2008). *Moringa* oil has a high concentration of oleic acid (>73%) and very low amount of polyunsaturated fatty acids (<1%), resulting in a high tendency to resist oxidation (Ayerza, 2011). Biodiesel derived from *Moringa* oil has been found to have a high cetane number (Rashid et al., 2008). In addition, biodiesel derived from vegetable oils with a high fraction of monounsaturated fatty acids is known to have satisfactory balance between different fuel properties (Moser, 2012). Therefore, *Moringa* oil, specifically, is a new promising feedstock for biodiesel production with the added advantage of the edibility of the other parts of the tree. Consequently, *Moringa* tree can potentially replace the other conventional non-edible feedstock for biodiesel

production, such as *Jatropha curcas* which is inherently toxic (Devappa et al., 2010; Schill, 2008).

In this paper, a new prospect for *M. peregrina* seeds is investigated. The seed oil cake and seed husk (seed coat) were evaluated as sources for bio-fuel using thermochemical characterization. Physico-chemical characteristics, thermo-oxidative stability and fatty acid profile of the seed oil were studied to investigate its potential as a new promising source for biodiesel production. The properties of *M. peregrina* seed oil and biomass residues were compared to the properties of *J. curcas* and *M. oleifera* seeds as reported in literature. 100% utilization of *M. peregrina* seeds as a source of bio-fuel may give this tree additional economic value for domestication and cultivation, making biodiesel industry more sustainable and environmentally friendly.

2. Materials and methods

2.1. Seed collection

Dried *M. peregrina* seeds were obtained from Wadi Alkasinger in the Northern State of Sudan. The seeds were collected with the aid of Forest National Corporation of River Nile State during the season of 2011. The seeds were cleaned to remove damaged seeds, wood, leaves, stones, dust and any other foreign materials. Cleaned seeds were stored in black plastic bags. The seeds were then characterized according to the scheme shown in Fig. 1.

2.2. Physical characteristics of the seeds

Seed and kernel were characterized for weight and oil yields. For weight determination, 100 seeds were selected randomly and weighed to the nearest ± 0.0001 g using a sensitive digital electronic analytical balance. The weight of the kernel was measured after removing the husk (seed coat) by a nutcracker. The weight of the seed and kernel were reported as mean \pm SD of triplicate determination.

Prior to oil extraction, kernels were ground and sieved to less than 1 mm in size before being dried in oven at 60 °C for 24 h. Soxhlet extraction and n-hexane (300 ml) were used to extract oil from the 50 g-sample. The solvent was recovered after 8 h of extraction by a rotary vacuum evaporator at 40 °C and 280 mbar. The oil was then placed in the oven at 70 °C until there was no significant drop in the weight to ensure complete solvent evaporation. The oils yield

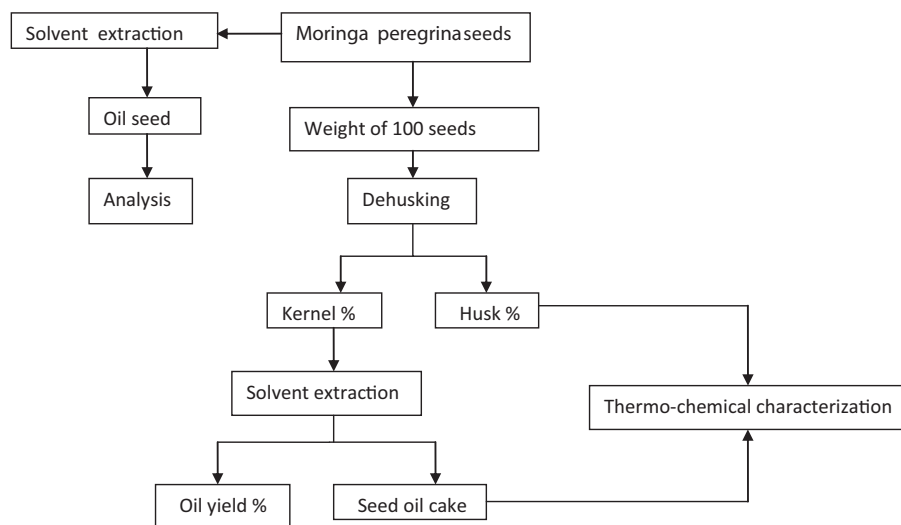


Fig. 1. Scheme of analytical procedure followed for seed characterization.

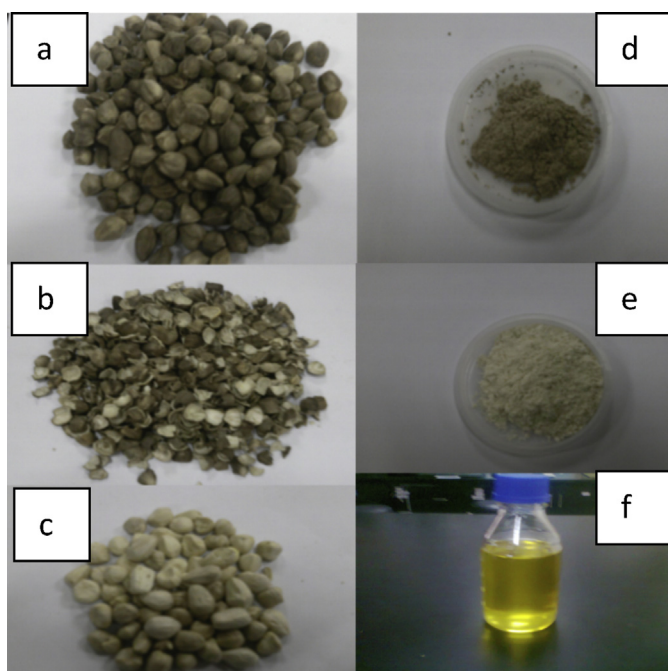


Fig. 2. (a) *Moringa peregrina* seeds, (b) *Moringa peregrina* seed husk, (c) *Moringa peregrina* kernel, (d) *Moringa peregrina* seed husk powder, (e) *Moringa peregrina* seed oil cake and (f) *Moringa peregrina* seed oil.

(dry weight basis) were calculated and reported as mean \pm SD from triplicate determination Fig. 2 shows the images of *M. peregrina* seeds, seed kernel, seed husk, seed oil, and seed oil cake.

2.3. Thermochemical characterization of *M. peregrina* seed husk and *M. peregrina* seed oil cake

Thermochemical characterization is an effective tool to assess the efficiency of thermochemical conversion processes of new biomass feedstock into solid bio-char, liquid fuel and gases. Proximate analysis, ultimate analysis, heating value, thermo-gravimetric analysis and ash elemental compositional analysis were carried out on the two biomass samples. Prior to analysis, the biomass samples were ground and sieved to less than 1 mm in size before being dried in oven at 60 °C for 24 h.

2.3.1. Proximate and ultimate analysis

Proximate analysis was performed on the biomass samples to determine moisture, volatiles, ash and fixed carbon contents while ultimate analysis was carried out to determine carbon, hydrogen, nitrogen, sulfur and oxygen contents in the biomass samples. Moisture and volatile matter were determined by thermo-gravimetric analysis; Ash content was determined according to the standard laboratory analytical procedure developed by National Renewable Energy Laboratory (NREL) (Sluiter et al., 2008); The fixed carbon content was calculated by difference; Carbon, hydrogen, nitrogen and sulfur were determined simultaneously by using Perkin Elmer 2400 elemental analyzer based on flash combustion of samples in a pure oxygen environment; Oxygen content was calculated by difference; Major ash forming metals and other minor elements were determined by using PANalytical Axios lower power (1 kW) wavelength dispersive X ray fluorescence (WDXF) spectrophotometer. The results were reported as metal oxides percentage of ash.

2.3.2. Heating contents

C2000 basic IKA adiabatic oxygen bomb calorimeter was used to measure the higher heating values of the two biomass samples

according to the ASTM 2015 standard test method and the results were reported on dry basis. Since the heat content of a biomass depends on its chemical composition, a unified correlation, as presented below, was used to calculate the higher heating values based on the elemental analysis (Channiwala and Parikh, 2002).

$$\text{Higher heating value (HHV, MJ/kg)} = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211\text{Ash}, \quad (1)$$

where C, H, S, O, N, are carbon, hydrogen, sulfur, oxygen and nitrogen respectively.

2.3.3. Thermo-gravimetric analysis

A thermo-gravimetric analyzer (TA instrument Q500 TGA) was used to investigate the thermal behavior of the biomass samples in an inert atmosphere (N₂ at a flow rate of 100 ml/min). The sample (5–7 mg) was placed in a ceramic pan. Initially, the heating rate of 10 °C/min was used to raise the temperature of the sample from room temperature to 110 °C with a holding time of 10 min to obtain the weight loss caused by the removal of water. Then, the heating rate was increased to 20 °C/min and the sample was heated up to 950 °C with a holding time of 10 min to assess the devolatilization of organic matter (Munir et al., 2009). The software of the instrument was used to analyze the data obtained from the TGA (i.e. weight loss percentage versus temperature) and DTG (i.e. derivative weight loss versus temperature) curves. The reproducibility of the analysis was satisfactory since the difference between two consecutive runs was less than 3%.

2.4. Potentiality of *M. peregrina* seed oil for biodiesel production

The quality of biodiesel depends on the chemical, physical and thermal properties of the feedstock. Characterization was done on the oil extracted from the whole seed (kernel and husk) because it was impractical to dehusk sufficient amount of the seeds manually. Dried *M. peregrina* seeds were crushed to fine powder and extracted by a soxhlet extractor (500 g) using n-hexane. After evaporation of the solvent, the oil was dried with sodium sulfate anhydrous, filtered and kept in refrigerator at 4 °C until analysis.

2.4.1. Physicochemical characterization

Acidity, iodine number and saponification values were determined according to the methods of Kuntom et al. (2005). Acidity was expressed as free fatty acids percentage (FFAs %) as oleic. Acid value was obtained by multiplying FFAs% by the factor of 1.99.

The calorific value was determined by using C2000 basic automatic calorimeter (IKA, UK). The other physical properties were carried out according to the ASTM D6751 standard. Automatic SVM 3000 Stabinger Viscometr (Anton Paar, UK) was used to determine viscosity (D445) and density (D1298) simultaneously at 40 °C. A fully automated cloud point (CP) and pour point (PP) tester (model NTE 450, REF 60300 (Normalab, France)) was used to determine CP (D2500) and PP (D97).

2.4.2. Phosphorus analysis

The analysis was carried out by using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Perkin Elmer Optima 7300 Dv, Shelton CT, USA) equipped with Winlab32 software version 4. The samples were diluted by using weight ratio of 1:5 and directly injected into the plasma of the ICP-OES spectrophotometer. For external calibration, standard solutions of 0, 0.5, 5, 10 ppm were prepared from a 1000 ppm-organic-P standard solution in base oil (Conostan, SPC, Canada). Xylene (ACS reagent, J.T. Baker, USA) was used to dilute the samples and standards while Base oil 75 cSt was used as blank.

2.4.3. Thermo oxidative stability

The crude oil sample (10 mg) was placed in a ceramic pan and put on the thermo-balance of a thermo-gravimetric analyzer (TA instruments, TGA Q500) in order to study the thermal behavior of the oil in an inert atmosphere of N₂ (at a flow rate of 100 ml/min). The temperature of the sample was raised from 30 °C to 700 °C with a heating rate of 10 °C/min. The onset and offset temperatures of decomposition of oil were obtained using the software of the instrument to evaluate the thermal stability and volatility of the oil. A differential scanning calorimeter (Mettler-Toledo DSC822e) was used to obtain the heat of decomposition. The oil sample (10 mg) was sealed in an aluminum crucible by using a lid with a hole and scanned with a constant heating rate (10 °C/min) from 30 °C to a maximum of 500 °C under the flow of N₂ (50 ml/min). An empty pan was used as a reference. The software of the instrument was used to calculate the area under the endothermic peaks to obtain the heat of decomposition. Oxidative stability of the crude oil was determined according to Method EN 14112 by using 873 biodiesel Rancimat from Metrohm.

2.4.4. Fatty acid profiles

Triglycerides were converted to methyl esters according to the base catalyzed-transesterification method described by Christie (1989). The fatty acid methyl esters (FAMES) were analyzed by using gas chromatography. 1 µl of the sample was injected into a gas chromatograph (GC Shimadzu, GC 2010 series) equipped with FID detector and polar capillary column (BPX70) of 30 mm × 0.32 mm ID and 0.25 µm film thickness. The temperature of the column was raised from 140 °C to 220 °C at a rate of 8 °C/min. The initial and final temperatures were held for 2 and 5 min respectively. The temperatures of the injector and detector were 240 °C and 260 °C respectively. Helium was used as a carrier gas with a column flow rate of 1.1 ml/min at a split ratio of 50:1. Reference FAMES (C₄–C₂₄) from Supelco, Bellefonte, USA was used to identify the FAMES qualitatively. The percentage of each component was calculated from the integrated peak area.

3. Results and discussion

3.1. Physical characteristics of the seeds

Weight of seed, kernel and husk, along with the oil yield from the kernel of *M. peregrina* seed are given in Table 1. These data revealed that *M. peregrina* seed is a potential source for solid and liquid biomass materials.

From Table 1, the weight of 100 seeds of *M. peregrina* was 70.54 ± 0.15 g. The seed contained 59.90 ± 1.05% kernel and 41.34 ± 0.76% husk. The weight of 100 seeds of *M. oleifera* (the common species of the family) was observed to be in the range of 29.6–30.2 g with 75:25 kernel to husk percentage ratio of the whole seed (Foidl et al., 2001). There was a large difference in the weight of 100 seeds between the two species as the two species were grown under different climates. *M. oleifera* is thought to be native to tropical dry forests of northeastern India (Olson, 2010), which are much moister than the dry lands where *M. peregrina* is

Table 1
Physical characteristics of *Moringa peregrina* seed.^a

Parameter	Value
Weight of whole seed (kernel + husk) (g/100 seeds)	70.54 ± 0.15
Weight of kernel (g/100 seeds)	41.38 ± 0.42
Kernel fraction (% of entire seed)	58.90 ± 1.05
Husk fraction (% of entire seed)	41.34 ± 0.76
Oil yield (wt% of kernel) ^b	38.33 ± 0.65

^a All values are mean ± SD from triplicate determination on dry basis.

^b Dry base.

found. As a result, we expect that *M. peregrina* would perform better than *M. oleifera* in the Red Sea area, Southern Arabia and areas with similar climates, where it is native. Therefore, trials are currently conducted to compare *M. oleifera* with *M. peregrina*.

The oil yield from *M. peregrina* seed kernel in this study was found as 38.33 ± 0.65% on dry weight basis, falling in the range of 38–42% that was reported by many researchers for *M. oleifera* seed kernel (Mani et al., 2007). However, this yield can be improved by proper propagation and cultivation since higher values (54.29–57.25%) were reported by Osman and Abohassan (2012) for *M. peregrina* kernel seed oil from Saudi Arabia. According to Ibrahim et al. (1974), content and properties of Moringa seed oil depend on the species and the environmental condition.

3.2. Thermochemical characterization of *M. peregrina* seed husk and *M. peregrina* seed oil cake

3.2.1. Proximate analysis, ultimate analysis and heating value

Table 2 shows the results of proximate analysis, ultimate analysis and heating values of the solid biomass derived from *M. peregrina* seed. The table also compares such results with those of *M. oleifera* and *Jatropha* published in literature. Biomass residues are produced as by-products in the oil extraction process from the seeds. These parameters indicate the suitability of biomass for bio-fuel production using thermochemical conversion processes. High moisture and ash contents have a negative impact on the process. Both of them reduce the heating content of the biomass at high level. Moisture reduces combustion temperature and accelerates microbial degradation. Generally, ash content in biomass varies from 10% to 40% and high ash content (>10%) leads to slag deposition on the bottom of the furnace. On the other hand, high volatile matter in biomass has a positive impact on the thermochemical conversion process, where high yields of bio-oil and syngas can be produced (García et al., 2012). The results of proximate analysis presented in Table 2 show that both *M. peregrina* seed husk and *M. peregrina* seed oil cake had low moisture and ash contents (<5%) with high volatile matter (>75%). These results indicate the suitability of these residues to produce energy by a thermochemical conversion process such as pyrolysis or gasification. Moreover, low moisture content indicates the capability of these residues to last longer in storage without excessive deterioration in their energy content. Low moisture content may be attributed to the dry climate in the North of Sudan where this plant grows wildly. Fixed carbon of both husk and seed oil cake falls within the common range of biomass between 7% and 20% (García et al., 2012). No previous studies on *M. oleifera* seed husk were found. However, a report on *M. oleifera* seed oil cake from West Africa has been reviewed (Titiloye et al., 2013). This report, as well as the information depicted in Table 2, show that *M. oleifera* seed oil cake had higher moisture and ash contents but similar volatile matter and smaller fixed carbon compared to the biomass residues from *M. peregrina* seeds. The difference in moisture and ash contents observed for *M. oleifera* and *M. peregrina* is attributed to different soil properties and climate conditions under which they grow. Same observations were noted when the comparison was carried out on the *Jatropha* seed oil cake. However, *Jatropha* seed husk, besides higher water content, showed relatively low volatile matter and almost doubled fixed carbon compared to *M. peregrina* seed husk, indicating that the latter is more reactive than *Jatropha* seed husk.

Higher heating value is an important property to evaluate the quality of a biomass to be used as a feedstock for bio-fuel. It depends on the chemical composition of the biomass. From Eq. (1), higher heating value is affected positively by C and H contents but negatively by O, N and ash contents. However, O content affects the conversion efficiency positively. Carbon conversion to CO depends on the oxygen content in the biomass (bio-oxygen) to prompt the

Table 2Proximate analysis, ultimate analysis and higher heating values (HHVs) of the solid biomass derived from *M. peregrina* seeds in comparison with *Jatropha* and *M. oleifera* seeds.

Parameter	<i>M. peregrina</i> seed husk (this study)	<i>Jatropha</i> seed husk (Kratzeisen and Müller, 2013)	<i>M. peregrina</i> seed oil cake (this study)	<i>M. oleifera</i> seed oil cake (Titiloye et al., 2013)	<i>Jatropha</i> seed oil cake (Titiloye et al., 2013)
Proximate analysis % db^a					
Moisture	4.48	8.96	2.21	10.38	8.5
Volatile matter	75.05	64.9	78.44	75.08	75.13
Fixed carbon	17.73	31.1	15.22	8.26	18.89
Ash	2.40	3.9	4.01	6.28	5.89
Ultimate analysis % daf^b					
C	45.42	50.9	46.42	45.59	44.42
H	6.34	5.8	7.76	6.28	6.23
O	46.73	39.5	36.6	41.45	44.51
N	0.94	0.8	8.03	6.47	4.33
S	0.57	0.08	3.19	–	0.51
Carbon conversion %	77.16	58.20	59.13	68.18	75.15
Higher heating value (MJ/kg)	18.21	17.98	20.65	20.47	21.24
Higher heating value ^c (MJ/kg)	18.49	20.36	19.05	19.05	18.09

^a Dry basis.^b Dry and free ash.^c Calculated from the Eq. (1).

auto-gasification reaction (Kirubakaran et al., 2009). Results of ultimate analysis, calculated and experimental higher heating values, along with carbon conversion percentage are presented in Table 2. Higher heating values (HHVs MJ/kg on dry basis) of *M. peregrina* seed husk and *M. Peregrina* seed oil cake based on the calorimetric measurements were 18.21 and 20.65 with a deviation of +0.28 and –1.29, from the calculated values respectively. Higher measured value for the seed oil cake may be due to the trace of residual oil retained in the particles of the seed oil cake. These values indicate the potentiality of these biomass residues to produce bio-oil liquids by thermochemical conversion. Both *M. peregrina* seed husk and *Jatropha* seed husk were found to contain a small amount of N and S (<1%), minimizing the emission and impacts of NO_x and SO₂ on the environment. However, the emission behavior during the combustion of the seed oil cake of *M. peregrina*, *M. oleifera* and *Jatropha* which contained 8.03%, 6.47% and 4.33% of N (on dry basis) respectively should be observed. Furthermore, *M. peregrina* seed oil cake had high sulfur content (3.19% on dry basis). High sulfur content in biomass affects the efficiency of heat exchanger due to depositions of sulfate or ashes which are generated by SO₂ emissions. Nitrogen content of *M. peregrina* seed oil cake yields 50% of protein when multiplied by the universal factor of 6.25. High protein content indicates the potential use of *M. peregrina* seed oil cake as an animal feed or fertilizer since the cake contains no toxic (Foidl et al., 2001). Moreover, many reports have proven that Moringa seed oil cake extract contains proteins that are effective in purification of water and wastewater (Ghebremichael et al., 2005; Bhatia et al., 2007; Pritchard et al., 2010). Aqueous extraction of soluble protein from *M. peregrina* seed oil cake prior to combustion may reduce the content of nitrogen. However, further verification is needed.

3.2.2. Ash composition

The combustion behavior of biomass depends on the ash composition. The major ash forming elements are K, Na, Ca, Mg, Si and P (Díaz-Ramírez et al., 2012). Alkali oxides (K₂O, Na₂O) have high volatility and therefore they vaporize and condensate at low temperature (around 760 °C) on the coldest part of the reactor (Bizzo et al., 2014). Significant fouling and slagging occur when there is high concentration of alkali in combination of sulfur and chlorine (Díaz-Ramírez et al., 2012). Sulfur and chlorine are consumed in the formation of alkali sulfates and chlorides at temperatures less than 800 °C (Raclavska et al., 2011). In Si-rich biomass, slagging is possible at low temperatures due to the formation of alkali silicate (Jenkins et al., 1998). Phosphorus can influence the ash melting behavior in the presence of Ca and K (Darvell et al., 2010). The role

Table 3Ash composition of *M. peregrina* seed husk and *M. peregrina* seed oil cake.^a

Ash composition %	<i>M. peregrina</i> seed husk	<i>M. peregrina</i> seed cake
Na ₂ O	1.43	0.08
MgO	13.37	2.97
Al ₂ O ₃	2.11	0.04
SiO ₂	4.45	0.12
P ₂ O ₅	3.89	13.77
SO ₃	11.26	60.16
K ₂ O	14.30	15.84
CaO	40.39	6.19
Fe ₂ O ₃	4.56	0.17
ZnO	0.29	0.2
SrO	0.36	0.05
Cl	1.41	0.21
TiO ₂	0.45	–
NiO	0.32	–
Pr ₂ O ₃	1.38	–
Al ^b (kg/GJ)	0.21	0.24

^a Dry basis.^b Alkali Index.

of alkali in ash deposition is obvious. The slagging and fouling can be predicted from the alkali index (AI), which is the quantity of alkali oxide in the fuel per unit of fuel energy as presented in Eq. (2). The tendency of fuel to foul and slag increases above the alkali index of 0.17 kg/GJ and becomes inevitable when the index exceeds the threshold value of 0.34 kg/GJ (Jenkins et al., 1998).

$$\text{Alkali Index (AI)} = \left(\frac{1}{Q} \right) \text{Ash\% (K}_2\text{O} + \text{Na}_2\text{O)\%} \quad (2)$$

Q is the higher heating value in GJ/kg.

From Table 3, the major elements in the ash of *M. peregrina* seed husk and seed oil cake in descending order were Ca, K, Mg, S and Si, K, P, Ca, respectively. Both of them had low content of silica. *M. peregrina* seed husk had high content of chloride (1.43%) compared to its seed oil cake (0.216%). The alkali indices (AI, kg/GJ) of the seed husk and seed oil cake were 0.21 and 0.24, respectively. These values indicate that high concentration of K₂O leads to high tendency of fouling and slagging. Besides, *M. peregrina* seed oil cake contained SO₃ in considerable amount, whereas *M. peregrina* seed husk contained significant amount of P₂O₅ and CaO. Leaching of alkali metals and chlorine from biomass fuel by water washing has been found effective in improving the fusion temperature and reducing the ash depositions (Jenkins et al., 1998). Blending the biomass with coal fuel has also been found effective to prevent the slagging and fouling problems (Raclavska et al., 2011).

3.2.3. Thermo-gravimetric analysis

Pyrolysis is the most attractive thermo-chemical conversion process because it produces gases, bio-oil and char. The thermal behavior of the biomass samples was investigated by thermo-gravimetric (TGA) and derivative thermo-gravimetric

(DTG) analyses in an inert atmosphere of nitrogen with a heating rate of 20 °C/min. Both TGA and DTG are a useful tool to reveal the thermal characteristics of biomass which is to be considered in the optimal design of a thermochemical conversion reactor. Figs. 3 and 4 show the TGA and DTG curves of *M. peregrina* seed

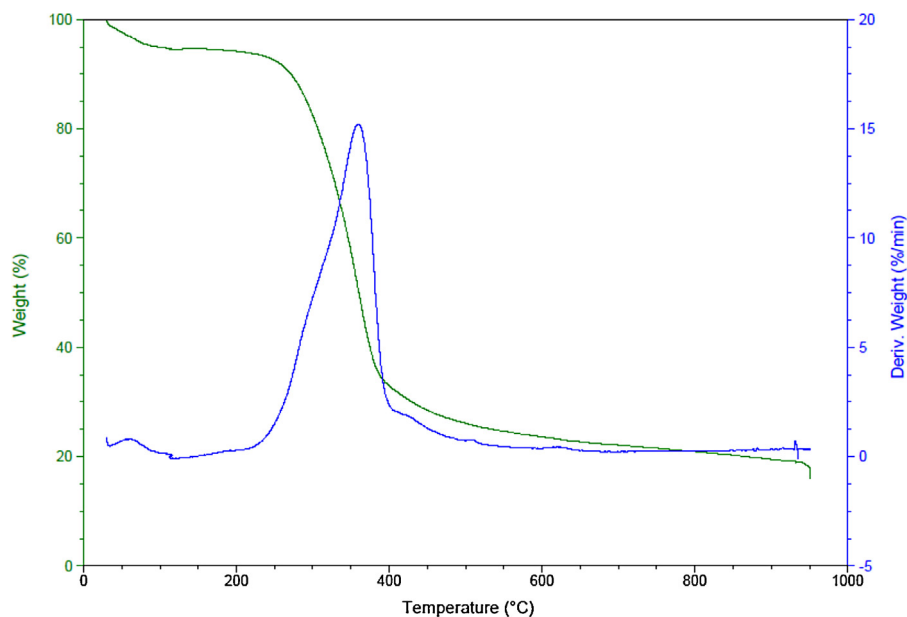


Fig. 3. TGA and DTG of *M. peregrina* seed husk, heating rate 20 °C/min in nitrogen.

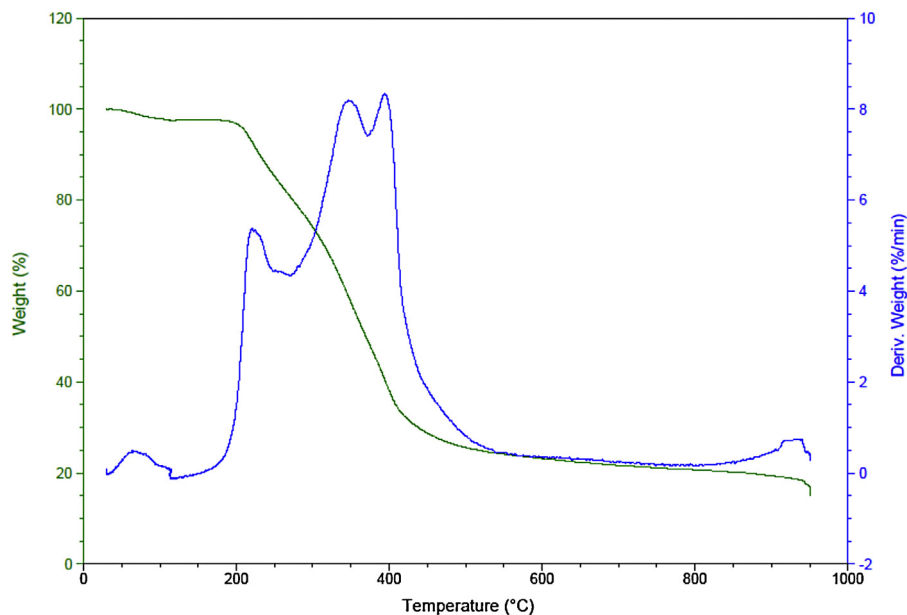


Fig. 4. TGA and DTG of *M. peregrina* seed oil cake, heating rate 20 °C/min in nitrogen.

Table 4

Devolatilization of *M. peregrina* seed husk and *M. peregrina* seed oil cake with heating rate 20 °C/min in nitrogen.

Biomass material	Pyrolysis active zone temperature range (°C)	T_{\max}^a (°C)	R_{\max}^b (wt%/min)	VM ^c (wt%)
<i>M. peregrina</i> seed husk	202–536	360.68	15.20	69.64
<i>M. peregrina</i> seed oil cake	175–538	221.17 348.12 395.27	5.36 8.185 8.832	72.97

^a Temperature of the maximum weight loss.

^b Maximum degradation rate.

^c Volatile matter.

husk and *M. peregrina* seed oil cake, respectively. Table 4 shows the thermal degradation temperature range in the active zone of pyrolysis, along with the corresponding percentage of volatile matter (VM) released. Maximum degradation rate (R_{\max} i.e. peak height) and corresponding temperature of maximum weight loss (T_{\max} i.e. peak temperature) were also included. The reactivity of the biomass fuel is directly proportional to the maximum degradation rate and inversely to the temperature of maximum weight loss (Ghetti et al., 1996). TGA curve, confirmed by the DTG curve shows three distinct stages of mass loss. The first stage ranges from ambient temperature to about 115 °C due to evaporation of intrinsic water from dried biomass samples. This stage appears as a small peak in the DTG curve with a very low degradation rate because of low water content in the samples. The second stage is considered as the active zone of pyrolysis because it shows a great loss of mass due to devolatilization of organic matter. The third stage is considered as a passive zone because it extends as a tail with a very low degradation rate and loss of mass with no remarkable peak. In this study, it was found that both *M. peregrina* seed husk and *M. peregrina* seed oil cake had almost comparable final temperature of 536 and 538 °C, respectively, at the active zone. However, *M. peregrina* seed oil cake showed low initial degradation temperature (175 °C) compared to *M. peregrina* seed husk (202 °C). The initial degradation temperature varies among biomass fuels because of their difference in elemental and chemical composition (Munir et al., 2009). Mineral contents, particularly potassium and phosphorus decrease the initial degradation rate of pyrolysis due to their catalytic effect (Fahmi et al., 2007; Fuentes et al., 2008). It was observed that *M. peregrina* seed oil cake had higher phosphorus content (13.78% of ash on dry basis) than *M. peregrina* seed husk (3.89% of ash on dry basis) but they had comparable fractional content of K_2O in their ash. However, higher ash content of *M. peregrina* seed oil cake (4.01% db) compared to *M. peregrina* seed husk (2.41% db) may cause the lower initial degradation temperature of *M. peregrina* seed oil cake. The DTG curve shows three peaks for *M. peregrina* seed oil cake and a single peak for *M. peregrina* seed husk in the pyrolytic active zone, indicating that the pyrolysis of *M. peregrina* seed oil cake is more complex than *M. peregrina* seed husk. In addition, *M. peregrina* seed husk is more reactive than *M. peregrina* seed oil cake, because it was found to have maximum degradation rate (15.20 wt%/min), almost doubling the maximum degradation rate of *M. peregrina* seed oil cake (8.83 wt%/min); and lower maximum temperature of mass loss, as presented in Table 4. The pyrolytic behavior of a biomass fuel is usually discussed in the light of its structural composition. Hemi-cellulose, cellulose and lignin are the major components of biomass.

Hemi-cellulose and cellulose are saturated polysaccharide compounds and lignin has aromatic cross-linked structure (Ghetti et al., 1996). According to Yang et al. (2007), lignin decomposes in a wide range of temperature of 100–900 °C. Hemi-cellulose and cellulose decompose at a narrower range of 220–315 °C and 315–400 °C respectively. Hence, devolatilization in the active zone is due to the decomposition of hemicelluloses, cellulose and part of lignin. High initial degradation temperature and maximum degradation rate of *M. peregrina* seed husk are indications of high contents of cellulose (Mansaray and Ghaly, 1998). The humps shoulder peaks observed on the DTG curve of *M. peregrina* seed oil cake indicate decomposition of hemi-cellulose (Titiloye et al., 2013). During pyrolysis, biomass fuels rich in hemi-cellulose produce higher CO_2 , while those rich in cellulose produce higher CO. Meanwhile, biomass fuels rich in lignin produce higher H_2 and CH_4 besides generating high char (Yang et al., 2007). The total volatile matter in the active zone was slightly higher for *M. peregrina* seed oil cake compared to *M. peregrina* seed husk. This coincides with the result of proximate analysis, which showed higher volatile matter for *M. peregrina* seed oil cake compared to *M. peregrina* seed husk. The residues for both *M. peregrina* seed husk and *M. peregrina* seed oil cake at 950 °C were almost similar, suggesting that they have comparable contents of lignin.

3.3. Potentiality of *M. peregrina* seed oil as a feedstock for biodiesel production

Properties and fatty acid profile of the raw vegetable oil determine its suitability as a feedstock for biodiesel production. Table 5 shows some chemical and fuel properties of *M. peregrina* seed oil. Table 6 shows the fatty acid profile of *M. peregrina* seed oil in comparison to the fatty acid profile of *J. curcas* seed oil, which has been given wide attention as a promising non-edible feedstock for biodiesel production. This comparison was meant to prove the competitiveness of *M. peregrina* seed oil over *J. curcas* seed oil which is apparently produced from toxic plants. Fatty acid profile of *M. oleifera* seed oil from Pakistan, reported by Anwar et al. (2005) was also included for comparison study between the two species in the same family.

3.3.1. Physicochemical characterization and thermo oxidative stability of *M. peregrina* seed oil

Density is defined as mass of a volume unit, commonly expressed as kilogram of one cubic meter (kg/m^3). Therefore, fuel density, in relation to the heat content, can be used to calculate the fuel consumption (Lapuerta et al., 2010). Fuel density is directly

Table 5
Chemical properties and some fuel properties of *M. peregrina* seed oil in comparison to *M. oleifera* seed oil, *J. curcas* seed oil and Diesel 2.

Parameter	<i>M. peregrina</i> seed oil (this study)	<i>J. curcas</i> seed oil ^a	<i>M. oleifera</i> seed oil ^b	Diesel 2 ^c
Fuel properties				
Density (kg/m^3)	896.7	901–940 ^d	897.1	–
Kinematic viscosity (mm^2/s)	34.184	24.5–52.76 ^d	29.63	2.5
Calorific value (MJ/kg)	39.99	38.2–42.15 ^d	–	45.5
Cloud point (°C)	3.00	–0.01–2.9	5	–15
Pour point (°C)	0.00	–3.25–0.7	4	–28
Chemical properties				
Acid value (mg KOH/g)	0.70	0.9–35.3	2.9	–
Free fatty acid (oleic %)	0.35	0.45–17.65	1.45	–
Iodine value ($gI_2/100g$)	67.73	90–98	67.2–71 ^e	–
Saponification value (mg KOH/g)	187.53	–	–	–
Phosphorus (ppm)	12.75	10.9–251.9	–	–
Induction period (h)	30.06	10–24.9	15.32	–

^a Rathbauer et al. (2012).

^b Rashid et al. (2008).

^c Zhang et al. (1996).

^d No (2011).

^e Anwar et al. (2005).

Table 6
Fatty acid profile of *M. peregrina* seed oil (% by weight) in comparison to *M. oleifera* seed oil and *J. curcas* seed oil.

Fatty acid	Formula	<i>M. peregrina</i> seed oil present study ^a	<i>M. oleifera</i> seed oil ^b	<i>J. curcas</i> seed oil ^c
Palmitic (C16:0)	C ₁₆ H ₃₂ O ₂	9.90 ± 0.06	0.5–6.26	17.03–19.3
Palmitolic (C16:1)	C ₁₆ H ₃₀ O ₂	3.03 ± 0.02	0.5–1.10	0.94–1.19
Stearic (C18:0)	C ₁₈ H ₃₆ O ₂	3.85 ± 0.03	4.47–6.00	6.08–9.23
Oleic (C18:1)	C ₁₈ H ₃₄ O ₂	72.19 ± 0.13	72–76.00	35.08–42.76
Linoleic (C18:2)	C ₁₈ O ₃₂ O ₂	4.27 ± 0.07	0.87–1.65	31.58–38.5
Linolenic (C18:3)	C ₁₈ H ₃₀ O ₂	–	0–0.2	0
Arachidic (C20:0)	C ₂₀ H ₄₀ O ₂	2.19 ± 0.08	3.5–4.0	0
Eicosenoic (C20:1)	C ₂₀ H ₃₈ O ₂	1.73 ± 0.05	0.97–2.00	0
Behenic (C22:0)	C ₂₂ H ₄₄ O ₂	2.84 ± 0.04	5.65–7.00	–
Total unsaturated fatty acids		81.24 ± 0.08	73.47–86.1	67.6–82.45
Total saturated fatty acids		18.76 ± 0.08	14.12–23.26	23.11–25.38

^a The values are a mean ± SD from three injection.

^b Anwar et al. (2005).

^c Rathbauer et al. (2012).

proportional to its molecular weight (Shahabuddin et al., 2012). From Table 5, the density of *M. peregrina* seed oil (896.7 kg/m³) is comparable to *M. oleifera* seed oil (897.1 kg/m³) and *J. curcas* seed oil (901–940 kg/m³), indicating that *M. peregrina* seed oil has a molecular weight in the range of 600–900 as a typical vegetable oil (Srivastava and Prasad, 2000). However, the density of *M. peregrina* seed oil is higher than the standard range (820–845 kg/m³) as currently required by the international ASTM standards and European specifications (prEN:590:2003) for automotive diesel fuel. Consequently, this affects the proper engine operation and increases the emissions due to delivery of greater amount of fuel to the atomization unit (Kesari et al., 2010; Lapuerta et al., 2010).

Kinematic Viscosity is a measurement for the fluidity of fuel that is inversely proportional to the flow rate of the fuel through the fuel tube line (Shahabuddin et al., 2012). Therefore, it is the most important property in evaluation of a vegetable oil as a fuel. From Table 5, *M. peregrina* seed oil had a kinematic viscosity (34.18 mm²/s) at 40 °C which is 13 times greater than the viscosity of diesel fuel at the same temperature. High viscosity of vegetable oils is attributed to high molecular weight and chemical structure of triglycerides (Srivastava and Prasad, 2000). The volatility of *M. peregrina* seed oil can be deduced from the thermo-gravimetric analysis. Both TGA

and DTG curves of *M. peregrina* seed oil (Fig. 5) show 97.06% of mass loss of the oil between 378.35 °C (T_{onset} temperature) and 432.00 °C (T_{offset} temperature). The temperature at which the maximum mass loss occurred was 409.35 °C and the rate of maximum mass loss was 16.98 wt%/min. This thermal behavior of *M. peregrina* seed oil was further investigated by differential thermal analysis. The DSC curve (Fig. 6) shows only a single endothermic peak, which was definitely due to decomposition of the unsaturated and saturated triglycerides with enthalpy change (227.43 J/g). No exothermic peaks appear in the curve, indicating the absence of auto-oxidation (Neto et al., 2009). High initial degradation temperature and high value of heat of decomposition of *M. peregrina* seed oil indicate that *M. peregrina* seed oil has significant thermal stability. However, low volatility besides the high viscosity in *M. peregrina* seed oil lead to poor atomization, incomplete combustion, polymerizations and depositions when used directly in a compression ignition engine. Conversion of vegetable oil to fatty acid alkyl ester through transesterification process could reduce the volatility and viscosity to a range comparable to diesel fuel (Srivastava and Prasad, 2000). High thermal stability of *M. peregrina* seed oil was accompanied with high oxidative stability as indicated by high induction period i.e. 30.06 h at 110 °C, obtained by the Rancimat apparatus (Fig. 7).

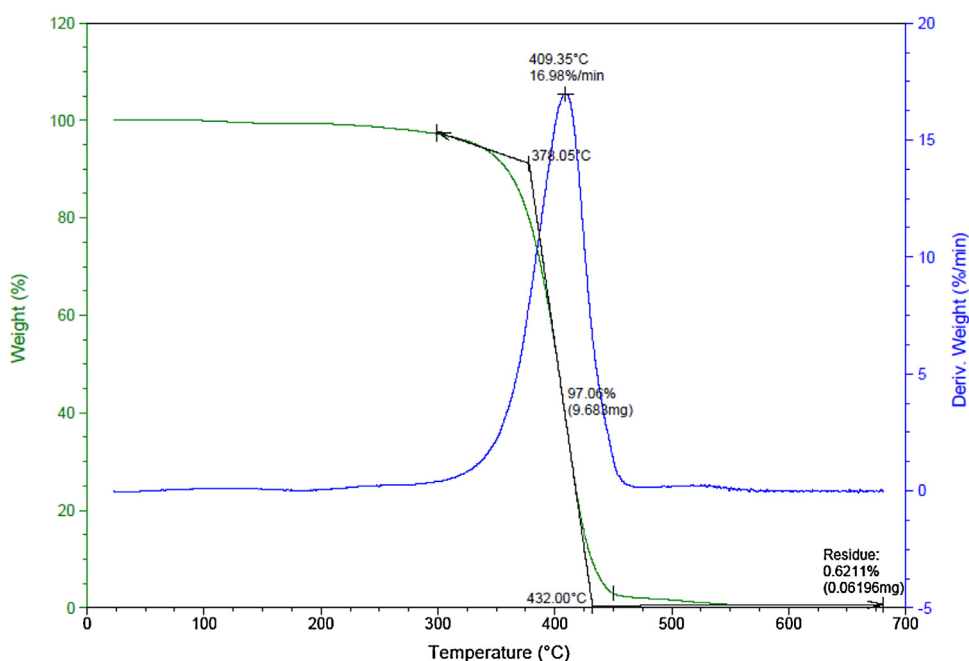


Fig. 5. TGA and DTG of *M. peregrina* seed oil in nitrogen, heating rate 10 °C/min.

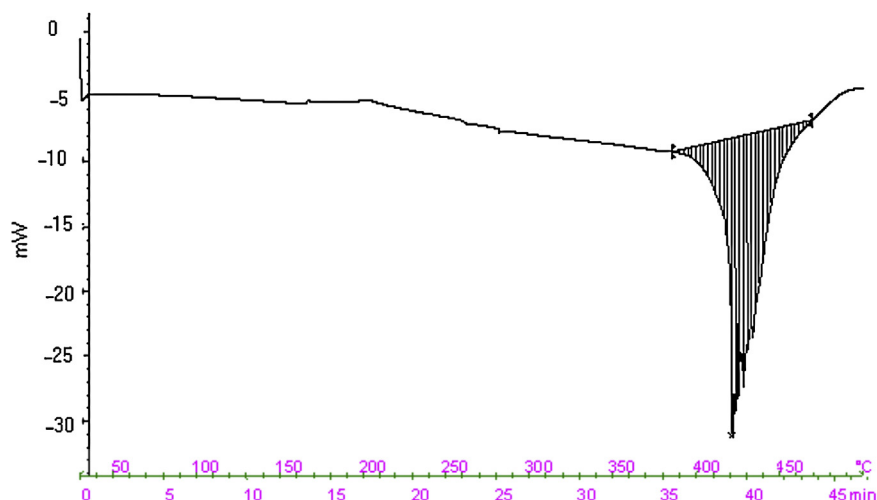


Fig. 6. DSC curve of *M. peregrina* seed oil in nitrogen heating rate 10 °C/min.

In contrast, the induction period of *J. curcas* seed oil ranged from 10.0 to 24.9 h whereas the induction period of *M. oleifera* seed oil was 15.32 h as presented in Table 5. Additionally, the initial thermal degradation temperatures of *J. curcas* seed oil and *M. oleifera* seed oil were 347 °C and 322 °C respectively, when exposed to heat in an inert atmosphere of nitrogen with a heating rate of 10 °C/min, as reported by Sharma et al. (2009). High thermal and oxidative stability of *M. peregrina* seed oil compared to *J. curcas* seed oil and *M. oleifera* seed oil may indicate higher concentrations of natural antioxidants in *M. peregrina* seed oil (Rashid et al., 2008).

The calorific value of *M. peregrina* seed oil (39.99 MJ/kg) falls in the range that is common for vegetable oils (39–40 MJ/kg). However, it is less than the value of diesel fuel, which is around 45 MJ/kg. Attachment of oxygen directly to the backbone of the triglyceride structure reduces the heating value by approximately 10% compared to diesel fuel (Srivastava and Prasad, 2000).

Cloud point and pour point are two important parameters to assess fuel efficiency in compression ignition engines in

low-temperature seasons. They are usually used to describe the crystallization behavior of fuel. Cloud point is the temperature at which crystals of the fuel components become visible. Pour point is the lowest temperature at which the fuel cannot flow. Vegetable oil or its derived biodiesel that has high cloud point and pour point causes severe operational fouling when used in engines during cold seasons due to blockage of the tubing system (Atabani et al., 2012; Dunn, 2009). *M. peregrina* seed oil has cloud point and pour point of 3.00 and 0.00 °C, respectively, whereas, higher values of 5.00 and 4.00 °C were reported for *M. oleifera* seed oil by Rashid et al. (2008). The cold flow property of a vegetable oil depends on its mass fraction of saturated fatty acid esters (melts at temperature higher than 0 °C) and unsaturated fatty esters (melts at temperature lower than 0 °C) (Dunn, 2008).

Acid, iodine and saponification values are the most important chemical properties to assess the viability of a vegetable oil as a feedstock for biodiesel production. Acid value indicates the amount of free fatty acids in vegetable oils. All vegetable oils contain

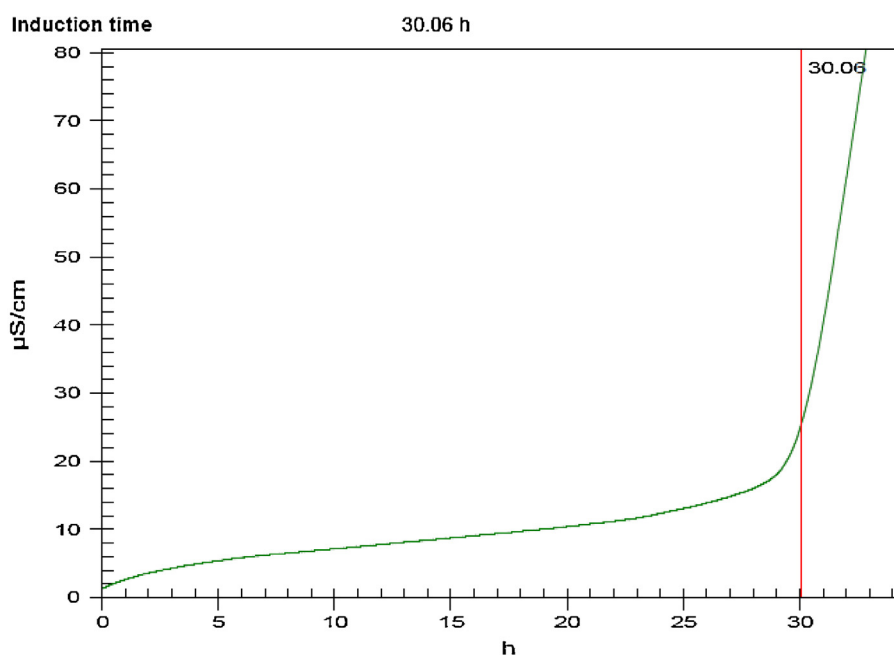


Fig. 7. Rancimat profile of *M. peregrina* seed oil.

naturally low concentrations of free fatty acids due to the lipolysis effect. However, acid value varies among vegetable oils depending on cultivation, harvesting and storage conditions (Rathbauer et al., 2012; Cho et al., 2013). Acid value is a crucial factor that determines the route of transesterification process. Acid value greater than 1 mg KOH/g leads to soap formation that interferes with glycerol separation when alkali is used as a catalyst. This effect reduces the yield of biodiesel substantially (Freedman et al., 1984). The acid value of *M. peregrina* seed oil in this study was found to be very low (0.70 mg KOH/g). Therefore, *M. peregrina* seed oil could be converted to biodiesel in one step by alkaline catalyst. The previously reported acid values for *M. peregrina* seed oil from Egypt and Saudi Arabia were 0.02 mg KOH/g (Abd El Baky and El-Baroty, 2013) and 0.3 mg KOH/g (Tsaknis, 1998), respectively. Anwar et al. (2005) studied the properties variation demonstrated by *M. oleifera* produced in three different provinces in Pakistan. They reported that *M. oleifera* seed oil had an acid value in the range of 1.0–1.47 mg KOH/g while Foidl et al. (2001) reported that *M. oleifera* had an acid value of 5.93 mg KOH/g. Based on Table 5, *J. curcas* seed oil had an acid value in the range of 0.9–35.3 mg KOH/g, obtained from 25 samples investigated in Mali during the 2009 season. Most of them had an acid value more than 1.0 mg KOH/g. The free fatty acids content of *J. curcas* seed oil in the literature varies from 5.0% to 15%, which is equivalent to 10–30 mg KOH/g (Mazumdar et al., 2012). High free fatty acids content in vegetable oil necessitates a pretreatment step by acid catalyst to reduce the acid value to less than 1 mg KOH/g. This incurs additional cost to biodiesel production and it may reduce the oil's oxidative stability due to excessive washing which may remove the natural antioxidants in the feedstock (Rashid et al., 2008). Moreover, free fatty acids work as prooxidant and therefore high contents of free fatty acids in vegetable oils reduce their oxidative stability drastically, especially in long term storage (Waraho et al., 2011). Hence, derived biodiesel from *M. peregrina* seed oil is expected to comply with the maximum limits of oxidation stability (3 and 6 h) required by EN14214 2009 and ASTM 6751, respectively.

Iodine value is directly related to the degree of unsaturation. It can be used as a primary parameter to evaluate the suitability of triglycerides as feedstock for biodiesel production. High iodine value indicates the presence of polyunsaturated fatty acids, which cause bad performance in compression ignition engines due to deposition and polymerization. Moreover, the emission profile of fuel with high iodine value contains higher concentration of NO_x (Puhan et al., 2010). In this study, *M. peregrina* seed oil was found to have an iodine value of 67.73 g I₂/100 g which coincides with its high oxidative stability, making it suitable for biodiesel production. From Table 5, *M. peregrina* seed oil had similar iodine value to *M. oleifera* seed oil (67.2–71 I₂/100 g) and lower iodine value than *J. curcas* seed oil (90–98 I₂/100 g).

Cetane number is another parameter that is related to fuel efficiency in a compression ignition engines. Cetane number indicates the quality of fuel ignition and it is inversely related to the time required for ignition, which means high cetane number indicates satisfactory engine performance (Oliveira and Da Silva, 2013). Cetane number decreases with increasing degree of unsaturation but increases with increasing number of carbon atoms in the fatty acid methyl ester. Saponification value which is the amount of KOH (in milligrams) required to saponify one gram of fat or oil, is inversely related to the molecular weight of the vegetable oil. A relatively high saponification value (187.53 mg KOH/g) was obtained for *M. peregrina* seed oil in this study. Iodine value and saponification value of fatty acid methyl ester do not differ significantly from the parent vegetable oil. Therefore, Krisnangkura (1986) proposed to calculate the cetane number of a vegetable oil methyl ester based on the iodine value (unsaturation factor) and saponification value (length of the carbon chain factor) of the feedstock, as given in Eq. (3). Cetane number is an important parameter which

is considered in the selection of fatty acid alkyl esters as a fuel. The minimum cetane numbers are 47, 49 and 51 for USA (ASTM D6751), Germany (DIN51606) and European Organization (EN14214) standard, respectively. However, high cetane number indicates bad cold flow properties due to increasing degree of saturation (low iodine number). Therefore, the US biodiesel standard, ASTM PS121–99 limits the cetane number by the maximum value of 65 (Azam et al., 2005). According to Eq. (3), the cetane number of *M. peregrina* seed oil methyl ester is 60.16, indicating that the derived biodiesel from *M. peregrina* seed oil has high ignition quality and relatively acceptable cold flow properties. Rashid et al. (2008) reported that the cetane number of biodiesel derived from *M. oleifera* seed oil was 67. The cetane number of *J. curcas* seed oil falls in the range 43–59 as reported by No (2011).

$$CN = 46.3 + \frac{5458}{SV} - 0.225 \times IV \quad (3)$$

CN stands for cetane number, whereas SV and IV are saponification value and iodine value, respectively.

Phosphorus content is a quantitative measurement of the presence of phospholipids in crude oil. High contents of phospholipids render the separation of glycerol from biodiesel difficult. Biodiesel yield can be reduced by 3–5% when the content of phosphorus exceeds 50 ppm. Moreover, high concentration of phosphorus increases the particulate emission (Lu et al., 2009). Therefore, phosphorus content is restricted to 10 ppm in ASTM D6751–11a, whereas EN 1413 (2009) specifies 4 ppm as the maximum limit (Rathbauer et al., 2012). As shown in Table 5, *M. peregrina* seed oil had low concentration of phosphorus (12.75 ppm), eliminating the necessity to degum the oil prior to transesterification and saving the cost of biodiesel production eventually. *J. curcas* seed oil investigated in Mali (Rathbauer et al., 2012) showed higher phosphorus content that varied in the range of 10.9–251.9 ppm. Sanford et al. (2009) reported high phosphorus content (322.9 ppm) for *J. curcas* seed oil and low phosphorus content for *M. oleifera* seed oil (7.3 ppm). The variation in phosphorus content among vegetable oils may be due to different agronomic and environmental conditions or types of extraction (Rathbauer et al., 2012).

3.3.2. Fatty acid profile of *M. peregrina* seed oil

Transesterification reaction does not change the fatty acid composition of vegetable oils. Therefore, biodiesel quality can be predicted from the fatty acid profile of the feedstock (Karmakar et al., 2010). Azam et al. (2005) used fatty acid profile as a tool in screening different feedstock for biodiesel production. Fig. 8 shows the GC chromatogram of methylated *M. peregrina* seed oil. Table 6 shows the fatty acid profiles of *M. peregrina* seed oil in comparison to *M. oleifera* seed oil and *J. curcas* seed oil. The GC analysis revealed that the unsaturated fatty acid composition of *M. peregrina* seed oil was 81.24% in which the total monounsaturated fatty acids was 76.92% due to the presence of oleic acid C18:1 (72.19%), palmitolic C16:1 (3.03%) and eicosenoic acid C20:1 (1.73%). The remaining fraction was polyunsaturated fatty acids due to the presence of linoleic acid C18:2 (4.27) and no linolenic acid was observed. High monounsaturated fatty acids explain the high oxidative stability of *M. peregrina* seed oil observed in this study. It is well known that monounsaturated fatty acids are more resistant to oxidation and deterioration compared to polyunsaturated fatty acids (Moser, 2012). Low content of polyunsaturated fatty acids indicates high value of cetane number. The oils of feedstock like soybean (*Glycine max*), sunflower (*Helianthus annuus*) and grape seed (*Vitis vinifera*) have low cetane numbers because they contain high amount of polyunsaturated fatty acids (C18:2, C18:3) (Karmakar et al., 2010). Moreover, biodiesel with low amount of polyunsaturated fatty acids produces emission profile with low level of NO_x (Nettles-Anderson and Olsen, 2009). The composition of saturated

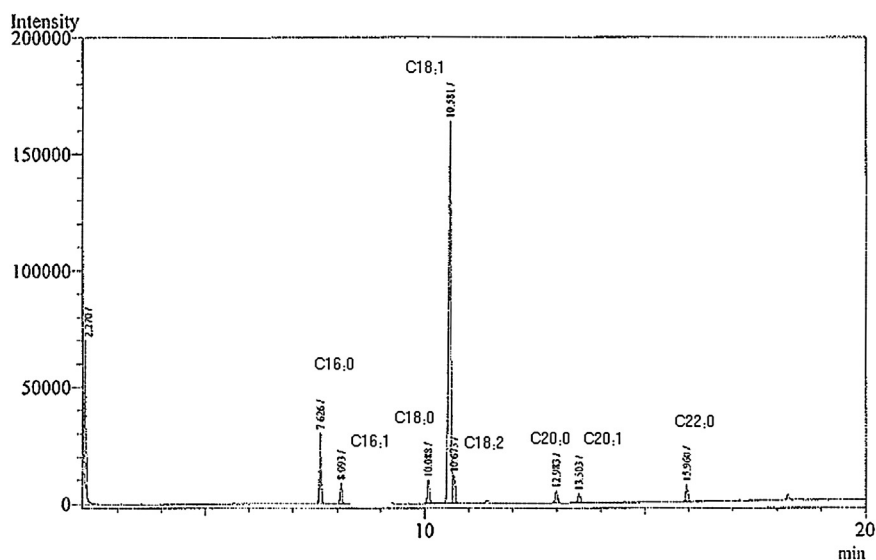


Fig. 8. GC chromatogram of methylated *M. peregrina* seed oil.

fatty acid in *M. peregrina* seed oil was 18.76%. The predominant saturated fatty acid was palmitic C16:0 (9.9%) followed by stearic C18:0 (3.85%), arachidic C20:0 (2.19%) and behenic C22:0 (2.84%). Very long-chain fatty acid composition (C20:0 + C20:1 + C22:0) contributes to 6.76% of the total fatty acid composition of *M. peregrina* seed oil. Saturated fatty acids have high melting points. Hence, oils from feedstock like palm (*Elaeis guineensis*) that contains high amount of saturated fatty acids (C16:0 and C18:0) and peanut (*Arachis hypogaea*) which contains a significant amount of very long-chain saturated fatty acids (C22:0), produce biodiesel with very bad cold flow properties (Karmakar et al., 2010). Therefore, *M. peregrina* seed oil is considered as a promising feedstock to produce high quality biodiesel since it contains high amount of monounsaturated fatty acids and low amount of saturated fatty acids. However, significant amount of behenic acid C22:0 (2.84%) and palmitic acid (9.90%) in *M. peregrina* seed oil, may yield biodiesel with relatively high cold flow properties. Fatty acid composition of *M. peregrina* seed oil reported in this study agrees with those reported for *M. peregrina* seed oil in Saudi Arabia (Tsaknis, 1998) and Jordan (Al-Dabbas et al., 2010) with the exception that *M. peregrina* seed oil in this study contained relatively higher linoleic acid (4.27%) compared to those (0.62% and 0.46%) in Saudi Arabia and Jordan. However, Abd El Baky and El-Baroty (2013) reported significantly higher concentration of linoleic acid C18:2 (15.32%) in Egypt. Compared to *M. oleifera* seed oil, *M. peregrina* seed oil has a similar fatty acid composition but slightly higher linoleic acid. However, *M. peregrina* seed oil still has higher oxidative stability. This may be attributed to their difference in natural antioxidant content. Generally, oil from all species of *Moringa* is characterized by oleic acid as the major component, significant amount of very long-chain fatty acids and very low polyunsaturated fatty acids (Kleiman et al., 2008). It is noteworthy to mention that behenic acid content reported in this study for *M. peregrina* seed oil was approximately half the average amount of that reported for *M. oleifera* seed oil. The same observation was reported by Al-Dabbas et al. (2010). This may be advantageous for *M. peregrina* seed oil in comparison to *M. oleifera* seed oil in terms of cold flow properties.

4. Conclusions

M. peregrina is a wild plant that can survive in arid and marginal waste land. Plantation trials of this tree have been promising with reasonably rapid growth and easy cultivation. All parts of this plant

are edible and valuable for different nutritional, medicinal and water purification purposes. This study aims at investigating the potential of *M. peregrina* seeds as a source for bio-fuel, in view of the edibility of the other parts of the plant. The use of this plant is deemed more beneficial from the economic and environmental points of view compared to other non-edible feedstock like *Jatropha*, which is inherently toxic. It is concluded from this work that *M. peregrina* seeds can potentially produce liquid and solid biomass. Both *M. peregrina* seed husk and *M. peregrina* seed oil cake are potential feedstock to produce energy by thermochemical conversion processes. However, further investigations are required to minimize the possible slagging and fouling in the reactor. *M. peregrina* seed oil can be converted to biodiesel in only one step by alkaline catalyst, without pretreatment. The produced biodiesel is expected to have high cetane number and remarkable oxidative stability due to high concentration of oleic acid and low concentration of polyunsaturated fatty acids.

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