Energy Conversion and Management 84 (2014) 497–502

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Orychophragmus violaceus L., a marginal land-based plant for biodiesel feedstock: Heterogeneous catalysis, fuel properties, and potential

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ARTICLE INFO

Article history:
Received 17 January 2014
Accepted 13 April 2014
Available online 16 May 2014

Keywords:
Orychophragmus violaceus L.
Biodiesel
Marginal land
Heterogeneous catalysis
Fuel properties

ABSTRACT

The development of biomass on marginal lands has been investigated and proven to be feasible. *Orychophragmus violaceus* grows naturally in the karst region and shows a stronger bicarbonate-use capacity and adaptability than some other plants. In the present study, the systemic parameters of seed samples from four locations were determined, including the oil contents (30.59–36.81 wt%), acid values (2.76–5.68 mg KOH/g), iodine values (111.02–147.58 g I_2/100 g), and fatty acid composition. *O. violaceus* oil was mainly composed of palmitic acid (C16:0, 10.65–13.06 wt%), stearic acid (C18:0, 6.41–8.31 wt%), oleic acid (C18:1, 16.56–25.58 wt%), and linoleic acid (C18:2, 46.07–52.16 wt%). *O. violaceus* seed oil from Guiyang was converted to biodiesel by calcined porous calcite. The catalyst amount was optimised, and refined biodiesel was prepared by vacuum distillation. The fuel properties of the *O. violaceus* biodiesel samples all met the EN 14214 (2012) standards, except for the cetane number and oxidation stability. In summary, *O. violaceus* from the karst marginal land is highly recommended as a biomass feedstock.

1. Introduction

Feedstock cost is widely regarded as a principal barrier for the development of the biodiesel (fatty acid methyl ester, FAME) industry; this cost represents approximately 70–95% of the total cost of biodiesel production [1,2]. Hence, considerable efforts have been devoted to exploring and selecting the ideal feedstock based on higher yields, better use of co-products, and wide adaptability [3,4]. Another important technological challenge is to explore highly effective heterogeneous catalysts and their corresponding processes. Among the numerous reported basic heterogeneous catalysts, significant research efforts have focused on CaO catalysts because of their heterogeneous catalytic behaviour, low-cost, wide availability, environmental-friendliness, and reusability [5–7]. However, a Ca^{2+} residue is always observed in the catalytic products due to the use of calcium soaps and solution [6,8]. To meet European Standard EN 14214, the Australian Biodiesel Standard, and the South African Biodiesel Standard, the Ca^{2+} concentration in the biodiesel product should be under 5 ppm. Thus, a feasible purification process is essential.

Recently, attention has turned to the development of bioenergy on marginal lands, which has proven to be a feasible prospect [9,10]. A comprehensive assessment of the bioenergy potential for marginal lands in China found that there was 130.34 million ha of marginal land that is suitable for the cultivation of energy plants, distributed mainly in Inner Mongolia and Southwestern and Northeastern China. In particular, the potential for biomass production in Southwestern China represents more than 30% of the total potential across all of China. However, some of the characteristics of marginal lands are poorly suited for plant growth, such as their poor soil quality, harsh climate, rough terrain, and higher levels of pollution [10]. Karst landscape developed on limestone is typical and is the main type of marginal land in Southwest China, especially in the Yunnan, Guizhou, Sichuan Provinces and Chongqing City. However, only a few biodiesel plants are available on the marginal lands and have been listed in the 11th Five-Year Plan of China because of their natural habitats, including *Helianthus tuberous* L., *Pistacia chinensis* B., *Jatropha curcas* L., and *Vernicia fordii* H. [10].

Orychophragmus violaceus L., a member of the family *Brassicaceae*, has been identified as a karst-adaptable plant that is able to grow across the karst regions in limestone soil that has low concentrations of nitrogen and phosphorus [11]. Despite being edible,

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http://dx.doi.org/10.1016/j.enconman.2014.04.047
0196-8904/

it has not been widely used because of its low yield (1050–2055 kg/ha) [12]. However, it is an attractive plant that is used in horticulture across China. In karst habitats, plants must tolerate stress derived from frequently arid–humid alternation; high concentrations of Ca^{2+}, Mg^{2+}, and HCO^{3-}; phosphorus deficiency; and shallow and patchy soil that has a low water retention capacity [13]. Some plants have the ability to use HCO_3^- for photosynthesis in the presence of carbonic anhydrase under stressful conditions [14,15]. In our pervious study, *O. violaceus* was found to show higher shade-tolerance and photosynthetic activity compared to *Brassica juncea* and higher bicarbonate-use capacity and karst adaptability compared to *Morus alba* L. and *Brassica napus* L. because of its higher carbonic anhydrase activity [15–17]. In our previous work, the seed yield of *O. violaceus* reached 970 kg/ha in karst regions. We believe that this species, which is able to grow in karst marginal lands, is a candidate for use as a feedstock alternative in biomass production and for carbon sequestration. In this study, the biodiesel feedstock potential of *O. violaceus* was evaluated and presented. Four *O. violaceus* seed samples were collected from Guiyang (karst region), Beijing, Wuhan, and Nanjing City, China. Their oil contents, acid values, iodine values, and fatty acid composition (FAC) were determined. The resulting biodiesel sample derived from Guiyang City (karst region) was obtained by transesterification catalysis in the presence of calcined porous calcite (CPC) [6]. The fuel properties were determined according to EN 14214 standards (2012), and the other three samples were predicted based on the relationship between the FAC and fuel properties [18,19]. To the best of our knowledge, there have been no previous studies on the biodiesel preparation and evaluation of *O. violaceus*.

2. Methods

2.1. Materials and reagents

A series of information regarding four *O. violaceus* seed samples is summarised in Table 1. Analytical grade anhydrous methanol, boron trifluoride, stearic acid, and sodium hydroxide were purchased from Sinopharm Chemical Reagent Co., Ltd., Shanghai. All of the standards used in the quantitative analysis were purchased from Sigma (USA), including palmitic acid (C16:0), palmitoleic acid (C16:1), stearic acid (C18:0), oleic acid (C18:1), linoleic acid (C18:2), linolenic acid (C18:3), cis-11-eicosanoic acid (C20:1), and Erucic acid (C22:1) methyl ester. Natural calcite powder (400-mesh) was collected from Guizhou Province, China. The components (wt%) were analysed by an energy dispersive X-ray spectrometer (Oxford INCA-350) as follows: calcite: Ca 46.2 wt%, Mg 1.2 wt%, C 18.2 wt%, O 33.4 wt%, Si 0.6 wt%, Fe 0.1 wt%, and S 0.2 wt%.

CPC was prepared according to a previous study [6]. A sample of 60 g of stearic acid was melted at 80 °C, then 10 g of calcite was added with vigorous stirring. The mixture was heated at 100 °C for 1 h and then at 170 °C for 1 h. The mixture was heated to 750 °C for 1 h under air flow (50 L h^{-1}) and then continuously calcined at 850 °C for 1 h in static air. The surface area of the catalyst was determined according to the BET method by a Micromeritics ASAP 2010.

2.2. Determination of the oil content, acid value, iodine value, saponification value, and average molecular weight of the seed samples

Every seed sample was dried under vacuum conditions (100 °C, 0.08 MPa) for 1 h to remove excess moisture. The dried products were ground and passed through a 20-mesh (0.9 mm) sieve. The oil content (wt%), acid value (mg KOH/g), iodine value (g I_2/100 g), and saponification value (mg KOH/g) were determined according to ISO 659:1998, ISO 660:1996, ISO 3961:1996, and ISO 3657:2002. The average molecular weight of four samples was calculated by Zhu et al.'s method [20].

2.3. FAC, FAME content, FAME yield, Ca^{2+} content analysis of the biodiesel product

A Shimadzu GC/MS-QP2010E equipped with a HP-Innowax column (30 m × 0.32 mm, 0.5 μm) and a flame ionisation detector was used in the qualitative and quantitative analyses. After methylation according to ISO 5509–2001, the main fatty acid species were identified by GC/MS. The chromatographic conditions reported in our previous work were used as follows [21]: inlet temperature: 523 K; detector temperature: 553 K; split ratio: 25:1; oven temperature program: 463 K for 3 min, ramp rate of 15 K/min to 513 K, then hold for 10 min; injection volume: 1 μL; carrier gas: helium, at a flow rate of 1.0 mL/min; air flow: 450 mL/min; and H_2 flow: 40 mL/min. Mass spectrometry was conducted according to the following conditions: carrier gas: helium; electron energy: 70 eV; interface temperature: 553 K; ion source temperature: 503 K; quadrupole temperature: 423 K; mass scan range: 50–550 *m/z*; and solvent delay: 3.0 min. The FAC and FAME contents were obtained by the external standard method, and the GC data were compared to those of known standards. The FAME yield was calculated by the following equation:

$$\text{FAME yield}(\%) = \frac{\text{Total weight of FAME}}{\text{Total weight of oil}} \times 100\% \quad (1)$$

The amount of Ca^{2+} residue in the resulting biodiesel samples was determined by atomic absorption spectroscopy (Shimazu AA-7000), and sample pre-treatment was performed by Verziu et al.'s method [22]. A volume of 0.5 mL of the biodiesel sample was added into a digestion vessel, and 10 mL of nitric acid (65 wt%) and 2 mL of hydrogen peroxide (30 wt%) were added. After closing, the system was heated in a microwave oven at 483 K for 15 min.

2.4. Oil extraction

For biodiesel preparation, an *O. violaceus* seed collected from Guiyang was dried under vacuum conditions (100 °C, 0.08 MPa) for 1 h, and 500 g of dried seed powder (20-mesh) was poured into

Table 1
Detailed properties of the four samples.

Origins	Harvesting time	Oil content (wt%)	Acid value (mg KOH/g)	Iodine value (mg I_2/100 g)	Saponification value (mg KOH/g)	Average molecular weight
Guiyang, China	May 2013	35.21 ± 1.92b	2.76 ± 0.15c	111.02 ± 2.89c	171.21 ± 3.01c	970.31
Beijing, China	June 2013	34.72 ± 0.65b	5.68 ± 0.34a	147.58 ± 3.41a	201.82 ± 2.97a	858.06
Wuhan, China	June 2013	30.59 ± 1.12a	3.59 ± 0.27b	129.16 ± 2.17b	187.37 ± 2.60b	920.38
Nanjing, China	June 2013	36.81 ± 0.96b	3.61 ± 0.23b	117.58 ± 1.94c	192.59 ± 3.93b	890.57

The mean ± SE followed by different letters in the same line differ significantly at $P \leqslant 0.05$ between the group means, according to one-way ANOVA and the *t* test.

a three-necked flask equipped with a reflux condenser and a thermometer. Then, 3000 g of petroleum ether was added and heated at 90 °C for 3 h, twice. The petroleum ether was removed by rotary evaporation under vacuum distillation (60 °C, 0.08 MPa) to obtain *O. violaceus* seed oil.

2.5. Heterogeneous transesterification catalysis and purification of the biodiesel product

Based on the optimised reaction conditions (3 wt% CPC, methanol-to-oil molar ratio of 10:1, and 338 K for 2 h) obtained from our previous study [6], the effect of the amount of catalyst (2.5, 3, 3.5 and 4 wt%) on the transesterification reactions was investigated by single-factor experiments in an inert atmosphere (N_2). The other reaction conditions were maintained for *O. violaceus* seed oil, 100 g; methanol-to-oil molar ratio, 10:1; with vigorously stirring (600 r min^{-1}) at 338 K for 2 h. To investigate the effect of the catalyst amount on the yield, the reaction system was quickly immersed into an ice-salt bath to stop the reaction after the transesterification reaction. The mixture was filtered, and the excess methanol was recovered by rotary evaporation (40 °C, 0.08 MPa for 10 min). Then, the liquid phase was transferred into a separatory funnel and was allowed to settle overnight. The top layer was separated and further centrifuged to remove partial CaO and glyceride. Thus, a crude *O. violaceus* biodiesel sample was prepared.

Crude *O. violaceus* biodiesel samples were purified by vacuum distillation. The distillation fraction was collected from 175 °C to 230 °C under 35 ± 5 mmHg and was named refined *O. violaceus* biodiesel.

2.6. Fuel properties

The fuel properties of the refined biodiesel sample obtained from Guiyang seeds were determined using the standard test methods according to European standards (EN 14214 (2012)). The same properties of the other three samples were deduced based on the relationship between FAC and the fuel properties, which were the cetane number (CN, Eq. (2)), cold-filter plug point (CFPP, Eqs. (3) and (4)), and kinematic viscosity (kV, Eq. (5)) [18,23–25].

$$CN = \sum X_{FAME}(wt\%) \bullet CN_{FAME} \quad (2)$$

$$LCSF = 0.1 \bullet C16(wt\%) + 0.5 \bullet C18(wt\%) + 1 \bullet C20(wt\%) + 1.5 \bullet C22(wt\%) + 2 \bullet C24(wt\%) \quad (3)$$

$$CN = 3.1417 \bullet LCSF - 16.477 \quad (4)$$

where LCSF is the long chain saturated factor;

$$KV = \exp \sum X_{FAME}(wt\%) \bullet \ln(n_{FAME}) \quad (5)$$

where n is the KV value of the individual FAME.

2.7. Statistical analysis

All of the experiments were replicated three times, and the data were expressed as the mean ± standard deviation, except for the fuel properties determinations. SPSS 13.0 (SPSS Inc., Chicago, Illinois, USA) was employed for statistical analysis. Differences between the means were compared by the Duncan's Multiple Range Test (DMRT) at a significance level of $P < 0.05$.

3. Results and discussion

3.1. Detailed properties for the seed samples from four locations

As far as biodiesel feedstock is concerned, the oil content is an important parameter to determine its commercial potential. From Table 1, the oil contents of four *O. violaceus* seed samples were 30.59–36.81 wt%; the acid values were 2.76–5.68 mg KOH/g; and the iodine values were 111.02–147.58 g I_2/100 g. Among the seeds, the *O. violaceus* seed from Guiyang, China (karst region), displayed the lowest acid value (2.76 ± 0.05 mg KOH/g). The transesterification reaction employing alkali catalysts was somewhat limited because the free fatty acids contained in the oil resulted in the formation of soap, which should be less than 2% (4 mg KOH/g oil) [26]. The free fatty acids contained in the four oil samples ranged from 1.38% to 2.84% (Table 1). Thus, the transesterification of the oil samples from Guiyang and Nanjing was performed directly and was catalysed by alkaline catalysts. The iodine number was a visual index of the unsaturated degree for raw oil and the biodiesel samples, which greatly influenced the oxidation stability, viscosity, cetane number, and cold flow characteristics of the resulting biodiesel samples. Apart from that, it also resulted in the formation of deposits in diesel engine injectors [23]. Logically, the resulting biodiesel from Beijing with a high iodine content would possess the worst oxidation stability and cetane number compared to the other samples.

3.2. Fatty acid composition of O. violaceus oil samples

After methylation according to ISO 5509–2001, the fatty acid species contained in the oil samples were identified by GC/MS. Five GC chromatograms of the standard mixture and samples were overlapped, as shown in Fig. S1†. Their contents were then determined by the external standard method by GC. Previous studies concluded that the ideal vegetable oil biodiesel should possess a high C16:1 and C18:1 content, a low polyunsaturated fatty acids content, and limited saturated acids content [18,19]. From the data listed in Table 2, C18:2 (46.07–52.16 wt%) was the main fatty acid contained in the four oil samples, followed by the C18:1 (16.56–25.58 wt%) and C16:0 (10.65–13.06 wt%). In contrast to the other three samples, the *O. violaceus* oil sample from Guiyang (karst region) possessed the highest content of C18:1 (25.58 wt%) and the lowest degree of unsaturation. It had the most ideal fuel properties among the resulting *O. violaceus* biodiesel samples. However, the saturated fatty acid content (C16:0, 10.65–13.06 wt%; C18:0, 6.41–8.31 wt%; total 17.99–19.89 wt%) and the degree of unsaturation (130.01–136.9) of the *O. violaceus* oil samples were higher than that of rapeseed oil, which resulted in weaker cold flow performance and oxidative stability and superior kinematic viscosity in the *O. violaceus* biodiesel compared to rapeseed biodiesel.

3.3. Production of the crude O. violaceus biodiesel sample

The leaching of Ca^{2+} into the product during the transesterification reaction of oil and methanol was inevitable because of saponification and dissolution [6,8]. To obtain crude biodiesel samples of *O. violaceus* (Guiyang, China), CPC was first prepared. Its special surface area was determined as 9.13 m^2/g by the BET method, which agreed well with previous work [6]. Based on previously optimised reaction conditions, four different catalyst amounts (2.5, 3, 3.5 and 4 wt%) were screened, with a methanol-to-oil ratio of 10:1 at 338 K for 2 h. The effect of the CPC amount on the FAME yield is illustrated in Fig. 1. The highest FAME yield (92.13 ± 2.17%) was achieved with 3.5 wt% CPC, producing a FAME content of 97.02 wt%. When the transesterification reaction was performed

Table 2
The FAC of the four oils.

FAC (wt%)	*O. violaceus* oil				Rapeseed oil
	Guiyang, China	Beijing, China	Wuhan, China	Nanjing, China	(Ramos et al., [18])
Palmitic acid (C16:0)	11.58	10.65	12.34	13.06	4.9
Palmitoleic acid (C16:1)	0.19	0.21	0.21	0.91	0
Stearic acid (C18:0)	6.41	8.31	7.12	6.83	1.6
Oleic acid (C18:1)	25.58	16.56	19.68	21.12	33.0
Linoleic acid (C18:2)	46.07	52.16	51.22	47.79	20.4
Linolenic acid (C18:3)	3.37	4.94	4.23	3.74	7.9
11-Eicosenoic acid (20:1)	4.74	4.12	2.64	3.03	9.3
Erucic acid (C22:1)	0.42	1.81	0.51	2.08	23.0
Proportion of saturation (Cn:0)	17.99	18.96	19.46	19.89	6.5
Proportion of monounsaturation (Cn:1)	31.13	22.7	24.04	27.14	65.3
Proportion of polyunsaturation (Cn:2, 3)	49.44	57.1	55.45	51.53	28.3
Degree of unsaturation (Ramos et al., [18])	130.01	136.90	133.94	130.20	121.9

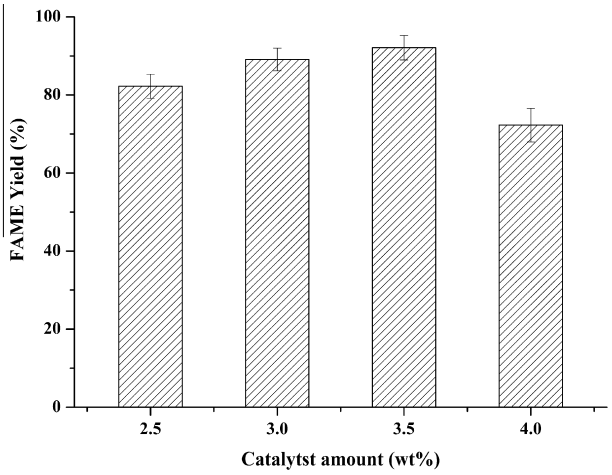

Fig. 1. Effect of the catalyst amount on the FAME yield of *O. violaceus* biodiesel (Guiyang, China).

in the presence of 4 wt% CPC, the interface of the phase separation was ambiguous due to the occurrence of saponification, which decreased the FAME yield (72.27 ± 4.32%).

3.4. Ca^{2+} content and purification

The content of Ca^{2+} in the crude biodiesel sample produced from *O. violaceus* (Guiyang, China) was determined by atomic absorption spectroscopy; the content was 139.71 ppm. This value far exceeded the upper limit of European Standard EN 14214, the Australian Biodiesel Standard, and the South African Biodiesel Standard (i.e., 5 ppm). In the present study, the crude biodiesel sample was refined by vacuum distillation (30 ± 5 mmHg), and the fraction from 175 °C to 230 °C was collected. The yield of the vacuum distillation procedure was 96.11 ± 4.79%, and the total yield, including synthesis and purification, was 88.54 ± 3.62%. Finally, no Ca^{2+} was detected in the resulting refined biodiesel sample, and the FAME content increased to 99.61 wt%.

3.5. Analysis and comparison of the fuel properties of O. violaceus biodiesel

To evaluate the fuel properties of *O. violaceus* biodiesel, the biodiesel sample from Guiyang was analysed according to the standard (EN 14214 (2012)), and the data from the other three samples were predicted with the fitting equations reported in the literature [18,23,24]. As it is in the same family of plant, rapeseed is the most used biodiesel raw material in the European Union, accounting for nearly 80% of the total European biodiesel feedstock. Therefore, the parameters of rapeseed biodiesel were used as a comparison. All indices summarised in Table 3 for *O. violaceus* biodiesel met the European standards (EN 14214 (2012)), except for the cetane number and oxidation stability.

The cetane number of the refined *O. violaceus* biodiesel sample from Guiyang (50.1) and the other three samples (Beijing 48.10, Wuhan 47.97, and Nanjing 48.36) were lower than the value of rapeseed biodiesel (55) and the minimum limit of 51 specified in the EN 14214 (2012) standard. In fact, biodiesel was more prone to oxidation than petroleum-based fuels. Oxidation stability is an index that reflects the anti-oxidation ability of biodiesel and increase with the increasing chain length and saturation. Here, refined *O. violaceus* biodiesel from Guiyang provided inferior oxidation stability (1.6 h) compared to rapeseed biodiesel (2.0 h). In addition to the presence of unsaturated fatty acids, the oxidation stability of biodiesel was also influenced by the water content, metal, and acid value. From the high iodine value and degree of unsaturation of the *O. violaceus* biodiesel samples shown in Tables 1 and 2, we deduced that the other three *O. violaceus* biodiesel samples would provide worse oxidation stability than the sample from Guiyang. The kinematic viscosity (40 °C) of the refined *O. violaceus* biodiesel sample from Guiyang was determined to be 4.09 mm^2/s, which met the specified range in EN 14214 (2012, 3.5–5.0 mm^2/s). It was superior to rapeseed biodiesel (4.4 mm^2/s), and we attributed the superior kinematic viscosity to the high percentage of polyunsaturated fatty acids (C18:2, 46.07–52.16 wt%; and C18:3, 3.37–4.94 wt%; Table 2) and the low percentage of longer-chain fatty acids (C20:1, 2.64–4.74 wt% and C22:1, 0.42–2.08 wt%) in our biodiesel samples. Saturated fatty acids (such as C16:0 and C18:0) would also limit the cold flow performance of biodiesel because of their higher melting points [27]. Therefore, for both the predicted and measured values of the four *O. violaceus* biodiesel samples, the higher percentage of saturated fatty acids (17.99–19.89 wt%) resulted in their higher cold-filter plug points (−8.91, −8.97, −8.96, and −9 °C) compared to rapeseed biodiesel (−10 °C). According to Luo et al. [28], *O. violaceus* biodiesel provided superior lubrication because of its higher degree of unsaturation than rapeseed biodiesel. Similar to concerns about air pollution from the use of petroleum diesel, the emission of biodiesel is also a topic of concern. Several studies have focused on the influence of the fatty acid composition on the emission, which revealed that lower NO_x emissions were produced from more saturated feedstock, and shorter chain saturated esters produced more NO_x emissions than those with longer chains [29]. Consequently, *O. violaceus* biodiesel produced lower NO_x emissions than rapeseed biodiesel.

To make better use of *O. violaceus* biodiesel, there are several appropriate routes: (1) use fuel additives to improve its cetane number and oxidation stability; and (2) modify the FAME

Table 3
Fuel properties of *O. violaceus* biodiesel compared to the EN14214 (2012) standard.

Property	Test method	Limits	Samples				
			O. violaceus biodiesel				Rapeseed biodiesel[b] [18]
			Beijing, China[a]	Wuhan, China[a]	Nanjing, China[a]	Guiyang, China[b]	
FAME content % (*m*/*m*)	GC[c]	96.5 min	–	–	–	99.61	99.5
Density at 15 °C (kg/m^3)	EN ISO 3675	860–900	–	–	–	883.7	–
Viscosity (mm^2/s; 40 °C)	EN ISO 3104	3.5–5.0	4.01	3.99	3.98	4.09	4.4
Flash point (°C)	EN ISO 2719	101 min	–	–	–	174	170
Cetane number	EN ISO 5165	51.0 min	48.10	47.97	48.36	50.1	55
Copper strip corrosion (3 h at 50 °C)	EN ISO 2160	Class 1	–	–	–	1[a]	–
Oxidation stability (h, at 110 °C)	EN 14112	8.0 min	–	–	–	1.6	2.0
Acid value (mg KOH/g)	EN 14104	0.50 max	–	–	–	0.09	0.16
Linolenic acid content % (*m*/*m*)	GC[c]	12.0 max	4.94	4.23	3.74	3.37	7.9
Free glycerol % (*m*/*m*)	EN 14105	0.02 max	–	–	–	0.004	0.01
Total glycerol % (*m*/*m*)	EN 14105	0.25 max	–	–	–	0.131	0.09
Water content (mg/kg)	EN ISO 12937	500 max				310	–
Sulfated ash content % (*m*/*m*)	ISO 3987	0.02 max	–	–	–	0.01	–
Cold filter plug point (CFPP, °C)[c]	EN 116	–	−8.98	−9.01	−8.99	−9	−10
Conradson carbon residue (10%, wt%)[c]	EN ISO 10370	0.3 max				0.04	–

[a] Predicted value.
[b] Measured value.
[c] Determination was performed by GC.

composition by blending it with another biodiesel that contains more C16:1 and C18:1 methyl esters, such as *Euphorbia lathyris* L. biodiesel [21].

4. Conclusion

The use of marginal lands for the development of biomass and bioenergy has been regarded as a promising route. The selection of appropriate energy plants is a key step to meeting this challenge. This study demonstrates the potential of using *O. violaceus* L., a karst-adaptable plant, as a biomass feedstock on marginal land. Seed samples from four different locations across China contained relatively high oil contents (30.59–36.81 wt%) and appropriate acid values (2.76–5.68 mg KOH/g), especially the sample from the karst region of Guiyang. Under the optimised heterogeneous catalysis and purification conditions for biodiesel production, a total yield of 88.54% was obtained. Compared to rapeseed biodiesel, *O. violaceus* L. biodiesel samples provided superior kinematic viscosity, lubrication, and NO_x emissions. However, their cetane number and oxidation stability should be improved. In conclusion, *O. violaceus* L. is highly recommended as a marginal land-based biomass feedstock.

Acknowledgements

This work was financially supported by the Postdoctoral Science Foundation of China (Grant No. 2012M521720), the National Natural Science Foundation of China (Grant No. NSFC41201577), and the National Natural Science Foundation of China (Grant No. NSFC31070365).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enconman.2014.04.047.

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