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Improving the fuel properties of biodiesel via complementary blending with diesel from direct coal liquefaction

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Complementary blending of biodiesel from waste cooking oil (BWCO) with diesel from direct coal liquefaction (DDCL) was evaluated to improve the fuel properties. The fuel properties of the biodiesel blends with the addition of 0%, 2.5%, 5%, 10%, and 20% DDCL (vol) were determined. It indicated that blending complemented the individual deficiencies and superiorities of the two fuels. The oxidative stability and cold flow properties of BWCO were strongly improved. Simultaneously, the flash point and kinematic viscosity of DDCL were also enhanced. With the blending of 20 vol% DDCL with BWCO, all the main fuel properties of the blends were in accordance with EN 14214 and ASTM D6751. The fuel properties of DDCL–BWCO after storage for 100 days were also determined. In addition, variance analysis was performed using IBM SPSS Statistics to clarify the effect of adding DDCL on the fuel properties of BWCO.

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1. Introduction

With the onset of economic globalization, increasing environmental pollution, and the energy shortage in the world, energy has grown to be a topic of great significance. Biodiesel has been investigated since the early 1990s. As a kind of new green energy, biodiesel has caught the attention of researchers.^{1–8} Biodiesel is obtained from various raw oils such as vegetable oils, animal oils, or used frying oils.^{9–15} Biodiesel has several advantages over petro-diesel fuel. First, biodiesel has renewable plant sources and good biodegradability.^{16,17} Second, biodiesel has a low sulfur content, which is beneficial to the environment.¹³ In sum, biodiesel is eco-friendly and non-toxic. However, the main obstacles which limit the utilization of biodiesel are the feedstock cost and some of its defective fuel properties. Generally, the cold flow properties and oxidation stability of biodiesel are inferior as compared with those of diesel from direct coal liquefaction (DDCL).¹⁸ On the other hand, some fuel properties of DDCL are not good enough as commercial fuel, such as the flash point (FP) and the kinematic viscosity (KV).^{19,20} It may be a promising way for the generalization of biodiesel to complementarily blend biodiesel with

diesel from direct coal liquefaction (DDCL), especially in coal-rich country like China.

Given the country's large coal reserves and the relatively stable prices of this energy source, coal has been the first choice of fuel for Chinese power production.^{21,22} Since 1950s, the coal-to-oil process has grown up to be an important trend in China's energy strategy, especially with the shortage of petroleum resources. In a previous investigation, the properties of diesel from direct coal liquefaction (DDCL) were reported.^{19,23–25} DDCL is a new commercial fuel that has different properties from diesel and biodiesel which has become a popular research topic.^{19,26,27} Upon approval by the State Council, the largest coal liquefaction project in China was initiated by the Shenhua Group Corporation Limited, the world's largest coal dealer.²³ Coal liquefaction can be direct or indirect, which was transformed coal to oil at high pressure, high temperature and hydrogen.^{19,28–30} DDCL is produced through catalytic hydrogenation and the direct liquefaction.^{24,27,29,30} Compared with biodiesel, DDCL exhibits incomparable cold flow properties.^{19,20}

To the best of our knowledge, few scholars have investigated biodiesel–DDCL blends. In the present study, the complementary blending of biodiesel derived from waste cooking oil (BWCO) with DDCL was investigated to enhance the cold flow properties, oxidative stability (OS), and calorific value (CV) of biodiesel with concomitant promotion in FP and KV of DDCL. Two biodiesel fuel standards were shown in Table 1 (EN 14214 and ASTM D6751). BWCO was included in this study because waste cooking oil is abundant and serves as a low-cost feedstock.^{31–36} As a biodiesel resource, waste cooking oil is an important part of China's energy strategy. The reasonable use of

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waste cooking oil not only prevents harm to human health through the food chain but also directly avoids environmental pollution.^{13,15} In addition, this study performed a variance analysis (VA) using the IBM SPSS Statistics software.

2. Experimental

2.1. Materials

Waste cooking oil was purchased from Shanghai Zhongming Chemical Co., Ltd. (Shanghai). DDCL was obtained from China Shenhua Coal to Liquid and Chemical Co., Ltd. (Shanghai Institute). All other chemicals and reagents were purchased from Aladdin Reagent Co., Ltd. (Shanghai).

2.2. Preparation of biodiesel from waste cooking oil

Biodiesel is obtained by the transesterification process of raw oil and alcohols.³⁴ In the current study, the waste cooking oil was purified by water-washing, deodorization, caustic neutralization, and bleaching to remove undesirable substances.¹⁵ Then methanolysis of waste cooking oil was carried out at 65 °C with 1 : 7 mole ratio of oil to methanol for 2.0 h in a 500 mL three-necked round bottom reactor. The reactor was equipped with a mechanical overhead stirrer (500 rpm), reflux condenser, sampling outlet and thermostat. Sodium methoxide (0.8 wt%) was used as catalyst. After reaction, the mixture needed 4.0 hours' standing in a separating funnel. The upper layer and the lower layer were biodiesel and crude glycerol, respectively. Then, the glycerol was removed by gravity separation and washed the FAMES twice with deionized water after neutralization with hydrochloric acid. Finally, biodiesel from waste cooking oil was obtained after dehydration by reduced pressure distillation.

2.3. GC-MS analysis

Agilent 6890A-5973c GC-MS was used to analyze the composition of biodiesel and DDCL. GC has been operated under these conditions: hp-Innowax quartz capillary column (60 m × 0.25 mm × 0.25 μm); capillary column temperature of DDCL and biodiesel were raised by 5 °C min⁻¹ from 90 °C to 290 °C and by 5 °C min⁻¹ from 70 °C to 240 °C, respectively; interface temperature of DDCL and biodiesel were 280 °C and 260 °C, injector temperature were 260 °C; diffuent ratio were 100 : 1,

Table 1 Selected specification of biodiesel fuel standards

Specifications	EN 14214	ASTM D6751
Pour point, °C	—	—
Cloud point, °C	—	—
Cold filter plugging point, °C	—	—
Oxidation stability, 110 °C, h	6.0 min	3.0 min
Calorific value, kJ kg ⁻¹	—	—
Acid value, mg KOH g ⁻¹	0.5 max	0.5 max
Flash point, °C	101 min	93 min
Kinematic viscosity, 40 °C, mm ² s ⁻¹	3.5 to 5.0	1.9 to 6.0
Density, 15 °C, g cm ⁻³	0.86 to 0.90	0.87 to 0.89
Water content, mg kg ⁻¹	500 max	500 max

Table 2 Test methods for fuel properties of BWCO–DDCL blends

Specifications	Test methods
Pour point, °C	ASTM D97-12
Cloud point, °C	ASTM D2500-11
Cold filter plugging point, °C	ASTM D6371
Oxidation stability, 110 °C, h	EN 14112
Calorific value, kJ kg ⁻¹	ASTM D5468-02
Acid value, mg KOH g ⁻¹	AOCs Cd 3d-63
Flash point, °C	ASTM D93-02
Kinematic viscosity, 40 °C, mm ² s ⁻¹	ASTM D445
Density, 15 °C, g cm ⁻³	EN ISO 3675
Water content, mg kg ⁻¹	EN ISO 12937

the gas flow rate of high purity helium carrier were 1.2 mL min⁻¹; and the injection volume were 0.2 μL.

2.4. Fuel properties

The methods for determining the fuel properties of BWCO–DDCL blends are listed in Table 2.

Pour point (PP, °C), cloud point (CP, °C), and cold filter plugging point (CFPP, °C) are important indicators of the cold flow properties of biodiesel. Oxidation stability (OS, h) is the ability of petroleum products to resist the effect of oxygen and thus avoid permanent changes in their properties. Calorific value (CV, kJ kg⁻¹) is a basic indicator of engine power performance. Acid value (AV, mg KOH g⁻¹) is an important basis for measuring the performance and use of corrosive oil. Flash point (FP, °C) was the temperature of the oil explosion limit (except for gasoline). FP is a crucial indicator of oil in the area of transportation and is used to identify the risk of oil fires. Kinematic viscosity (KV, mm² s⁻¹) is an important indicator of oil that is used to measure the flow properties and atomization performance of fuel. Oil density (15 °C, g cm⁻³) has a significant effect on the atomization quality and nozzle range of fuel. Meanwhile, water content (WC, mg kg⁻¹) has a significant effect on the combustion properties of diesel.

2.5. Blending and storage of samples

To ensure mixing uniformity, BWCO and DDCL were blended in a beaker by continuous stirring at ambient temperature (25 ± 1 °C). The blending ratios were 2.5, 5.0, 10.0, 15.0, and 20.0 vol% of DDCL. The samples were stored in airtight glass bottles for 100 days at ambient temperature. The blends were measured for PP, CP, CFPP, OS, AV, FP, KV, CV, density, and WC at both 0 and 100 days.

2.6. Data analysis

The VA was performed by employing the general linear model using IBM SPSS Statistics (version 19.0). In this analysis where α = 0.05, linear contrasts were used to test the effect of DDCL percentage on blend properties.

Table 3 GC-MS analysis of DDCL

Peak no.	Name	Retention time (min)	Mass percent (%)	Peak no.	Name	Retention time (min)	Mass percent (%)
1	Propylcyclohexane	9.3	1.78	26	1-(Cyclohexylmethyl)-cyclohexane	27.5	0.84
2	<i>trans</i> -Octahydro-1 <i>H</i> -indene	11.0	1.63	27	1-Pentyl-cyclohexene	27.9	0.91
3	1-Cyclopentyleth-dichloroacetic acid	12.4	0.52	28	Undecane	28.6	3.44
4	1-(1-Methylcyclohexyl)-ethanone	13.3	1.36	29	<i>trans</i> -2-Methyl-decalin	28.8	10.47
5	<i>cis</i> -Octahydro-1 <i>H</i> -indene	13.6	4.64	30	<i>trans</i> -2-Methyl-decalin	31.1	3.80
6	1-Methylethylidene-cyclohexane	14.1	0.92	31	<i>trans</i> -2-Methyl-decalin	32.5	2.90
7	<i>cis</i> -1,2-Diethyl-cyclohexane	14.4	0.56	32	Pentyl-cyclohexane	33.3	1.04
8	Decane	15.2	2.79	33	<i>cis</i> -2- <i>syn</i> -Methyl-decalin	33.3	1.13
9	Octahydro-5-methyl-1 <i>H</i> -indene	15.6	1.57	34	<i>cis</i> -2- <i>syn</i> -Methyl-decalin	34.9	1.23
10	4-Methyl-1-methyle-cyclohexene	16.0	0.67	35	Decahydro-2,6-dimethy-naphthalene	38.4	1.14
11	2-Methyl-1-propenyl-cyclohexane	16.3	1.15	36	Decahydro-2,6-dimethy-naphthalene	42.8	0.60
12	2,6-Dimethylbicyclo[3.2.1]octane	17.9	0.74	37	Dodecane	47.6	2.65
13	Butyl-cyclohexane	18.2	2.37	38	2-Ethyldecahydro-naphthalene	49.9	2.11
14	Octahydro-5-methyl-1 <i>H</i> -indene	18.9	3.04	39	Cyclopentylmethyl-cyclohexane	60.4	1.00
15	4-Methyl-1-methyle-cyclohexene	19.1	1.24	40	1,1'-Bicyclohexyl	66.6	1.14
16	Iridomyrmecin	19.6	1.06	41	Tridecane	69.3	2.40
17	1,4-Dimethyl-5-(1-met)-cyclopentene	20.6	0.84	42	2-Butyldecahydro-naphthalene	70.3	1.00
18	Decahydro-naphthalene	20.8	16.91	43	Perhydrophenalene (3a.alpha., 6a.alp)	72.2	1.95
19	<i>cis</i> -Decahydro-naphthalene	21.0	1.29	44	Cyclohexanepropanol	73.0	0.86
20	3-Pentyl-cyclohexene	22.1	1.47	45	7-Octylidenebicyclo-[4.1.0]heptane	73.1	0.65
21	<i>trans</i> -2-Methyl-decalin	22.5	0.60	46	Tetradecahydro-anthracene	75.8	0.64
22	Oxalic acid-cyclohexylmethyl propy	25.3	1.30	47	Tetradecane	76.6	2.19
23	Carvenone	25.7	0.85	48	2-Butyldecahydro-naphthalene	77.5	0.88
24	1-Ethyl-2-propyl-cyclohexane	26.0	0.78	49	Hexadecane	80.6	1.40
25	<i>cis</i> -Decahydro-naphthalene	26.6	2.79	50	Hexadecane	83.6	0.78

3. Results and discussion

3.1. DDCL properties at 0 and 100 days

The mass percent and the total ion chromatogram of DDCL are shown in Table 3 and Fig. 1, respectively. DDCL was mainly composed of alkanes, alkenes, cycloalkanes, aromatic hydrocarbons, and polycyclic aromatic hydrocarbons. The properties of DDCL, namely, PP, CP, CFPP, OS, AV, FP, KV, CV, density, and WC were analyzed in this study at both 0 and 100 days (Table 4). The properties of DDCL at 0 day were in agreement with previous report.³⁷ As previously mentioned, DDCL has extraordinary cold flow properties, with PP and CP of $-64\text{ }^{\circ}\text{C}$ and $-30\text{ }^{\circ}\text{C}$, respectively. This can be attributed to the high content of alkenes, which had better cold flow properties because of their unsaturated bonds.^{5,13} After being stored for 100 days, PP and CP of DDCL decreased to $-63.5\text{ }^{\circ}\text{C}$ and $-30\text{ }^{\circ}\text{C}$, respectively. Although PP and CP are not specified in the fuel standards (Table 1), which are important indexes of the cold flow properties of fuel, the PP and CFPP values (Table 4) of DDCL in this study were considerably lower than those of biodiesel and petrodiesel.²⁵

As it can be seen in Table 4, DDCL demonstrated fine OS and good CV. These values were much higher than those of biodiesel. In addition, the AV and water content of DDCL were

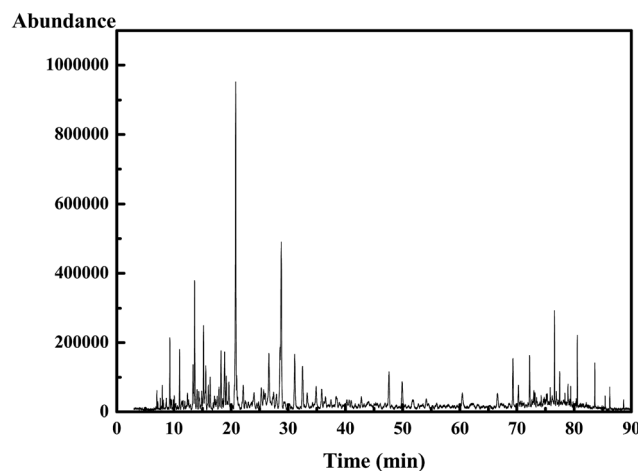


Fig. 1 Total ion chromatogram of DDCL.

Table 4 Fuel properties of neat BWCO and neat DDCL stored for 0 and 100 days

Specifications	BWCO		DDCL		EN 14214	ASTM D6751
	0 days	100 days	0 days	100 days		
Pour point, °C	−4	−3.5	−64	−63.5	—	—
Cloud point, °C	2.5	2.4	−30	−30	—	—
Cold filter plugging point, °C	2	2.1	−31	−30.3	—	—
Oxidation stability, 110 °C, h	4.6	3.7	28	28	6.0 min	3.0 min
Calorific value, kJ kg ^{−1}	39 971	38 542	46 018	45 201	—	—
Acid value, mg KOH g ^{−1}	0.38	0.97	0.08	0.10	0.5 max	0.5 max
Flash point, °C	152	153	75	75	101 min	93 min
Kinematic viscosity, 40 °C, mm ² s ^{−1}	4.68	4.70	2.13	2.15	3.5–5.0	1.9–6.0
Density, 15 °C, g cm ^{−3}	0.8847	0.8825	0.8601	0.8578	0.86–0.90	0.87–0.89
Water content, mg kg ^{−1}	121.8	123.4	4.9	5.1	500 max	500 max

considerably lower than those of biodiesel. However, The FP and KV of DDCL were lower than those of biodiesel. DDCL demonstrated strong stability since its properties changed little after 100 days' storage.

3.2. Biodiesel properties at 0 and 100 days

The mass percent of fatty acid methyl esters (FAMES) in BWCO is shown in Table 5. The composition of FAMES is presented in the total ion chromatogram of BWCO (Fig. 2). The FAMES were mainly composed of methyl hexadecanoate (12.87 wt%), methyl 9,12-octadecadienoate (29.92 wt%), and methyl 9-octadecanoate (43.74 wt%), as well as lesser constituents such as methyl 9-oxo-nonanoate (1.32 wt%), methyl tetradecanoate (1.14 wt%), methyl 9-hexadecanoate (1.63 wt%), and methyl stearate (9.22 wt%). The percentage distribution of the FAMES in BWCO was characterized by high contents of monounsaturated FAMES (45.37%), followed by polyunsaturated FAMES (29.92%) and saturated FAMES (24.55%). These results were in agreement with those of previous reports.^{38,39}

Table 4 shows the properties of BWCO at both 0 and 100 days. At 0 day, the PP, CP, and CFPP values of BWCO were −4 °C, 2.5 °C, and 2 °C, respectively. After the storage of BWCO for 100 days, its PP, CP, and CFPP were barely affected, which were −3.5 °C, 2.4 °C, and 2.1 °C, respectively. The cold flow properties of BWCO were evidently unsatisfactory and considerably worse than those of DDCL. Thus, BWCO cannot be widely applied in the north cold regions. All the properties of BWCO at 0 day were basically in agreement with previous reports.^{40–42}

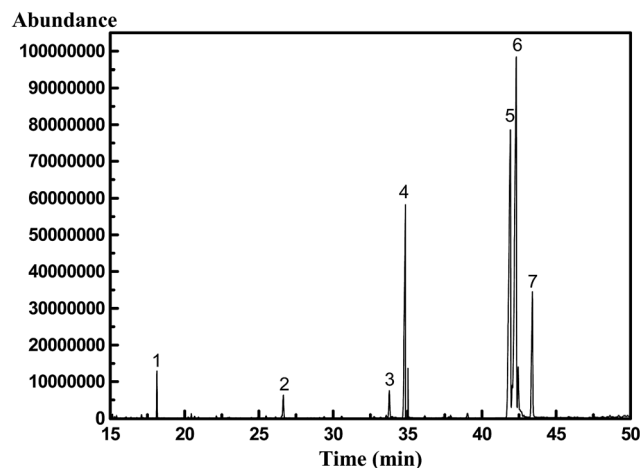


Fig. 2 Total ion chromatogram of BWCO.

OS decreased from 4.6 h (0 day) to 3.7 h (100 days). AV significantly increased from 0.38 mg KOH g^{−1} (0 day) to 0.97 mg KOH g^{−1} (100 days). EN 14214 and ASTM D6751 specify the minimum value of OS as 6.0 and 3.0 h, respectively, and the maximum value of AV (Table 1) as 0.5 mg KOH g^{−1}. Regardless of the number of storage days, the OS of BWCO was in agreement with that specified in ASTM D6751 (Table 1). The AV of BWCO (0 day) was also in agreement with that in EN 14214 and ASTM D6751 (Table 1) at 0 day. However, the AV increased and did not meet the standards increased after being stored for 100 days. The other properties of BWCO (Table 4), namely, FP, KV,

Table 5 GC-MS analysis of BWCO

Peak no.	Name of fatty acid methyl esters (FAME)	Retention time (min)	Corresponding acid	Mass percent (%)
1	Methyl 9-oxo-nonanoate	18.14	C9:0	1.32
2	Methyl tetradecanoate	26.64	C14:0	1.14
3	Methyl 9-hexadecanoate	33.78	C16:1	1.63
4	Methyl hexadecanoate	34.85	C16:0	12.87
5	Methyl 9,12-octadecadienoate	41.92	C18:2	29.92
6	Methyl 9-octadecanoate	42.31	C18:1	43.74
7	Methyl stearate	43.40	C18:0	9.22

density and WC satisfied the standards of EN 14214 and ASTM D6751 (Table 1) both at 0 and 100 days.

3.3. Fuel properties of the blends stored for 0 and 100 days

The properties of BWCO blended with DDCL at 0 and 100 days of storage are presented in Table 6 and 7, respectively. VA of blends properties were analyzed using the IBM SPSS Statistics (version 19.0). Overall, the *P* values in Table 6 change little as compared with those of Table 7, indicating the impact of DDCL on BWCO was independent of storing period.

As it can be seen in Table 4, some properties of DDCL and BWCO were complementary. For example, the cold flow properties of the blends were considerably better than those of BWCO. The OS of neat BWCO did not meet the specifications of EN 14214, whereas that of the blends ($\geq 10\%$ DDCL) satisfied the two standards (Table 6). It can be explained that the amount of unsaturated compounds in BWCO was too high, resulting in its sensibility to O_2 . On the other hand, DDCL was mainly composed of alkanes, alkenes, cycloalkanes, aromatic hydrocarbons, and polycyclic aromatic hydrocarbons, which were much lower in pour points than FAMES.⁴³

The AV of neat BWCO did not satisfy EN 14214 and ASTM D6751 after being stored for 100 days, whereas those of the blends (20% DDCL) exhibited qualified values (Table 7). On the other hand, the FP and KV of DDCL reached the specifications of EN 14214 and ASTM D6751 after blending with BWCO (Table 6 and 7).

Based on analysis using IBM SPSS Statistics (version 19.0), the PP of the blends obviously decreased ($P < 0.05$) as DDCL content increased. PP decreased by 8°C while blending DDCL at 20 vol% (Table 6). CP and CFPP also decreased significantly ($P < 0.05$) as DDCL content increased. The blending of DDCL with BWCO mainly resulted in lower PP and CP, as evidenced by a *P* value of less than 0.05. As the concentration of DDCL increased, the CP of BWCO decreased. This result can be attributed to the very low freezing point of DDCL (-64°C) in contrast to the CP of BWCO. As shown in Table 4, the prepared BWCO contained a large amount of saturated FAME that resulted in high CP. For the saturated FAME, DDCL acted as a diluent.

OS and CV increased significantly ($P < 0.05$). Blends containing 10 vol% or more DDCL exhibited high OS. All the blends satisfied the specification listed in ASTM D6751 (3 h). The blends containing 20 vol% DDCL resulted in an OS of 7.5 h at 0 day. Meanwhile, the calorific value increased ($P < 0.05$) from $39\,971\text{ kJ kg}^{-1}$ to $40\,808\text{ kJ kg}^{-1}$. Even after 100 days of storage, the OS of the blends containing 20 vol% DDCL still met the standards of EN 14214 and ASTM D6751.

As shown in Table 6, the blending of DDCL with BWCO resulted in effective AV reduction ($P < 0.05$). As the DDCL content increased, the AV of BWCO decreased significantly (from $0.38\text{ mg KOH g}^{-1}$ to $0.29\text{ mg KOH g}^{-1}$). Moreover, after being stored for 100 days, the AV of the biodiesel blends (Table 7) containing 20 vol% DDCL was $0.48\text{ mg KOH g}^{-1}$, which also met the specification of EN 14214 and ASTM D6751. All the values (20% DDCL) were in accordance with the standards provided in EN 14214 and ASTM D6751.

Table 6 Fuel properties of BWCO blended with DDCL stored for 0 day

Specifications	%DDCL (vol)						Contrasts ^a			
	0	2.5	5.0	10.0	15.0	20.0	EN 14214	ASTM D6751	0 vs. DDCL ^b	DDCL effect ^c
Pour point, °C	−4	−5.5	−8	−9	−10.5	−12	—	—	0.011	0.015
Cloud point, °C	2.5	2.5	1.5	0.7	−0.5	−1.5	—	—	0.050	0.034
Cold filter plugging point, °C	2	2	1	0	−1	−2	—	—	0.047	0.030
Oxidation stability, 110 °C, h	4.6	5.0	5.5	6.3	6.9	7.5	6.0 min	3.0 min	0.022	0.036
Calorific value, kJ kg ^{−1}	39 971	39 980	39 999	40 332	40 710	40 808	—	—	0.085	0.080
Acid value, mg KOH g ^{−1}	0.38	0.37	0.36	0.35	0.32	0.29	0.5 max	0.5 max	0.045	0.085
Flash point, °C	152	135	128	118	105	102	101 min	93 min	0.006	0.036
Kinematic viscosity, 40 °C, mm ² s ^{−1}	4.68	4.60	4.53	4.26	4.12	3.96	3.5–5.0	1.9–6.0	0.033	0.051
Density, 15 °C, g cm ^{−3}	0.8847	0.8845	0.8835	0.8823	0.8810	0.8798	0.86–0.90	0.87–0.89	0.042	0.038
Water content, mg kg ^{−1}	121.8	119.5	117.2	110.3	100.3	95.8	500 max	500 max	0.046	0.067

^a *P*-values and $\alpha = 0.05$. ^b Comparison between 0 DDCL and the mean of the DDCL volumes used. ^c Examines whether increasing DDCL vol in the range of 2.5% to 20% affects the response.

Table 7 Fuel properties of BWCO blended with DDCL stored for 100 days

Specifications	%DDCL (vol)						Contrasts ^a			
	0	2.5	5.0	10.0	15.0	20.0	EN 14214	ASTM D6751	0 vs. DDCL ^b	DDCL effect ^c
Pour point, °C	-3.5	-5.3	-7.8	-8.5	-10	-11	—	—	0.007	0.011
Cloud point, °C	2.4	2.5	1.6	0.8	-0.6	-1.5	—	—	0.064	0.040
Cold filter plugging point, °C	2.1	2.1	1.0	0.2	-1.1	-1.9	—	—	0.046	0.029
Oxidation stability, 110 °C, h	3.7	4.2	4.7	5.4	5.7	6.2	6.0 min	3.0 min	0.012	0.025
Calorific value, kJ kg ⁻¹	38 542	38 670	38 801	39 083	39 325	39 657	—	—	0.087	0.081
Acid value, mg KOH g ⁻¹	0.97	0.85	0.76	0.65	0.55	0.48	0.5 max	0.5 max	0.009	0.025
Flash point, °C	153	135	127	116	105	103	101 min	93 min	0.004	0.028
Kinematic viscosity, 40 °C, mm ² s ⁻¹	4.70	4.63	4.55	4.32	4.15	4.02	3.5-5.0	1.9-6.0	0.034	0.048
Density, 15 °C, g cm ⁻³	0.8825	0.8817	0.8809	0.8796	0.8781	0.8763	0.86-0.90	0.87-0.89	0.045	0.039
Water content, mg kg ⁻¹	123.4	121.5	116.6	108.5	103.8	99.8	500 max	500 max	0.044	0.063

^a P-values and $\alpha = 0.05$. ^b Comparison between 0 DDCL and the mean of the DDCL volumes used. ^c Examines whether increasing DDCL vol in the range of 2.5% to 20% affects the response.

^a P-values and $\alpha = 0.05$. ^b Comparison between 0 DDCL and the mean of the DDCL volumes used. ^c Examines whether increasing DDCL vol in the range of 2.5% to 20% affects the response.

As shown in Table 6 and 7, FP, KV decreased obviously ($P < 0.05$) in all blends, which was along with the increase of the content of DDCL. The FP and KV of all the blends were compliant with EN 14214 and ASTM D6751 regardless of the number of storage days.

As it can be seen in Table 7, after stored for 100 days, calorific value, density and water content of the blends still were compliant with EN 14214 and ASTM D6751.

4. Conclusion

In conclusion, the deficiencies and superiorities of BWCO and DDCL were complemented through blending. DDCL can be used to significantly enhance the properties of biodiesel. In blending 20 vol% DDCL with BWCO, the fuel properties of the blends still met the specifications of EN 14214 and ASTM D6751 after storage for 100 days. Regardless of the blend ratio, the FP and KV of DDCL blended with BWCO were within the requirements stated in EN 14214 and ASTM D6751.

The results indicate blending is a good way for full use of biodiesel and DDCL, which can alleviate the shortage of petroleum resources.

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