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Renewable diesel production from rapeseed oil with hydrothermal hydrogenation and subsequent decarboxylation

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Highlights

- Hydrocarbon production from rapeseed oil was studied.
- The process consists of hydrolysis/hydrogenation and subsequent decarboxylation.
- The composition of the obtained hydrocarbons can be foreseen from raw material.
- The product meets the Japanese diesel standard by blending with fossil diesel.

Abstract

Hydrocarbon (renewable diesel) production from rapeseed oil was studied with hydrothermal hydrogenation and subsequent decarboxylation in a batch-type reaction vessel. An appropriate reaction condition for hydrothermal hydrogenation was found to be 270 °C/ 5 MPa (H₂ pressure) with water and Pd/C catalyst for 60 min, under which triglycerides were simultaneously hydrolyzed and hydrogenated into saturated fatty acids in a yield of 98.4 mol%. The obtained saturated fatty acids were then decarboxylated to hydrocarbons under the condition of 300 °C/ 1 MPa (H₂ pressure) with Pd/C for 120 min in a yield of 91.5 mol% on rapeseed oil. In addition, the composition of the obtained hydrocarbons corresponded nearly to that of the fatty acid in rapeseed oil. Such a result indicates that the composition of hydrocarbons produced in this proposed process can be foreseen from fatty acid composition of the feedstock triglycerides. By blending the obtained hydrocarbons from rapeseed oil with an adequate amount of fossil diesel, the blended fuel could satisfy the specification standard of fossil diesel in Japan.

Keywords

Renewable diesel; Plant oil; Hydrolysis; Hydrogenation; Decarboxylation

1. Introduction

The fossil fuels are finite resources and their mass consumption has significant impacts on our environment and society. For these reasons, fatty acid methyl ester (FAME) is being used as an alternative diesel fuel produced by transesterification of triglyceride, a main component of plant oil, with methanol. Because FAME is renewable fuel containing no aromatics and sulfur, it can reduce exhaust emissions [1, 2]. However, FAME has some drawbacks caused by the difference in chemical structure from petroleum diesel, for example, corrosiveness against certain types of rubber and metal [3] and poor oxidation stability due to unsaturated double bonds [1-4]. To overcome such drawbacks, hydrocarbon productions from plant oils with the hydrotreating and catalytic cracking are being researched worldwide [5-19].

The hydrotreatment of plant oils was usually studied in the temperature range between 350 and 450 °C under the pressure between 4 and 15 MPa with H₂ and a catalyst [5-13]. As a catalyst, for example, sulfided CoMo and NiMo supported on SiO₂, Al₂O₃, ZrO₂, TiO₂ and zeolites were used [5-11]. Under the hydrotreating reaction, first, double bonds in fatty acid moieties of triglyceride are hydrogenated into saturated C-C bonds, followed by the cleavage of ester linkages to produce one molecule of propane and three molecules of saturated fatty acids [6, 12]. The obtained saturated fatty acids are then deoxidized into hydrocarbons having carbon numbers mainly between 15 and 18 through hydrodeoxygenation, decarbonylation and decarboxylation [8, 13]. This reaction also produces *i*-paraffin and naphthene through isomerization and cyclization of olefin intermediates, which

contributes to improving the cold-flow properties. In addition, CO, CO₂, H₂O and propane are produced as byproducts [6].

On the other hand, the catalytic cracking of plant oils was usually carried out in the temperature range between 300 and 500 °C under atmospheric pressure with zeolites, Al₂O₃ and MgO as a catalyst [14-17], under which the thermal decomposition is predominant. First, triglycerides are decomposed to fatty acids, ketones, aldehydes and esters [18]. These products undergo secondary cracking to form short and long chain paraffins and olefins with CO, CO₂, H₂O and alcohols by breaking C-O and C-C bonds via decarboxylation and decarbonylation. However, this process makes various hydrocarbons having wide range of carbon numbers with olefins and aromatics.

After all, the selectivity of the products is not so high with the conventional hydrotreating and catalytic cracking mentioned above. It should be caused by the presence of unsaturated fatty acid moieties, which leads to various side reactions. Actually, Dos Anjos et al. studied the catalytic cracking of prehydrogenated soybean oil as well as crude one, reporting that prehydrogenated oil yielded essentially pure hydrocarbon products, while crude oil yielded a mixture of oxygen-containing products and the lower molecular weight hydrocarbons [20].

In this study, therefore, hydrocarbon production from plant oil was studied through two-step reaction with hydrolysis and subsequent decarboxylation. During the hydrolysis step, hydrogenation was simultaneously conducted to produce stable saturated fatty acids, which may suppress undesirable side reactions during subsequent decarboxylation [19, 20]. In the literature [5-21], furthermore, an

organic solvent such as *n*-dodecane was usually added to enhance the fluidity of the reactants and to avoid the deactivation of catalyst, even though only a few studies without any solvent can be found [19, 22]. However, the use of such organic solvent requires additional separation and purification steps after the reaction, and it makes the whole process complicated. Therefore, the reactions of this study were conducted without any organic solvent so as to simplify the process for production of hydrocarbons as renewable diesel.

2. Materials and Methods

2.1. Experimental procedures

Fig.1 shows the schematic diagram of the saturated hydrocarbon (renewable diesel) production process in this study via saturated fatty acids from rapeseed oil. Prior to the experiment, Pd/C catalyst (Pd/C = 5/95 (w/w), Nacalai Tesque, Inc.) was dried overnight at 105 °C and reduced in H₂ flow (15 ml/min) at 200 °C for 60 min. Rapeseed oil (reagent grade, Nacalai Tesque, Inc.) was, then, treated in hot-compressed water with H₂ gas and Pd/C catalyst for hydrolysis and hydrogenation to obtain saturated fatty acids. The obtained saturated fatty acids were then decarboxylated with Pd/C catalyst to produce saturated hydrocarbons by decarboxylation.

75 **2.1.1. Hydrolysis coupled with hydrogenation (Hydrolysis/hydrogenation)**

76 A batch-type reaction vessel (inner volume: 5.0 ml) made of Inconel-625 [23] was used for
77 the reaction. One gram of rapeseed oil and 1.0 - 3.0 g of ion-exchanged water were placed into the
78 reaction vessel with 0.05 g of Pd/C. Hastelloy balls (total volume: 0.2 ml) were also placed into the
79 vessel to agitate the mixture efficiently. After the vessel was sealed, the inside of the vessel was purged
80 and pressurized to 5 MPa with H₂ gas using a gas-supplying system. The hydrolysis coupled with
81 hydrogenation (hydrolysis/hydrogenation) reaction was then conducted by immersing the vessel into a
82 molten salt bath preheated at 270 °C, which is the optimum temperature for hydrolysis of triglycerides
83 found in previous works [24, 25]. The reaction vessel was swung from side to side to agitate the
84 mixture during the reaction. After a designated treatment time, the vessel was moved into a water bath
85 to quench the reaction. The obtained reaction mixture dissolved in tetrahydrofuran (THF, specially
86 prepared reagent grade, Nacalai Tesque, Inc.) was, then, taken out from the vessel, sonicated for 30 min,
87 and the catalyst was removed with a filter paper in a micropore of 0.45 µm (Merck Millipore Co.). The
88 products were, then, warmed up in a water bath at 70 °C for 30 min and separated into THF and water
89 phases. By removing THF from the THF phase with a rotary vacuum evaporator, the products of the
90 hydrolysis/hydrogenation reaction were collected and their yield was determined.

2.1.2. Decarboxylation

For subsequent decarboxylation, approximately 0.9 g of the obtained saturated fatty acids and 0.05 - 0.45 g of Pd/C were placed into the 5 ml reaction vessel with Hastelloy balls. The inside of the reaction vessel was then purged and pressurized with N₂ or H₂ gas to be 1 MPa which is a favorable pressure for decarboxylation reaction [26]. The decarboxylation was, then, conducted with the molten salt bath at 300 °C for 120 min, which is an appropriate condition reported by Lestari *et al.* [27], and quenched into the water bath in the same way mentioned above. After the reaction, the obtained products dissolved in THF were taken out from the vessel, sonicated for 30 min, and the catalyst was removed with the filter paper. After removing THF by the evaporator, the decarboxylated products were obtained to determine its yield. To clarify the decarboxylation reaction of the saturated fatty acid, palmitic acid, stearic acid and arachidic acid (all being guaranteed reagent grade from Nacalai Tesque, Inc.) were also studied.

2.2. Analytical methods

The fatty acid composition of rapeseed oil used in this work was determined in accordance with the Japan Oil Chemists' Society standard method [28]. The products, obtained from hydrolysis/hydrogenation and subsequent decarboxylation, were analyzed by gel permeation chromatography (GPC, Shimadzu Co. LC-10VP system, column: GF-310 HQ (Showa Denko K.K.), oven temperature: 40 °C, mobile phase: THF, flow-rate: 1.0 ml/min, detector: refractive index detector

111 RID-10A) and high performance liquid chromatography (HPLC, column: Cadenza CD-C18 (Imtakt
112 Co.), oven temperature: 40 °C, mobile phase: methanol, flow-rate: 1.0ml/min, detector: RID-10A). By
113 the GPC analysis, the obtained products from hydrolysis/hydrogenation can be separated into four
114 peaks, which correspond to the groups of triglycerides, diglycerides, monoglycerides and fatty acids.
115 The amount of each group was quantified based on the corresponding peak area, using tristearin,
116 1,3-distearin, 1-monostearin (all being >99% grade from Olbracht Serdary Research Laboratories) and
117 stearic acid (guaranteed reagent grade from Nacalai Tesque, Inc.) as calibration standards. The HPLC
118 analysis, by which fatty acids can be separated into single ones, was then conducted to quantify the
119 amount of each fatty acid. In this way, the yields of the products were determined in mol%. The
120 obtained product from the decarboxylation reaction was also quantified in a similar manner.

121 The fuel properties of the renewable diesel were evaluated for flash point, pour point, cold
122 filter plugging point, kinematic viscosity and density as in Table 2. In addition, the renewable diesel
123 was blended in various ratios with fossil diesel (#1 diesel of the Japanese Industrial Standard (JIS),
124 purchased from SHOWA SHELL SEKIYU K.K.), and their fuel properties were also evaluated. The
125 density was determined in accordance with the ASTM International's standard ASTM D1298 [29],
126 while the flush point, pour point, cold filter plugging point and kinematic viscosity were measured by
127 the automated Pensky-Martens closed cup flash point tester (APM-7), the mini pour point tester
128 (MPC-102), the automated cold filter plugging point tester (AFP-102) and the automatic kinematic
129 viscosity measuring system (AKV-201), respectively. All of these measuring systems were made by

Tanaka Scientific Co. Ltd. The acid and iodine values were determined in accordance with ASTM D974 and D1959 [30, 31].

3. Results and Discussion

Table 1 shows the fatty acid composition of rapeseed oil and yields of the products obtained after hydrolysis/hydrogenation and subsequent decarboxylation. Rapeseed oil used in this study is composed of saturated and unsaturated fatty acids with 16, 18 and 20 carbon atoms. Through this study, appropriate reaction conditions for hydrolysis/hydrogenation and decarboxylation were evaluated as described in the following subsections.

3.1. Hydrolysis/hydrogenation

Figure 2(a) and 2(b) show respectively GPC and HPLC chromatograms of the obtained products through hydrolysis/hydrogenation reaction from 0.9 g of rapeseed oil as treated at 270 °C/ 5 MPa (H₂) with 3.0 g of water and 0.05 g of Pd/C. In Fig. 2(a), triglycerides (TG) in rapeseed oil are decreasing as reaction time is prolonged. For 20 and 40 min treatments, diglycerides (DG) and monoglycerides (MG) are being observed as intermediate compounds, but almost all of them also disappear after 60 min. Meanwhile, fatty acids (FA) are increasing with reaction time until 60 min treatment. Incidentally, the retention time of triglycerides in the GPC chart shifts slightly to the shorter retention time after 20 min treatment. It would imply that the double bonds in fatty acid moieties are

149 converted into saturated ones through hydrogenation, because saturated fatty acids have a slightly
150 shorter retention time than unsaturated ones on the GPC column used in this study. Actually, only
151 saturated fatty acids such as palmitic ($C_{16:0}$), stearic ($C_{18:0}$) and arachidic ($C_{20:0}$) acids can be found after
152 20 min treatment by HPLC analysis as shown in Fig. 2(b). It indicates that hydrogenation is faster than
153 hydrolysis and completed within 20 min.

154 From the above, an appropriate reaction time for hydrolysis/hydrogenation was found to be
155 60 min at the given conditions. Based on the HPLC and GPC analyses, the yield of the products from
156 rapeseed oil was determined as shown in Table 1. Triglycerides in rapeseed oil were converted into
157 saturated fatty acids and their yield was summed up to be 96.1 (= 4.5 + 89.7 + 1.9) mol%. In addition,
158 2.3 mol % of glycerides still remained as intermediate compounds. Finally, the total yield of fatty acids
159 and glycerides was 98.4 mol% and any other products were not observed in the HPLC chart. In
160 addition, no gaseous products were produced and saturated fatty acids are stable under the given
161 condition. Thus, no product decomposition would be occurred. Therefore, the rest of 1.6 mol% would
162 probably be lost through the purification steps. By excluding the lost portion, the molar ratio upon the
163 obtained products basis was shown in parenthesis in Table 1. As a result, the molar ratio of the obtained
164 saturated fatty acids ($C_{16:0} : C_{18:0} : C_{20:0} = 4.6 : 91.2 : 1.9$) is close to the fatty acid composition of
165 rapeseed oil ($C_{16:0} + C_{16:1} : C_{18:0} + C_{18:1} + C_{18:2} + C_{18:3} : C_{20:0} + C_{20:1} = 4.5 : 94.0 : 1.5$). It means that the
166 selective reaction to be saturated fatty acids has occurred during the hydrolysis/hydrogenation step.

167 With regard to the amount of water, on the other hand, 1.0 g of rapeseed oil was hydrolyzed
168 with 3.0 g of water. Thus, the weight ratio of water/rapeseed oil was 3.0/1.0 for Table 1 and Fig. 2.
169 However, when its ratio decreased from 3.0/1.0 to 1.0/1.0, the yield of saturated fatty acids decreased
170 from 97.7 mol% to 77.2 mol% due to the insufficient hydrolysis of glycerides and fatty acids under the
171 same reaction condition. From these results, it was concluded that an appropriate
172 hydrolysis/hydrogenation condition is 270 °C/ 5 MPa (H₂) with 3.0 g of water and 0.05 g of Pd/C for
173 1.0 g of rapeseed oil.

174

175 **3.2. Decarboxylation**

176 As a preliminary experiment, the effect of atmospheric gas (N₂ or H₂) was investigated on
177 decarboxylation reaction by using stearic acid as a model compound. When N₂ gas was used, no
178 conversion was observed at the conditions of 300 °C/ 1 MPa/ 0.05 g of Pd/C for 120 min. In the case of
179 H₂ gas, on the other hand, 16.3 mol% of *n*-heptadecane was obtained at the same condition. Although
180 H₂ is not essentially required by the decarboxylation reaction, it keeps the catalyst activity [32, 33].
181 Actually, some researchers have reported that an efficient decarboxylation was observed in the presence
182 of H₂ [19, 33, 34]. Therefore, H₂ gas was used in the following experiments.

183 Moreover, decarboxylation reaction was carried out for 0.9 g of stearic acid as a model
184 compound to determine an appropriate amount of the catalyst at the conditions of 300 °C/ 1 MPa (H₂)
185 for 120 min. When the two different amounts of Pd/C were studied to be 0.05 and 0.25 g, incomplete

conversions were found respectively to be 16.3 and 26.1 mol% from stearic acid into *n*-heptadecane. On the other hand, 90.3 mol% of *n*-heptadecane was achieved with 0.45 g of Pd/C. Therefore, it was concluded that 0.45 g of Pd/C is required for the efficient decarboxylation of 0.9 g of fatty acid at the given conditions. In general, decarboxylation of fatty acids proceeds in three phases, gaseous H₂, liquid fatty acids and a solid catalyst, in which the mutual accessibility is an important factor. Although an organic solvent is usually added to improve its accessibility in the literature [21], decarboxylation was conducted without any organic solvent in this study to simplify the reaction process. That might be the reason why such a large amount of Pd/C catalyst was needed. Therefore, an effective agitation would be required to reduce the amount of the catalyst.

On the other hand, Fig.3 shows HPLC chromatograms of rapeseed oil, the obtained fatty acids by hydrolysis/hydrogenation and hydrocarbons after decarboxylation. Triglycerides in rapeseed oil are composed of various fatty acids, thus many peaks are found in Fig.3. However, these peaks are converted mainly into three peaks of saturated fatty acids, palmitic (C_{16:0}), stearic (C_{18:0}) and arachidic (C_{20:0}) acids, by hydrolysis/hydrogenation of triglycerides. These saturated fatty acids are then converted into *n*-pentadecane (C₁₅H₃₂), *n*-heptadecane (C₁₇H₃₆) and *n*-nonadecane (C₁₉H₄₀), respectively, by subsequent decarboxylation. Therefore, the obtained renewable diesel from rapeseed oil consists of these three kinds of saturated hydrocarbons.

Based on the HPLC and GPC analyses, the yields of hydrocarbons were determined as shown in Table 1. The total yield of hydrocarbons was 91.5 mol% and any other products were not observed.

205 Since hydrocarbons are stable enough under the given condition, no decomposition of the products can
206 be occurred. Therefore, the rest of 8.5 mol% would probably be lost through the purification steps. The
207 loss of the products would be caused by using a large amount of catalyst, on which the products were
208 adsorbed. The molar ratio upon the obtained hydrocarbon basis was shown in parenthesis in Table 1. As
209 a result, the molar ratio of obtained *n*-pentadecane, *n*-heptadecane and *n*-nonadecane was found out to
210 be 4.5 : 93.6 : 1.9. This molar ratio is nearly close to the one of saturated fatty acids ($C_{16:0} : C_{18:0} : C_{20:0}$
211 = 4.6 : 91.2 : 1.9 in Table 1) obtained after hydrolysis/hydrogenation. Therefore, these saturated fatty
212 acids seem to be selectively converted without any side reaction into the corresponding hydrocarbons
213 through decarboxylation. In case of unsaturated fatty acids, however, various side reactions such as
214 hydrogenation, dehydrogenation, cyclization, ketonization, dimerization and cracking have been
215 reported to occur concurrently due to the unstable double bonds present [35, 36], which lead to
216 decrease the degree of the specific production of hydrocarbons. Therefore, unsaturated fatty acids
217 should be converted into saturated ones before decarboxylation to maintain its high selectivity. For this
218 specificity, the process shown in Fig. 1 is appropriate and promising.

219 After hydrolysis/hydrogenation, 2.3 mol% of glycerides such as monoglycerides and
220 diglycerides still remain as shown in Table 1. However, these intermediate compounds are disappeared
221 after decarboxylation, and converted into hydrocarbons. Actually, when 1-monostearin was treated at
222 the same condition, it was converted into *n*-heptadecane by decarboxylation treatment with H_2 gas and
223 Pd/C catalyst even though the reactivity was slightly low, compared with saturated fatty acids.

224 Therefore, the remaining glycerides must be converted to saturated fatty acids during decarboxylation
225 treatment.

226 The iodine and acid values of the obtained hydrocarbons from rapeseed oil were evaluated
227 and found out to be zero. This means that the obtained products have neither double bonds nor fatty
228 acids. It is, therefore, evident that hydrogenation and decarboxylation reactions are successfully
229 completed during the process.

230

231 **3.3. Fuel properties of saturated hydrocarbons**

232 It is very important to evaluate the fuel properties of the renewable diesel. However, the
233 prepared renewable diesel is not sufficient in amount to test the fuel properties. As in Table 1, it
234 consists of the saturated linear hydrocarbons of *n*-pentadecane, *n*-heptadecane and *n*-nonadecane in a
235 molar ratio of 4.5 : 93.6 : 1.9. In addition, it was confirmed that such a mixture does not contain any
236 contaminants. Therefore, a mixture of these three kinds of hydrocarbons was prepared from their
237 chemicals purchased as the renewable diesel and evaluated for the fuel properties.

238 Table 2 shows the evaluated fuel properties of the mixtures of renewable diesel with #1 fossil
239 diesel in various ratios. In case of 100 vol% renewable diesel, it has a higher flash point than that of the
240 fossil diesel (0 vol% renewable diesel in Table 2), and satisfies the specification standard of the fossil
241 diesel in Japan (JIS K2204) [37]. Such a property should be originated from *n*-heptadecane, a main
242 component of the fuel, which has a relatively high boiling point among the hydrocarbons in petroleum

diesel. In addition, the values of kinematic viscosity and density also satisfy the requirements for the Japanese diesel standard. These values are also close to the ones of *n*-heptadecane. On the other hand, the cold-flow properties such as pour point and cold filter plugging point are poor due to the presence of saturated linear hydrocarbons, because these have relatively high melting points, especially in case of *n*-heptadecane. Therefore, the cold-flow properties should be improved to meet the fossil diesel standard. Blending the renewable diesel with fossil one is a simple way for this purpose. In case of 20 vol% renewable diesel, as shown in Table 2, the pour point and cold filter plugging point are improved, and thus, it can satisfy the requirements for the fuel standard. However, when the ratio of renewable diesel is increased to be 30 vol%, the pour point exceeds the limit of the standard. From such a reason, the blending ratio would be limited up to around 20 vol% to meet all requirements of the specification standard in Table 2. This further indicates that the obtained hydrocarbons through this process can be used as renewable diesel by blending with fossil diesel.

4. Concluding Remarks

To produce hydrocarbons from plant oil as renewable diesel fuel, the conventional hydrotreating and catalytic cracking processes are not really specific for the products selectivity due to unsaturated double bonds. In this study, therefore, the process composed of hydrolysis/hydrogenation and subsequent decarboxylation was proposed. In the first treatment, triglycerides in rapeseed oil were converted into saturated fatty acids through hydrolysis in hot-compressed water and simultaneous

hydrogenolysis under the presence of Pd/C catalyst and H₂ gas. In the second treatment, the obtained saturated fatty acids were decarboxylated into the corresponding hydrocarbons under the presence of Pd/C. In this process, unsaturated double bonds in fatty acid moieties, which lead to various side reactions, were hydrogenated into saturated ones prior to the second treatment. Therefore, the selective conversion was achieved by this two-step treatment without any side reaction. As a result, the composition of the obtained hydrocarbons corresponded to the fatty acid composition of rapeseed oil.

However, the obtained renewable diesel fuel should be improved in cold-flow properties because saturated linear hydrocarbons have relatively high melting points, whereas other properties such as flash point, kinematic viscosity and density satisfied the requirements of the fossil diesel. To satisfy the requirements, a blend of renewable diesel with fossil diesel was found out to weaken the inferior fuel properties of pour point and cold filter plugging point. Consequently, 20 vol% blend of the renewable diesel was found out to satisfy the requirements for the Japanese specification standard of the fossil fuel.

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List of figures

Figure 1: Schematic diagram of the saturated hydrocarbon production process via saturated fatty acids from rapeseed oil.

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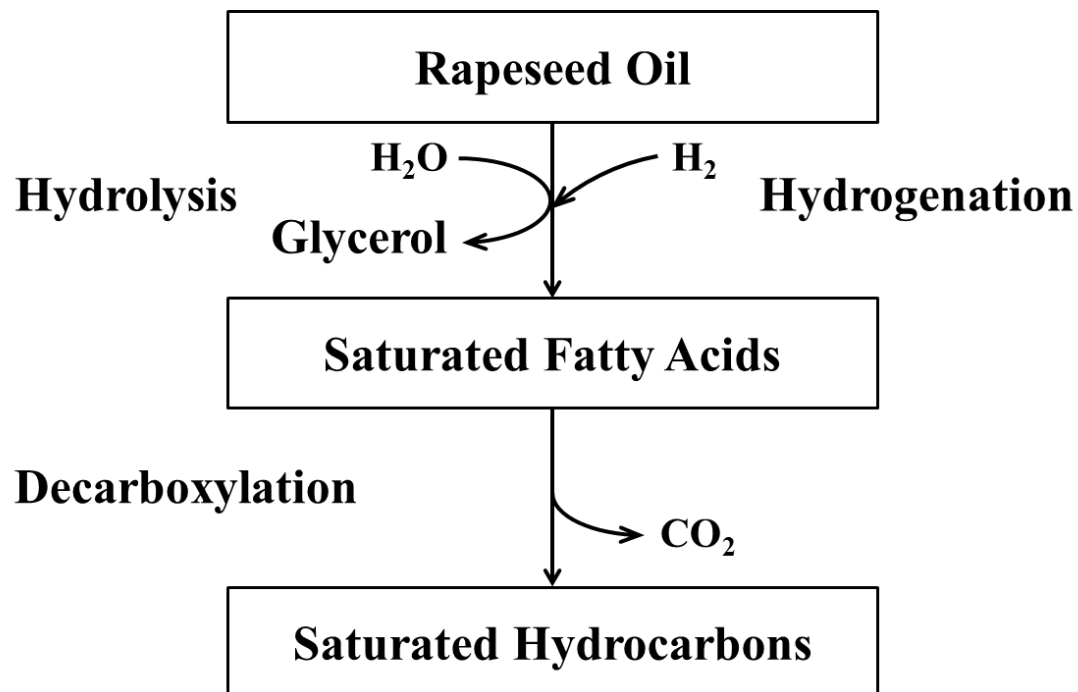
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372 Table 1: Fatty acid composition of rapeseed oil, the obtained saturated fatty acids by
373 hydrolysis/hydrogenation and saturated hydrocarbons by decarboxylation.

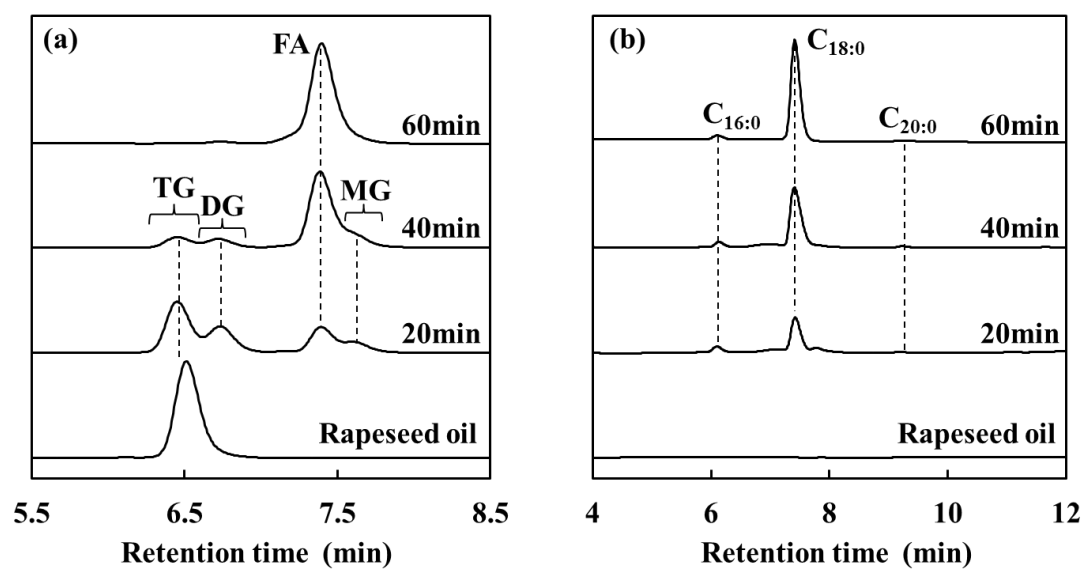
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375 Table 2: The fuel properties of renewable diesel blended with fossil diesel in various ratios compared
376 with Japanese #1 diesel standard (JIS K2204) [37].



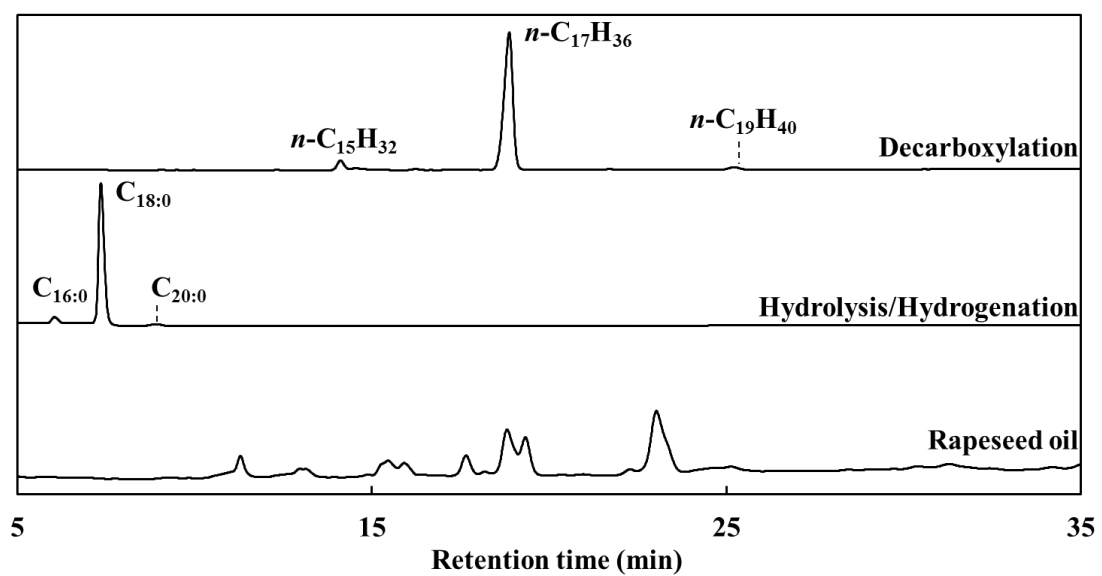
Fuel

Figure 1



Fuel

Figure 2



Fuel

Figure 3

Table 1: Fatty acid composition of rapeseed oil, the obtained saturated fatty acids by hydrolysis/hydrogenation and saturated hydrocarbons by decarboxylation.

Fatty acid composition of rapeseed oil (mol%)		Yield (mol%)* ¹		
		Saturated fatty acids by hydrolysis/hydrogenatio		Saturated hydrocarbons by decarboxylation * ³
		n * ²		
C _{16:0}	4.3	4.5 (4.6)	4.1 (4.5)	C ₁₅ H ₃₂
C _{16:1}	0.2	0.0	-	
C _{18:0}	0.7	89.7 (91.2)	85.7 (93.6)	C ₁₇ H ₃₆
C _{18:1}	66.4	0.0	-	
C _{18:2}	19.4	0.0	-	
C _{18:3}	7.5	0.0	-	
C _{20:0}	0.5	1.9 (1.9)	1.7 (1.9)	C ₁₉ H ₄₀
C _{20:1}	1.0	0.0	-	
Glycerides	-	2.3 (2.3)	0.0	
Total	100	98.4 (100)	91.5 (100)	

*1: The values in parenthesis indicate the mol% on the total yield basis of rapeseed oil.

*2: 270 °C/ 5 MPa (H₂) with 3.0 g of water and 0.05 g of Pd/C for 60 min

*3: 300 °C/ 1 MPa (H₂) with 0.45 g Pd/C for 120 min

Table 2: The fuel properties of renewable diesel blended with fossil diesel in various ratios compared with Japanese #1 diesel standard (JIS K2204) [37].

Property	Ratio of renewable diesel ^{*1}					#1 diesel standard
	to #1 fossil diesel (vol%)					
	100	30	20	5	0 ^{*2}	
Flash point (°C)	153	75.0	69.5	64.5	63.5	≧50
Pour point (°C)	20	3.0	-2.5	-7.0	-8.0	≦-2.5
Cold filter plugging point (°C)	22	-2.0	-6.0	-3.0	-5.0	≦-1
Kinematic viscosity at 30 °C (mm ² /s)	4.5	3.7	3.6	3.6	3.5	≧2.7
Density at 15 °C (g/cm ³)	0.77	0.82	0.83	0.83	0.83	≦0.86

*1: The renewable diesel is prepared by mixing pure hydrocarbons with the same molar ratio as in Table 1.

*2: Renewable diesel 0 vol% corresponds to fossil diesel 100 vol%.