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Review

Using Canola Oil Biodiesel as an Alternative Fuel in Diesel Engines: A Review

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Abstract: Due to the rapid development of the global economy, fossil oil is widely used, leading to its depletion and gradual deterioration of the global environment, including global warming, the greenhouse effect, fog, and haze. Therefore, many researchers have been interested in studying alternative fuels in an attempt to develop an eco-friendly fuel to replace traditional fuel and solve the above environmental problems. Biodiesel is a renewable and eco-friendly fuel that is the most promising alternative fuel for diesel engines, and a significant amount of research and development has focused on biodiesel. Canola oil biodiesel (COB) is one type of biodiesel, and it has an advantage in oil production per unit area compared with other biodiesels. This paper summarizes and reviews studies related to the use of COB in different diesel engines under a variety of operating conditions. We focus on evaluating the combustion and emission characteristics of COB based on a large number of papers (including our previous studies). In addition, this paper serves as a valuable reference for in-depth studies of COB use in diesel engines, as it covers the topic from the production of COB to its use in diesel engines.

Keywords: alternative fuel; biofuel; canola oil biodiesel; diesel engine; global environment; engine performance; emission characteristics

1. Introduction

Fossil oil resources are being widely exploited, due to the rapid development of the global economy and the ever-growing number of vehicles. Excessive exploitation and utilization of fossil oil can damage the environment [1–3]. Therefore, although people in modern society live in comfortable environments, they must endure the inconveniences caused by air pollution, including global warming, the greenhouse effect, desertification, acid rain, fog, haze, and volatile organic compounds [4–6]. In China, fog and haze are particularly important topics. Most of China's cities are shrouded in fog and haze in the winter. For example, in January 2013, there were only five days in Beijing that did not have fog or haze. Environmental pollution can significantly affect people's lives and health [7–9]. Figure 1 shows foggy and hazy weather in Chongqing, China on 5 January 2017. As shown in Figure 1, people put masks on copper statues of children, due to the serious fog and haze. Thus, environmental pollution is a problem that people have been aware of for a long time.

(**a**) (**b**)

Figure 1. Foggy and hazy weather in Chongqing, China (5 January 2017); (**a**) a tall building that was being built; (**b**) the corner of the park is shown.

Biodiesel is an alternative fuel that can solve or reduce the impact of air pollution because of various advantageous characteristics [10–15]. It has been reported that biodiesel can be used in diesel engines without (or with only minor) engine modifications [16,17]. Diesel engines are widely used in trucks and commercial vehicles because they have the advantages of large power output and fewer exhaust emissions. Although diesel engines produce lower hydrocarbon (HC) and carbon monoxide (CO) emissions than gasoline engines, their higher nitrogen oxides (NO_x) and particulate matter (PM) emissions are a problem [18,19]. However, the biofuel produced from animals and plants can reduce PM emissions due to its inherent characteristics. Biodiesel is a green renewable fuel that produces only carbon dioxide (CO_2), and can be absorbed by plants as they grow, making biofuels carbon neutral. Thus, using biofuels can significantly reduce global warming and the greenhouse effect [20–23]. However, pure biofuel cannot be widely used in diesel engines, due to its high viscosity and density. Diesel engines experience many problems when pure biofuels are used, including injector nozzle clogging and plastic tube and pad corrosion [24–27]. So, biofuels are widely used in the form of a mixed fuel (i.e., biofuel is blended with conventional diesel at a certain ratio) in vehicles in Europe and other developed countries. Figure 2 shows a biofuel station in the United States. There are more than 2700 public E85 stations in the U.S., and high-level ethanol blends are available in more than 40 states. However, in Asia, the blend rate of biodiesel can only reach 5–10% due to technical limitations and other reasons [28–31].

Figure 2. A biofuel station in the United States (B20: 20% biofuel blended with 80% diesel; E85: 85% ethanol blended with 15% gasoline; E10: 90% ethanol blended with 10% gasoline).

In this study, we review and summarize the characteristics and applications of canola oil biodiesel (COB) in diesel engines to further the development and application of biodiesel in Asia (especially in China, which has rich biomass resources). This work includes our experimental results that focus on COB, and compares them with others within biodiesel literature. Thus, our work can provide an effective reference for research and application of COB in Asia, especially China.

2. Biodiesel Production

Biodiesel is a renewable and eco-friendly fuel that is one alternative fuel for vehicles. Biodiesel can be produced from many renewable biological sources, such as plants, vegetables, animal fats, used cooking oils, waste oils, and microalgae [32–34]. The methods of producing biodiesel can be divided into "physical" and "chemical" methods according to processing method and biodiesel characteristics. The physical methods can be subdivided into the "direct mixed method" and the "microemulsion method" while the chemical methods can be subdivided into the "pyrolysis method" and the "transesterification method." Among these, the physical method involves mixing of biodiesel and diesel fuel, or other admixtures, in certain proportions, to obtain low viscosity and high volatility biodiesel. This method does not change the chemical properties of biodiesel itself. The polymerization of unsaturated fatty acids, and the formation of gum due to oxidation or pyrolysis, can cause incomplete combustion. So, more carbon will accumulate around the engine valves over time [35–38].

2.1. Physical Methods

2.1.1. Direct Mixing Method

Some biodiesel fuels are liquid at room temperature because they have high unsaturated fatty acid content; these biodiesel fuels can be directly used in diesel engines or mixed with pure diesel fuel without further treatment. The advantages of this method are low cost, convenient operation, and high thermal efficiency (the grease has a high heating value). However, there are greases in the biodiesel fuel that lead to its high density, high viscosity, and low volatility; these shortcomings have a negative impact on engine combustion performance, including poor atomization effects, plugging of injector nozzles, and increased corrosion. These problems can lead to a series of more serious problems, including inadequate fuel combustion; engine performance degradation; decreased engine life; increased CO, HC, and PM; and harmful exhaust emissions. Because there are many problems with this method, it serves as a basis for comparing other methods for producing biodiesel fuels using optimized production methods that can improve biodiesel fuels [37,38].

2.1.2. Microemulsion Method

The microemulsion method is used to improve the high viscosity, low liquidity, and other disadvantages of biodiesel fuels. The microemulsion method involves blending animal and vegetable oils with solvents and microemulsions or surfactants, to form a microemulsion biodiesel fuel. The microemulsion method is characterized by a simple and direct reduction in viscosity of biodiesel. However, when the engine burns fuel produced by the microemulsion method for a long time, problems can occur, such as the deposition of a large amount of carbon, incomplete combustion, and increased viscosity of lubricating oils [39,40].

2.2. Chemical Methods

2.2.1. Pyrolysis Method

Pyrolysis is a method conducted at a high temperature, with or without the aid of a catalyst, that decomposes plant raw materials or animal fats into a series of mixtures. The resulting mixtures include alkanes, olefins, dienes, aromatics, and carboxylic acids. This method must be carried out without air or oxygen to prevent the oil from being oxidized at high temperatures. This method requires complex equipment and has a high production cost. In addition, the reaction conditions (atmospheric pressure, rapid heating, ultra-short reaction time) are harsh, and quickly break down the organic polymers in biomass into short chain molecules. Therefore, this method has not been appreciated by researchers because of its low conversion rate, high energy consumption, and poor economy [41,42].

2.2.2. Transesterification Method

At present, the main method of producing biodiesel fuels is the transesterification method. Vegetable oils or animal fats and short-chain alcohols (methanol or ethanol) undergo a transesterification reaction in the presence of acid (WO_3/ZrO_2, ZnO, H_2SO_4, etc.) or base (NaOH, KOH, carbonates, etc.), catalysts, or other new catalysts (heterogeneous catalysts). Then, biodiesel fuel is obtained by washing and drying the corresponding fatty acid methyl ester or ethyl ester (products after transesterification) [43–51]. The specific process of the transesterification method for biodiesel production is shown in Figure 3. Crude animal fat or vegetable oil is first heated to remove impurities (pretreatment). Then, transesterification is performed in the presence of a catalyst (methanol or ethanol), and a mixture of crude biodiesel and glycerin is obtained (medium treatment). Finally, pure biodiesel fuel is obtained after repeated washing and drying (post-treatment). The transesterification method can be divided into acid–base catalysis, enzymatic catalysis, and a supercritical methanol process according to the catalytic method. The supercritical methanol process is an economical, efficient (complete response time was only 2–4 min), simple, and environmentally friendly method for producing biodiesel fuel, compared with the conventional commercial method due to non-catalytic process [52,53]. Kusdiana et al. [53] researched the kinetics effects of transesterification for producing biodiesel fuel via supercritical methanol. During the reaction, the temperature ranges from 200 °C to 500 °C, and they found that the optimum reaction temperature was 350 °C, while the molar ratio of methanol in rapeseed oil was 42. Hernandez et al. [51] studied the transesterification characteristics of vegetable oils, using frying oil as a new heterogeneous catalyst. They demonstrated that the highest methyl ester yield with sunflower oil and frying oil were 88% and 67%, respectively. The weight of all the catalysts used were 7 wt. % oil, and the reaction time and stirring speed were 8 h and 740 rpm, respectively. Ilgen et al. [54] investigated the biodiesel production from canola oil via Mg–Al hydrotalcite catalysts. They reported that methanol was the best alcohol for producing canola biodiesel fuel, and the highest triglyceride conversion rate was 71.9%, while the reaction temperature and time were, respectively, 60 °C and 9 h, with a 6:1 molar ratio of methanol to canola oil, and a 3 wt. % catalyst with 125–150 μm particles.

Although the esterification methods are different, their reaction mechanism is the same. Figure 4 shows the schematic diagram of transesterification mechanism. That is, the carbonyl carbon of the starting ester ($RCOOR^1$) undergoes nucleophilic attack by the incoming alkoxide (R^2O^-) to give a tetrahedral intermediate, which either reverts to the starting material or proceeds to the transesterified product ($RCOOR^2$). The various species exist in equilibrium, and the product distribution depends on the relative energies of the reactant and product [36,37].

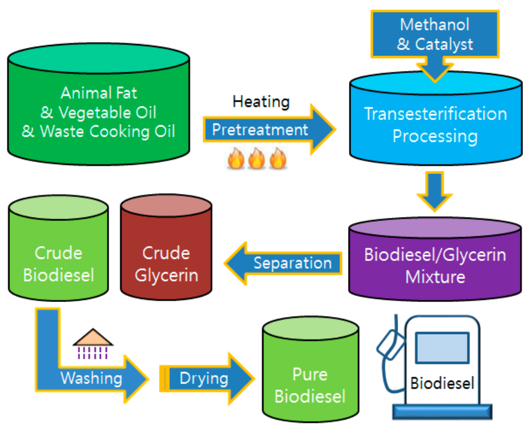


Figure 3. The specific process of transesterification method for biodiesel production.

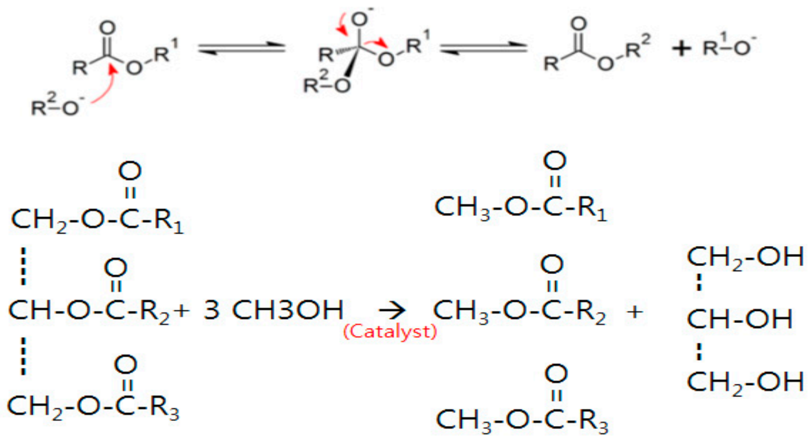


Figure 4. Schematic diagram of transesterification mechanism; where R_1, R_2, and R_3 are the long hydrocarbon chains (also called the fatty acid chains).

3. Properties of Canola Oil Biodiesel

COB is a good alternative fuel, and has great advantages compared with other biodiesel fuels. It contains approximately 40–45% oil (the same as sunflower oil), which is higher than other oilseeds, including soybeans (about 18–20%) [55]. The high-performance liquid chromatography (HPLC) chromatogram of COB is shown in Figure 5. Based on the location of the peaks in Figure 5, COB mainly contains triglycerides (16.174 min) and trace amounts of diglycerides (16.943 min) [56]. Some important physicochemical properties of COB will directly affect the application of COB to diesel engines, such as density and viscosity, oxygen content, cetane number, heating value, and oxidation stability. Table 1 shows the properties of COB and its blends with diesel oil [57].

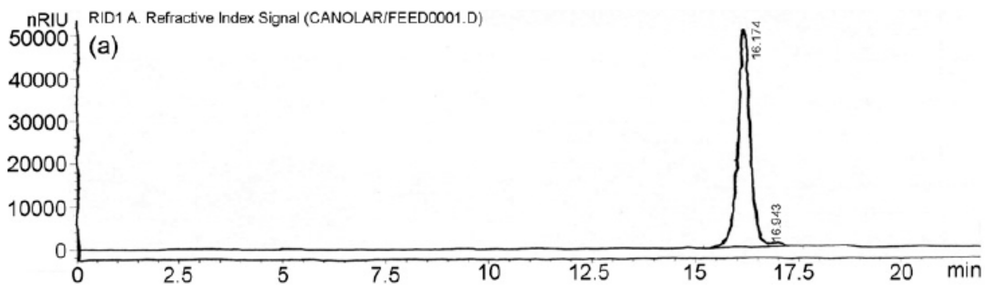


Figure 5. High-performance liquid chromatography (HPLC) chromatogram of canola oil biodiesel (reproduced with permission from [56], Elsevier, 2017).

Table 1. Properties of canola oil and its blends with diesel oil [57]. BD: Canola oil biodiesel blended with diesel fuel.

Properties (Units)	Pure Diesel	BD 100 [1]	BD 10 [2]	BD 20 [3]	BD 30 [4]	Test Method
Density (kg/m^3 at 15 °C)	836.8	880	842	846	850	ASTM D941
Viscosity (mm^2/s at 40 °C)	2.719	4.290	2.818	2.991	3.172	ASTM D445
Calorific value (MJ/kg)	43.96	39.49	43.29	42.71	42.12	ASTM D4809
Cetane index	55.8	61.5	-	-	-	ASTM D4737
Flash point (°C)	55	182	-	-	-	ASTM D93
Pour point (°C)	−21	−8	-	-	-	ASTM D97
Oxidation stability (h/110 °C)	25	15	-	-	-	EN 14112
Ester content (%)	-	98.9	-	-	-	EN 14103
Oxygen (%)	0	10.8	-	-	-	-

[1] Pure canola oil biodiesel; [2] 10% vol. of canola oil biodiesel blend with 90% Vol. of pure diesel; [3] 20% vol. of canola oil biodiesel blend with 80% vol. of pure diesel; [4] 30% vol. of canola oil biodiesel blend with 70% vol. of pure diesel.

3.1. Density and Viscosity

The density and viscosity of biodiesel fuel are important factors in engine operation. Density will directly affect the mixing of biodiesel and diesel, and excessively high density will lead to stratification of mixed oils. In addition, the density is also related to the cetane number, viscosity, and heating value of the fuel. Viscosity is an important factor that directly affects the combustion performance and exhaust characteristics of an engine. High viscosity deteriorates the atomization efficiency, extends ignition time, reduces injection pressure, and hinders full combustion of the fuel [58–60]. As a result, carbon deposition is increased, engine wear is increased, service life is shortened, and exhaust emissions are increased. Table 1 shows that the density and viscosity of pure diesel and canola oil biodiesel blended with diesel fuel (BD) 100 are 836.8 kg/m^3, 2.719 mm^2/s and 880 kg/m^3, 4.29 mm^2/s, respectively. Their density difference is not very large compared with the viscosity difference, which indicates that they can mix well. Al-Hamamre et al. [61] tested the density of biodiesel blended with diesel, with different amounts of biodiesel at different temperatures; these test results are presented in Figure 6, showing that most biodiesel density values fell between 838 kg/m^3 and 896 kg/m^3. On the other hand, in Table 1, the viscosity of BD10 and BD20 were reduced to about the same as that of pure diesel; these results are the same as Chhetri et al. [62] (see Figure 7). Many other researchers [63–67] have studied a variety of biodiesel blended fuels (diesel blended with sunflower, cottonseed, soybean, corn oils, and waste palm oil) and have also discovered that the viscosities of the 20% blend fuels are very close to that of pure diesel fuel.

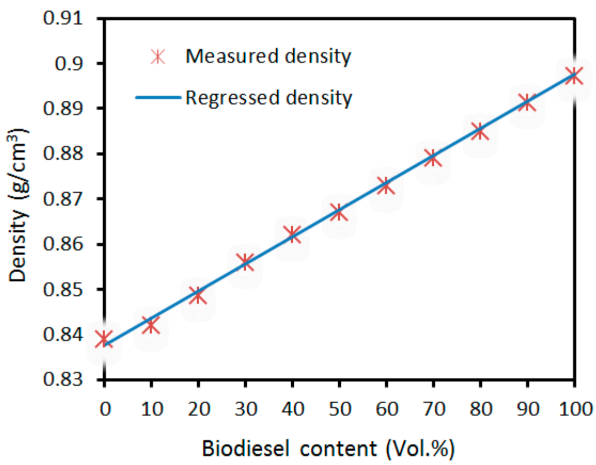


Figure 6. The density of biodiesels blended with diesel fuels.

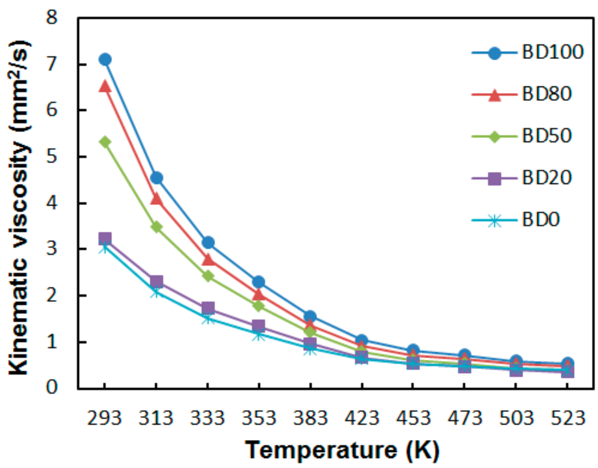


Figure 7. The viscosity change of canola oil biodiesel blended with diesel fuel at different temperatures.

3.2. Oxygen Content

The major difference between biodiesel and diesel is that biodiesel contains oxygen, while diesel does not. The molecular structures of the two fuels are presented in Figure 8. The presence of oxygen can reduce the ignition delay time, improve the combustion environment, and cause the fuel to burn more fully, which reduces CO, PM, and other exhaust emissions. Many researchers [68–70] have found that the high oxygen content of biodiesel can effectively reduce PM exhaust emission in diesel engines. However, this high oxygen content promotes combustion, increases combustion temperature, and increases the probability of combination with nitrogen, leading to an increase in NO_x emissions. Table 1 shows that the oxygen content of the BD100 is 10.8%. The oxygen content of the most common biodiesel is around 10% [71–73].

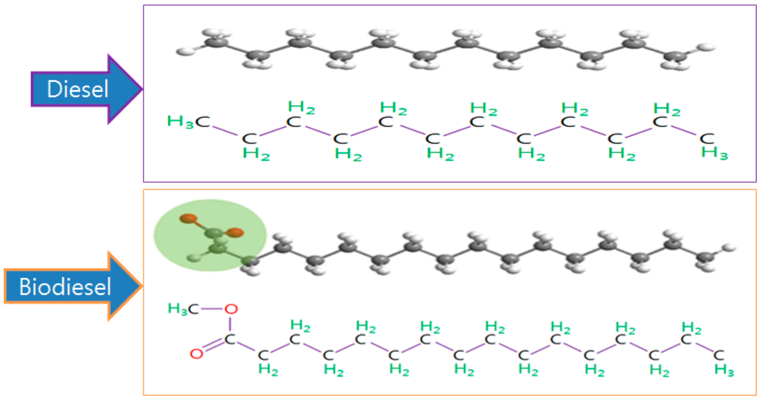


Figure 8. Molecular structure diagram of diesel and biodiesel.

3.3. Cetane Number

The cetane number (CN) is a factor closely related to ignition delay. A higher CN will shorten the ignition delay time, reduce engine knock, reduce the time of heat loss, and improve the thermal efficiency of the engine. Because most of the molecular structure of biodiesel is a long chain consisting of C and H atoms, there are almost no branches or aromatic structures in the middle. It is this characteristic that causes biodiesel to have a high CN [74]. Most biodiesel fuels have a cetane number between 40 and 60 [37], and the CN of BD100 is 61.5, which is 10.2% higher than that of pure diesel (55.8) [57].

3.4. Calorific Value

The calorific value of fuel is an important basis for measuring engine power. Consumption of a fuel with a low calorific value will be higher than that of a fuel with a high calorific value at the same power. The total content of carbon and hydrogen in biodiesel is lower than that in diesel. Thus, the calorific value of biodiesel is lower than that of diesel. Increasing the amount of biodiesel in the blended fuel (biodiesel blended with diesel) will therefore reduce the calorific value [37,57]. The calorific value of BD100 is shown in Table 1, and BD30 has the lowest calorific value among the three blend fuels, 42.12 MJ/kg, but is still close to that of diesel (43.96 MJ/kg) [57].

3.5. Oxidation Stability

Biodiesel is composed of fatty acid monomers, and biodiesel is easy to oxidize, due to the unsaturated fatty acids in the esters. This is one of the main reasons why the oxidation stability of biodiesel is less than that of diesel. Table 1 shows that the oxidation stability of BD100 is 15 h at 110 °C, which is higher than that of pure diesel (25 h). Biodiesel is susceptible to air oxidation during long-term storage, due to its low antioxidant capacity. The formation of deposits (aldehydes, alcohols, acids, peroxides, etc.) and gums, results in oxidation of biodiesel, darkening of the fuel color, and reduced fuel performance. Yaakob et al. [75] outlined two main reasons for the oxidation of biodiesel, auto-oxidation and photo-oxidation. The effect of auto-oxidation was greater than that of photo-oxidation. The use of antioxidants [76], or the combination of biodiesel and diesel fuel, is an important way to improve the oxidation stability of biodiesel. Focke et al. [77] have found that phenolic (DTBHQ) and phosphite (Naugard P) antioxidants can improve the antioxidant properties of COB fuel.

3.6. Iodine Index

The iodine index (or iodine value, iodine number, iodine adsorption value) is defined as the absorption amount of iodine (g) per 100 g of oil. In general, it is used to measure the amount of unsaturation in fatty acids. This unsaturation will react with iodine compounds because of the existence of double bonds. The average double bond number of fatty acids can be calculated by the determination of iodine value. And the number of unsaturated double bonds is related to the combustion performance, kinematic viscosity, and cold filter point of biodiesel fuel. Therefore, in general, the properties of biodiesel fuel can be determined by iodine value. The low degree of unsaturation of biodiesel fuels have low iodine value, high cetane number, and poor low temperature performance. The characteristics of high degree of unsaturation of biodiesel fuel are opposite with that of the low degree of unsaturation of biodiesel fuel. Canola oil has a lower iodine index than soybean oil, about 114 g I_2/100 g. On the other hand, the iodine index of biodiesel fuels has been limited in various regions of the world. For example: 120 g I_2/100 g in Europe and Japan, 130 g I_2/100 g in Europe for biodiesel as heating oil, 140 g I_2/100 g in South Africa, etc. [51,78,79].

3.7. Other Properties

In addition to the above common properties of COB, COB has the advantages of safer transportation and storage, due to its flash point being higher than diesel (see Table 1). The amount of sulfur in COB is also lower than that of diesel, which is an advantage compared with diesel. On the other hand, the use of biodiesel as an environmentally friendly lubricant is a hot topic at present. Borugadda et al. [80] reported that COB can be used as a good lubricant in engines.

4. Common Experimental Analysis Methods

4.1. Experiment Settings and Methods

When studying engine combustion performance and exhaust emission characteristics in diesel engines fueled with biodiesel, most researchers [57,59,81] have chosen the experimental scheme shown in Figure 9. Engines with a high pressure common rail system can provide a high precision injection pressure, precisely adjust injection advance angle, and control injection strategy (i.e., the timing of pre-injection and post-injection). Therefore, atomization and combustion of the fuel can achieve the highest efficiency. Based on these characteristics, we chose a 4 cylinder direct injection high pressure common rail diesel(2004 Hyundai Santa Fe, Ulsan, Korea) to study COB. As shown in Figure 9, the engine load and speed are regulated by a dynamometer connected to the left end of the engine. During the study, the combustion and exhaust emission characteristics of COB in a common diesel engine, the intake temperature, and engine oil temperature, are controlled at 70 ± 3 °C and 20 ± 3 °C, respectively. All data are obtained after the engine has reached steady operation, and the engine performance data are obtained over 200 engine cycles [57,81,82].

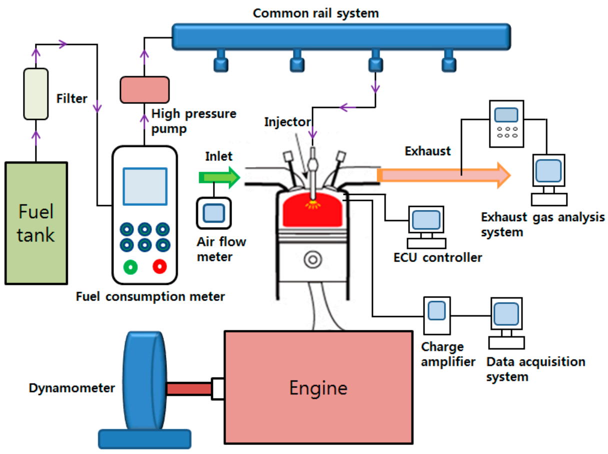


Figure 9. Schematic diagram of common experimental apparatus.

4.2. Traditional Analytical Formulas

There are many traditional analytical formulas that are used when studying the combustion performance of COB in a diesel engine. These formulas include the rate of heat release (ROHR), the exhaust gas recirculation (EGR), the brake specific fuel consumption (BSFC), and the coefficient of variation in indicated mean effective pressure (COV_{IMEP}). The combustion data (combustion pressure, maximum combustion pressure, piston position, volume change of combustion chamber, etc.) can be obtained through a charge signal amplifier and engine combustion software. The ROHR, BSFC, and COV_{IMEP} can be calculated using these data, and we can directly observe the characteristics of the COB in diesel engines [57,81,82].

4.2.1. The Rate of Heat Release

The rate of heat release (ROHR) is an important parameter that can directly reflect the combustion performance of an engine, such as ignition delay time, fuel injection characteristics, and fuel calorific value release characteristics. Based on this information, we can better control engine parameters and optimize engine performance parameters. The ROHR is calculated based on the first law of thermodynamics, as follows [57,82,83]:

$$\frac{dQ}{d\theta} = \frac{k}{k-1}P\frac{dV}{d\theta} + \frac{1}{k-1}V\frac{dP}{d\theta} \quad (1)$$

Here, $dQ/d\theta$ is the ROHR, k is the ratio of specific heat, P is the combustion pressure, and θ is the crank angle.

4.2.2. Exhaust Gas Recirculation

Biodiesel can promote fuel combustion more fully and increase the combustion temperature because biodiesel contains oxygen; however, this increases NO_x emissions. Exhaust gas recirculation (EGR) is an important parameter for reducing NO_x exhaust emission. This mechanism is used to inject the exhaust emissions (mostly nitrogen and carbon dioxide) into the combustion chamber to reduce the oxygen concentration, impede fuel combustion, and reduce the combustion temperature in the combustion chamber. The formula for EGR is as follows [57,82]:

$$EGR(\%) = \frac{Q_t - Q_{EGR}}{Q_t} \times 100 \quad (2)$$

Here, Q_t is the total air intake when there is no EGR action, Q_{EGR} is the total air intake when there is EGR action. The intake of EGR is expressed as a percentage.

4.2.3. Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) is an important indicator of fuel consumption. In general, the calorific value of biodiesel is lower than that of pure diesel fuel, resulting in greater fuel consumption. In other words, the BSFC of biodiesel is larger than that of pure diesel fuel. The formula for BSFC is as follows [57,82]:

$$BSFC = \frac{\dot{m}_f}{2\pi N T_e} \tag{3}$$

Here, $\dot{m}_f$ is the fuel consumption flow rate, N is the engine speed, and T_e is the brake torque.

4.2.4. Coefficient of Variation in Indicated Mean Effective Pressure

The coefficient of variation in the indicated mean effective pressure (COV_{IMEP}) is an important parameter for evaluating the stability of an engine. It is used to evaluate the cyclic variations of the combustion phasing parameters using the following formula [81]:

$$COV_{IMEP} = \frac{\left[\frac{1}{N}\sum_{i=1}^{N}\{IMEP(i) - X\}^2\right]^{\frac{1}{2}}}{X} \tag{4}$$

$$X = \frac{1}{N}\sum_{i=1}^{N} IMEP(i) \tag{5}$$

Here, X is a transition value, N is the number of engine cycles, $IMEP(i)$ is the indicated mean effective pressure.

5. Results and Discussion

5.1. Spray Characteristics of Canola Oil Biodiesel

Suh et al. [59] conducted an in-depth study of the spray pattern of pure diesel (BD0) and pure canola oil biodiesel (BD100) under low and high injection pressures. The study results are shown in Figure 10. They reported that the spray tip penetration of BD0 and BD100 was longer at 150 MPa (high injection pressure), and the spray tip penetration of BD100 was similar to the spray tip penetration of BD0 at the same injection pressure. However, there was a minimal effect on the spray development of BD100 due to its higher viscosity; thus, the injection velocity of BD100 was lower than that of BD0. This behavior became more pronounced as the start of injection (SOI) time was advanced.

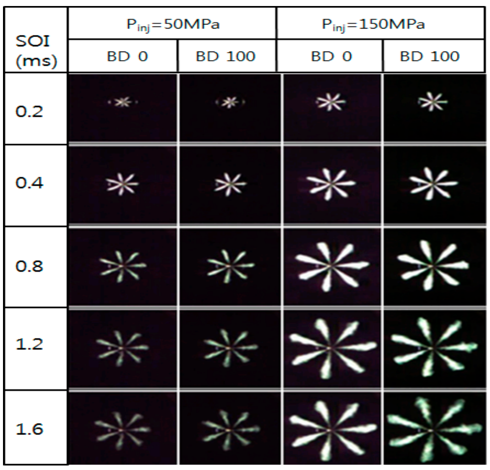


Figure 10. The spray pattern of diesel and canola oil biodiesel at different injection pressures (adapted with permission from [59], Elsevier, 2017). SOI: start of injection.

5.2. Combustion Characteristics

Yoon et al. [57] tested different ratios of COB blended with diesel fuels in a common rail diesel engine. The experimental results are shown in Figure 11. The tested fuels were noted as BD0 (pure diesel fuel), BD10 (10% COB blended with 90% diesel fuel by vol.), BD20 (20% COB blended with 80% diesel fuel by vol.), and BD30 (30% COB blended with 70% diesel fuel by vol.). As shown in Figure 11, they found that the combustion pressure decreased with an increase in the amount of COB at low engine speed (1500 rpm). This is because the atomization effect was not good, due to the higher viscosity of COB than that of diesel fuel. However, the opposite results were observed at high engine speed (2500 rpm), because the combustion conditions (atomization effect, injection pressure, etc.) were improved at high engine speed. The rate of heat release also increased due to the presence of oxygen in the COB. In addition, Yoon et al. [57] also found that the combustion pressure of pure diesel decreased significantly with increasing EGR. However, the combustion pressure of COB decreased slightly with increasing EGR, and the combustion pressure of BD30 with 10% EGR was higher than that of 0% EGR at 2000 rpm. Ge et al. [81] tested three ratios of COB blended with diesel fuel at different engine loads. They also showed that the combustion pressure of BD20 was a little higher than that of pure diesel at high engine load. These results showed that influence of the oxygen in the COB was greater than the influence of its high viscosity at high engine speed or load. To further prove that BD20 is a good blended fuel based on combustion characteristics at other test conditions, Ge et al. [82] researched the combustion characteristics of BD20 at different pilot injection timings. The results are shown in Figure 12. They reported that the combustion pressure and heat release rate of BD20 decreased slightly as the pilot injection timing was delayed.

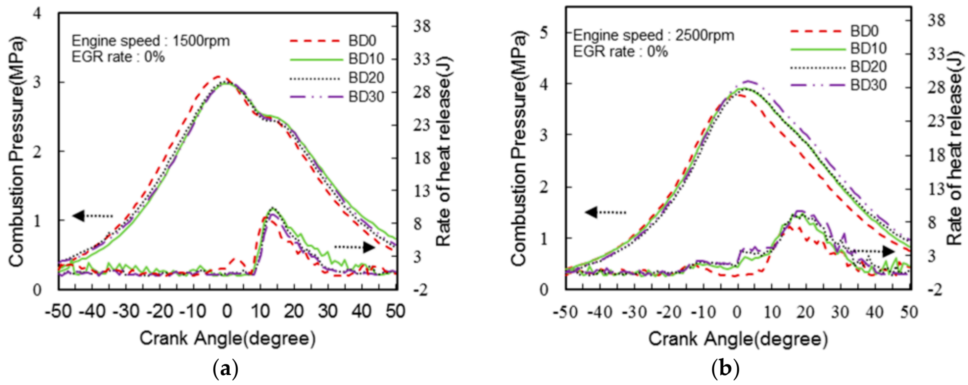


Figure 11. Combustion pressures and rate of heat releases of blend fuels at (**a**) 1500 rpm and (**b**) 2500 rpm. EGR: exhaust gas recirculation.

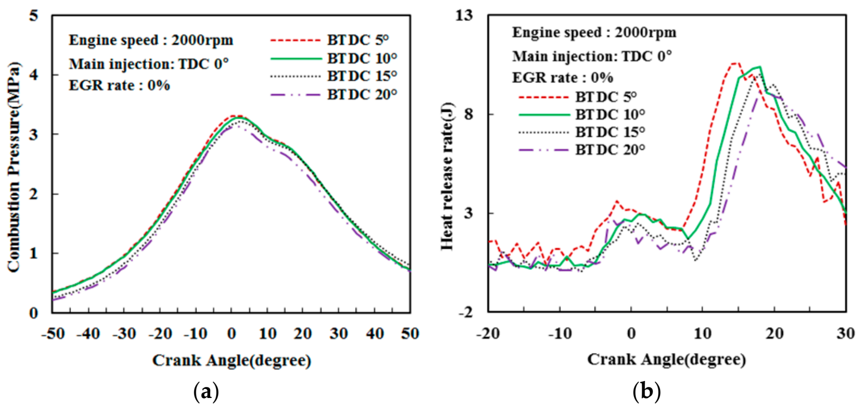


Figure 12. Combustion pressure (**a**) and heat release rate (**b**) of BD20 at various pilot injection timings. TDC: top dead centre; BTDC: before top dead centre.

Anbarasu et al. [84] studied five kinds of COB blended diesel fuels. The compounding ratios of COB and diesel fuel were 100:0 (B100), 60:40 (B60), 40:60 (B40), 20:80 (B20), and 0:100 (D100) by volume ratio. The brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) are exhibited in Figure 13. As shown in Figure 13a, the BTE of 5 fuels increased with increasing engine load, and the value of BTE was almost constant when the engine load was more than 75%. In addition, the BTE of pure canola oil (B100) was the closest to that of pure diesel (D100), about 98.2% of that of diesel fuel. As shown in Figure 13b, the BSFC of all fuels decreased with increasing engine load, and the B100 BSFC was the highest among all fuels. These results of BTE and BSFC are all because COB has a lower heat value, which means that the COB needs to burn more fuel to get as much power as diesel fuel. These results are the same as our previous results [57,81].

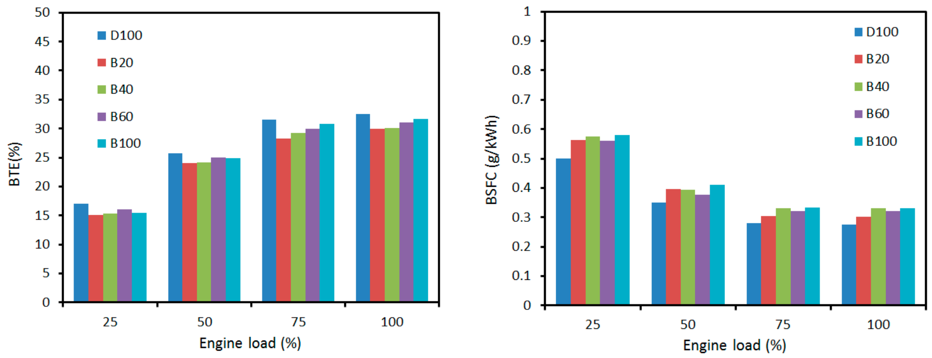


Figure 13. (**a**) Brake thermal efficiency (BTE) and (**b**) brake specific fuel consumption (BSFC) of canola oil biodiesel blended with diesel for various engine loads.

5.3. Ignition Delay and Coefficient of Variation in Indicated Mean Effective Pressure

Because COB has a high oxygen content and a high cetane number, it will have a great impact on engine ignition delay. Lee et al. [59] studied the ignition delay characteristics of four fuels (BD0, BD10, BD20, and BD40) at an engine load of 90 Nm. The results are shown in Figure 14. They reported that the ignition delay time was shortened as the COB ratio in the diesel fuel increased. All COB fuel ignition delay times were shorter than that of diesel fuel because COB has a high oxygen content, a high cetane number, and a low stoichiometric air requirement. Ge et al. [81] compared the ignition delay effect of pure diesel fuel, BD20, and pure canola oil (PCO) with the change in brake mean effective pressure (BMEP). They also showed a result similar to that of Lee et al. In addition, they also pointed out that the ignition delay time decreased as the BMEP increased. This is because the combustion conditions, such as injection pressure and the spray effect, become better with increasing BMEP.

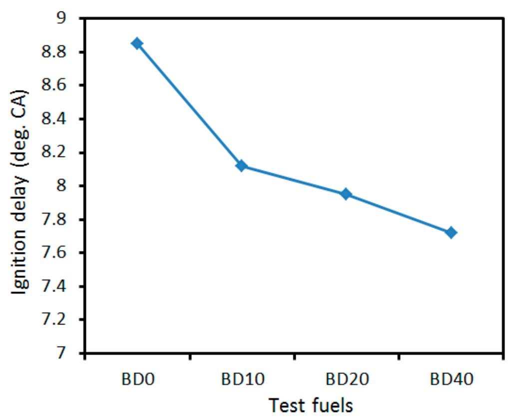


Figure 14. The ignition delay effects of diesel fuel and canola oil biodiesel. CA: crank angle (degree).

The coefficient of variation in indicated mean effective pressure (COV_{IMEP}) is an important parameter to evaluate the stability of an engine. In general, the COV_{IMEP} of a stable engine will not exceed 10%; if this value is exceeded, issues such as power instability, vibration, noise, and other problems will be observed [85,86]. Ge et al. [81] studied the running stability of a common rail diesel engine fueled with three fuels (ultra-low-sulfur diesel, ULSD; BD20; pure canola oil, PCO); the studied results are shown in Figure 15. They illustrate that the running stability of the engine increased as the brake mean effective pressure (BMEP) increased, and all tested fuel COV_{IMEP} values were less than 3.5%, showing very good engine stability. In addition, the COV_{IMEP} values of BD20 and PCO were slightly higher than that of ULSD. This was because PCO could not produce as much power as ULSD, due to its low heat value when the same amount of fuel was burned.

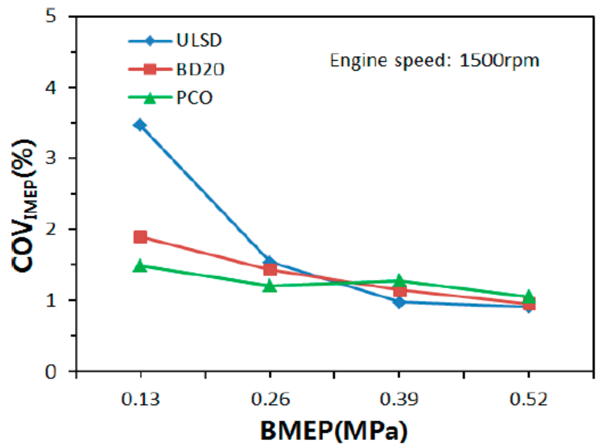


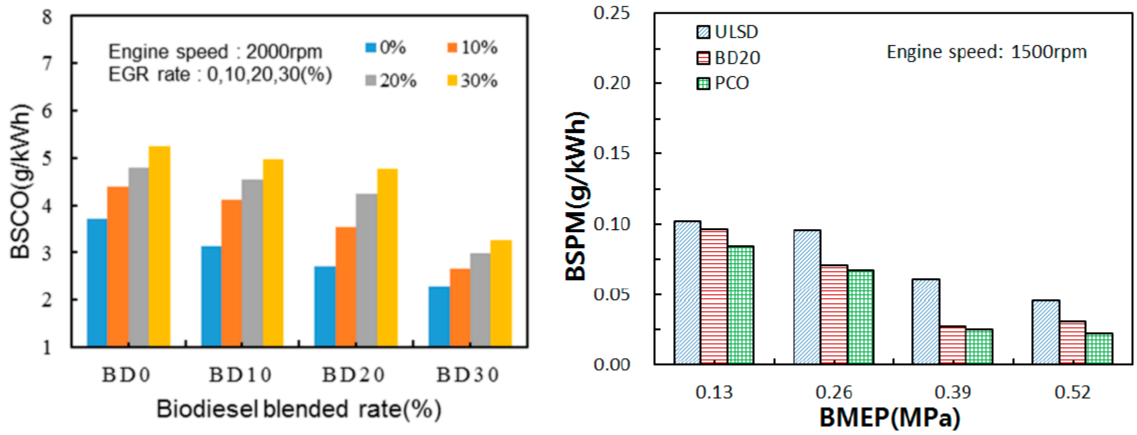
Figure 15. The coefficient of variation in indicated mean effective pressure of biodiesel fuels at various brake mean effective pressures. COV_{IMEP}: coefficient of variation in indicated mean effective pressure; BMEP: brake mean effective pressure; ULSD: ultra-low-sulfur diesel; PCO: pure canola oil.

5.4. Emission Characteristics

The main pollutants exhausted by the engine are CO, HC, NOx, and PM. However, CO and HC emissions from diesel engines are quite small compared with those from gasoline engines, because diesel engines are compression ignition engines with high combustion efficiency [18,19]. COB is an oxygenated fuel, which will play an important role in exhaust emissions. The diesel engine fueled with COB fuel exhaust emission characteristics are as follows.

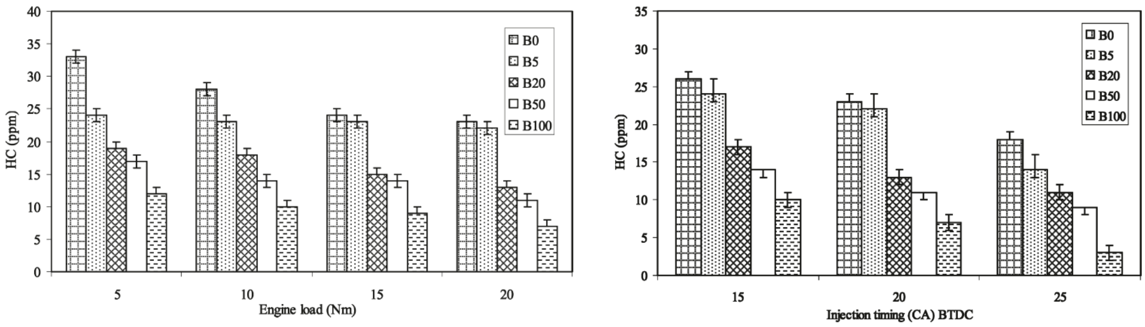
5.4.1. CO, HC, and PM Emissions

All CO, HC, and PM emissions are harmful environmental pollutants that cause damage to human respiratory systems after long periods of exposure. There is a close relationship between exhaust emission characteristics and combustion state of the engine [57,81,87]. The CO, HC, and PM emissions will increase when the combustion in the engine is incomplete. The CO, PM, and HC emissions of COB blended with diesel fuel are shown in Figures 16 and 17, respectively. In Figure 16a, the BSCO obviously increased with increasing COB blend ratio, and increased with increasing EGR rate. Based on Yoon's findings, BD20 is an excellent mixed alternative fuel. Ge et al. [81] did a more systematic study on BD20 by varying experimental conditions. They found that the BSPMs of BD20 and PCO (pure canola oil) were reduced significantly compared with diesel fuel, especially at high BMEP. This indicates that the atomization effect of biodiesel was poor at low BMEP, due to its high viscosity and lower injection pressure. The HC emission characteristics of COB blended with diesel fuel at various engine loads and injection timings are shown in Figure 17. Sayin et al. [87] studied the HC emission of COB and found that the HC emissions of all test fuels had a decreasing trend with increasing engine load; this is because the poor fuel distribution and low cylinder temperature of the low engine load affected the combustion state of the engine. On the other hand, as shown in Figure 17b, the HC emission of all test fuels decreased as the injection timing advanced. This indicated that, as the injection timing advanced, more uniform mixing of oil and air occurred, promoting combustion. In addition, the HC emission was significantly reduced with increased COB concentration, because the oxygen atoms in COB played a major role during combustion.



(**a**) (**b**)

Figure 16. Exhaust emission characteristics of test fuels on (**a**) BSCO: brake specific carbon monoxide (reprodeced with permission from [50], MDPI, 2012) and (**b**) BSPM: brake specific particulate matter.



(**a**) (**b**)

Figure 17. HC (hydrocarbon) of canola oil biodiesel blended with diesel at (**a**) various engine loads and (**b**) various injection timings (reproduced with permission from [87], American Chemical Society, 2010).

5.4.2. NO_x Emission

Normally, the combustion chamber temperature of biodiesel is higher than that of diesel fuel because biodiesel is an oxygenated fuel; this will result in higher NO_x emissions for biodiesel than of diesel fuel, and these results have been verified by many researchers [88,89]. Yoon et al. [57] studied different ratios of COB blended with diesel fuel at various engine speeds, and they found that the NO_x emissions increased slightly as the engine speed increased or the COB blended ratio increased. However, the NO_x emissions of all test fuels decreased significantly by increasing the EGR rate from 10% to 30%. Ge et al. [81] researched the NO_x emission characteristic of BD20 with different pilot injection timings and EGR rates. The results are shown in Figure 18. They pointed out that the NO_x emissions of BD20 decreased slightly as the pilot injection timing advanced. However, NO_x emissions had a clear decreasing trend with increasing EGR rate.

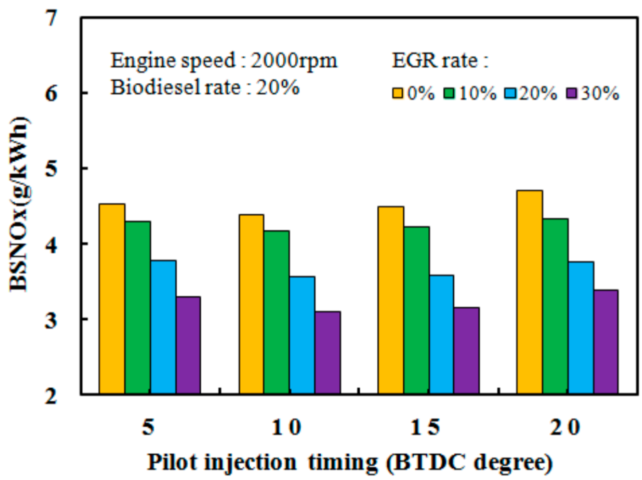


Figure 18. $BSNO_x$ (brake specific nitrogen oxides) of BD20 at various pilot injection timings and EGR rates.

6. Conclusions

This paper provides a detailed summary and review of the application of canola oil biodiesel to diesel engines based on the fuel performance (such as density, viscosity, oxygen content, cetane number, etc.), engine performance, and combustion and emission characteristics. Our findings are summarized as follows:

- COB can be used as a good alternative fuel and can be used in diesel engines without engine modifications.
- Based on engine combustion performance and exhaust emission characteristics, BD20 is a qualified alternative fuel compared with other blended COB fuels.
- The oxygen atoms in COB play a major role in reducing CO, HC, and PM emissions. However, their presence promote combustion, increase combustion temperature, and increase NO_x emissions. EGR technology can significantly reduce NO_x emissions.
- The optimum conditions for the direct injection of high common rail diesel engine fueled with COB are obtained based on a large amount of experimental data related to engine combustion performance and exhaust emission characteristics. The optimal conditions are 2000 rpm engine speed, 10% EGR rate, and 10 degree pilot injection timing.
- This paper reviewed the research findings of various blended ratios of COB fuels in a variety of complex experimental conditions. The optimum mixing ratio of biodiesel and optimum engine parameters were obtained. This paper will serve as a valuable reference for the development and application of COB to diesel engines and the design of engines.

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