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Review

Applications Characteristics of Different Biodiesel Blends in Modern Vehicles Engines: A Review

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Abstract: Two main aspects of the transportation industry are pollution to the environment and depletion of fossil fuels. In the transportation industry, the pollution to the environment can be reduced with the use of cleaner fuel, such as gas-to-liquid fuel, to reduce the exhaust emissions from engines. However, the depletion of fossil fuels is still significant. Biodiesel is a non-toxic, renewable, and biodegradable fuel that is considered an alternative resource to conventional diesel fuel. Even though biodiesel shows advantages as a renewable source, there are still minor drawbacks while operating in diesel engines. Modern vehicle engines are designed to be powered by conventional diesel fuel or gasoline fuel. In this review, the performance, emissions, combustion, and endurance characteristics of different types of diesel engines with various conditions are assessed with biodiesel and blended fuel as well as the effect of biodiesel on the diesel engines. The results show that biodiesel and blended fuel had fewer emissions of CO, HC, and PM but higher NOx emissions than the diesel-fuelled engine. In the endurance test, biodiesel and blended fuel showed less wear and carbon deposits. A high concentration of wear debris was found inside the lubricating oil while the engine operated with biodiesel and blends. The performance, emissions, and combustion characteristics of biodiesel and its blends showed that it can be used in a diesel engine. However, further research on long-term endurance tests is required to obtain a better understanding of endurance characteristics about engine wear of the diesel engine using biodiesel and its blends.

Keywords: sustainability; biodiesel blends; endurance characteristics; renewable energy; performance; combustion and emissions

1. Introduction

The significant development of the economy has led to tremendous energy demand to sustain society. Amid the development of numerous industries that demand energy from diverse sources, the energy sources are fossil fuel, nuclear power, solar, biomass, etc. [1]. The transportation industry is one of the rapidly developing industries in current society. For the transportation industry, fossil fuel is considered the main energy source to sustain the industry. With the high demand for fossil fuel needed to support transportation industry, the impacts on energy sources and climate change become more visible [2]. The Environmental Protection Agency (EPA) took a step in 2010 to decrease the impact of engine emissions on climate change [3]. The EPA requires that on-road diesel vehicles use ultra-low sulphur diesel (ULSD) because the sulphur content of diesel is the major component that converts to sulphuric acid and pollutes the environment [4]. According to Alleman et al. [5], diesel engines produce less hazardous pollutants while using gas-to-liquid (GTL) fuel. GTL fuel is made from natural gas/diesel/gasoline fuel that went through the refinery process to decrease the sulphur content in the fuels. The production of diesel and gasoline from biomass through the pyrolysis route could be more environmentally friendly [6].

The exhaust emissions from diesel engines when using clean fuel were significantly lower than predicted. Furthermore, the quality of the fuel has a significant impact on emissions. The traditional method of measuring fuel quality is costly and time-consuming; therefore, fast-sensing technology was introduced. This technique is critical because it reduces the amount of time required and the diesel fuel of varying quality may necessitate different adjustments in fuel injection settings [7]. Borecki et al. [8] stated that the sensor classified the quality of different unknown diesel fuel within less than few minutes with the measurement costs of a single disposable capillary probe and two plugs. However, the presently available fossil fuels reserves will not be able to sustain any longer as the demand will increase over time [9]. These circumstances cause researchers and industries to search for environment-friendly and sustainable energy sources to sustain the demands. Biofuel is introduced to the industry as a substitute fuel due to its non-toxic, renewable, and biodegradable properties and these are of high priority to the industry.

Biodiesel, one of the biofuels, is used to replace diesel fuel as an alternative resource. Biodiesel has a lower carbon content, better lubricity, and a higher flash point than diesel [10]. Biodiesel is also defined as mono-alkyl esters of long-chain fatty acids. It can be created from renewable feedstocks, the raw material will be preheated, thermally cracked, and undergo a transesterification process. In contrast with fossil fuels, the feedstocks of biodiesel can be easily seen in our daily life. The biodiesel feedstocks can be split into few types such as edible vegetable oil, animal fat, non-edible vegetable oil, and waste vegetable oil [11]. In recent years, thanks to the efforts of researchers, biodiesel had reached the third generation. Biodiesel is manufactured from edible vegetable oil in the first generation, and non-edible vegetable oil, waste oil, and animal fats in the second generation. The third generation of biodiesel is derived from microalgae feedstock [12].

Regardless of biodiesel generation, several researchers [13–15] who studied the effect of biodiesel in conventional diesel engines found that it shows convincing results, as it was discovered that there is a reduction in hydrocarbon (HC) and carbon monoxide (CO) emissions when compared to diesel. The use of biodiesel also shows a positive result with heavy-duty diesel engines. Heavy-duty diesel engines fuelled with biodiesel were tested and showed a significant improvement in the exhaust emissions, such as reductions in CO, HC, and PM, and biodiesel increased the efficiency of the engine performances as compared to diesel fuels [16]. However, there are minor drawbacks for pure biodiesel while operating in the diesel engine. Biodiesel contains higher kinematic viscosity, density, and low calorific value.

In the meantime, some researchers blended biodiesel with diesel to form a biodiesel–diesel blend and investigated its properties as an alternative fuel. Several researchers [17–19] observed lower smoke emissions, nitrogen oxides (NOx), and CO with the use of the biodiesel–diesel blend in diesel engines. The emissions of smoke and CO show a significant reduction but higher NOx in comparison with diesel. To reduce NOx emissions from diesel engines, a solution must be found. Researchers found a way to reduce NOx emissions by blending biodiesel and ethanol. By blending the fuel, the charging effect of ethanol components in blended fuel decreases the temperature in the cylinder, which results in a decrease in NOx emissions [20]. Moreover, Belgiorno et al. [21] claim that the NOx emissions were reduced at lower loads by using a single injection strategy with ethanol blends fuels. The combination of biodiesel ethanol blended fuel and injection strategy shows high potential in improving engine exhaust emissions.

With the advantages of biodiesel, it shows promising results for use in diesel engines. Despite the number of publications on the influence of performance and emissions on biodiesel, only a few studies have been conducted on the endurance characteristics of biodiesel and various blends in an unmodified and modified diesel engine. Hence, a review on the endurance characteristics of biodiesel and various blend in diesel engines shows a further understanding of the compatibility between the fuels and diesel engines. This review is focused on the use of biodiesel and various blend in endurance tests with different diesel engines on the performance and emissions. In this study, the impact on carbon deposition and lubricating oil with various biodiesel blends were investigated to shows the feasibility of biodiesel and various blend.

2. Biodiesel Endurance Test Operation in Diesel Engine

In general, modern vehicle engines are powered by conventional diesel fuel or gasoline fuel. However, owing to the depletion of fossil fuels, renewable alternative fuels such as biodiesel must be considered as a replacement. It became an important task for researchers to evaluate the impacts of biodiesel as an alternative fuel for a conventional diesel engine. In the engine operation, the physicochemical properties of biodiesel such as viscosity, density, cetane number, calorific value, flash point, and oxidation stability had an impact on the performance, emissions, and combustion characteristics. These are the properties of biodiesel that must be considered as an alternative fuel. In a diesel engine, fuel with a high viscosity will delay the mixing process of air and fuel in the combustion chamber [22]. Density is also an important physical properties in biodiesel, as it is used to determine the volume of the fuel that needs to be injected into the combustion chamber [23]. Higher density in biodiesel will cause higher viscosity and result in poor combustion [24]. Cetane numbers in engines are related to the fuel ignition delay; generally, biodiesel has higher CN than diesel. The higher cetane number in biodiesel will have shorter ignition delay, which will result in improved engine performance [25]. The calorific value of biodiesel is known to be lower than diesel fuel. In engine combustion, the calorific value increases the heat release and increases power output [26].

Engine tests of a diesel engine will include emissions, combustions, endurances, and performance characteristics, as shown in Figure 1. Several researchers discovered the positive effect of biodiesel on diesel engines through endurance tests [27–29]. Although biodiesel shows promising results, such as reducing HC and CO, it still contributes to numerous difficulties such as injector coking, dilution and deterioration of lubricating oil, fuel filter clogging, carbon deposit in the engine components, and engine components wear concern while running in diesel engines [30]. Wander et al. [31] conducted a 1000 h endurance test to investigate the durability of one-cylinder CI engines operated with diesel, castor oil, and soy methyl esters. Lubricating oil and internal engine parts were analysed. The results showed low concentrations for all elements in lubricating oil, and the engine wear was normal with the soy methyl ester-operated engine. Reksowardojo et al. [32] reported that the deposits and injector clogging will cause insufficient combustion and increase the HC and smoke emissions. The carbon deposit that forms on the injector's surrounds will affect the fuel flow rate and injection pattern inside the combustion chamber, resulting in a loss of engine performance [33]. Sharma et al. [34] found wear on the plunger, which causes a decrease in pressure in the injection system and impacts the fuel injection. Other researchers have also observed that cylinder-piston ring wear increases blow-by gases and engine vibrations. The endurance characteristics of an engine showed significant influence on the performance and emissions.

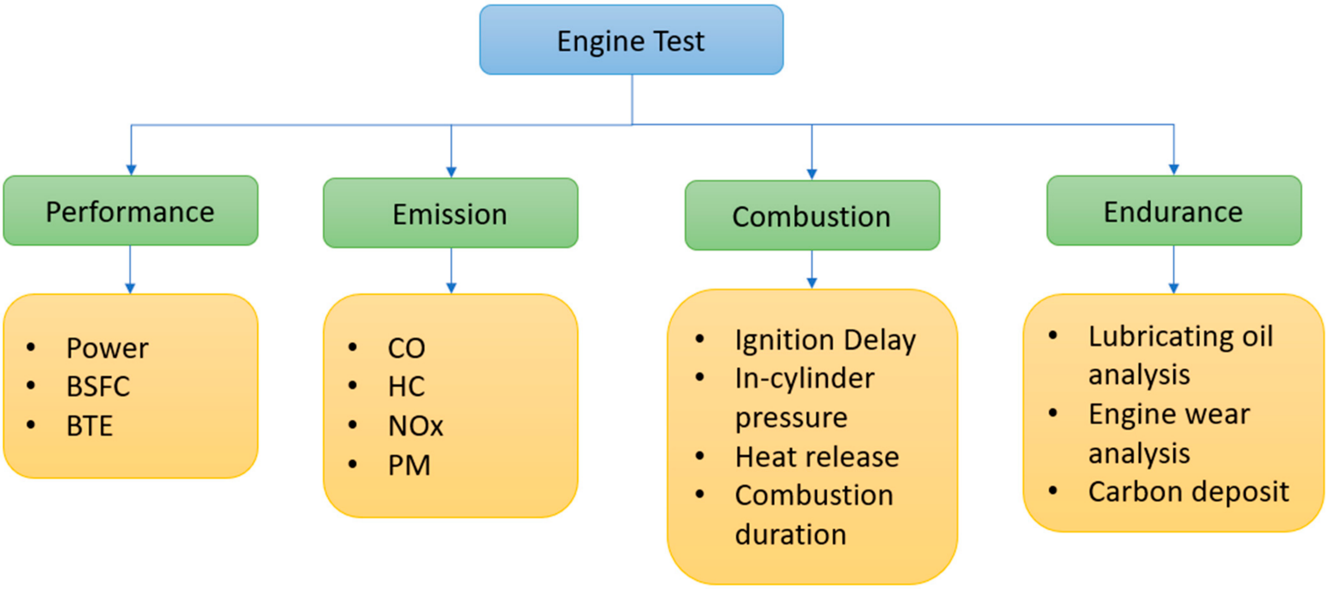

Figure 1. Overview of characteristics of an engine test.

3. Engine Performance

Engine performance such as power output, brake thermal efficiency (BTE), and the brake specific fuel consumption (BSFC) demonstrates an engine's compatibility. This section will contain investigations of BSFC, BTE, and power output of various types of engines fuelled by biodiesel–diesel blends. Furthermore, the performance comparison between diesel fuel and biodiesel fuel will be covered in this section and is shown in Table 1.

Table 1. Summaries of engine performance, emissions, and combustion results with biodiesel and blended fuel compared to diesel fuel in various types of engines.

Engine	Type of Biodiesel	Fuel Properties	Reference Fuel	Condition	Performance	Emissions	Combustion	References
1-cylinder, 4S, naturally aspirated, CI diesel engine	Diesel-ethanol blend	Density at 20 °C (kg/m^3): 824.5–819.4 Viscosity at 20 °C: 1.2 Pa s CN: 49.3	diesel	Constant load and different speed	BP ↓, BSFC ↑, BTE↑	NA	NA	[37]
4-cylinder, 4S, turbocharged, DI diesel engine	Diesel -rapeseed oil-n-butanol blend and ROME	DRSOnB Density at 15 °C (kg/m^3): 840 Viscosity at 40 °C (mm^2/s): 3.85 CN: 49.55	diesel	Constant load and different speed	BP ↓, BSFC ↑, BTE↓	CO ↑, HC ↓, NOx ↑	NA	[38]
WC, turbo-charged intercooled common rail DI diesel engine	Canola-safflower biodiesel	Density at 15 °C (kg/m^3): 884.3 Viscosity at 40 °C (mm^2/s): 4.35	diesel	Constant load and different speed	BSFC ↑	CO ↓, HC ↓, NOx ↑	MHRR →, ID →, CD ↓	[44]
Converted common rail diesel engine	Jatropha biodiesel	Density at 15 °C (kg/m^3): 882.7 Viscosity at 40 °C (mm^2/s): 4.42 CN: 58 Calorific value (MJ/kg): 39.98	diesel	Different load and constant speed	BSFC ↑, BTE ↑	CO ↓, NOx ↓	ID ↓, CD ↓	[45]

Table 1. *Cont.*

Engine	Type of Biodiesel	Fuel Properties	Reference Fuel	Condition	Performance	Emissions	Combustion	References
1-cylinder, 4S, AC, DI naturally aspirated, diesel engine	Diesel-palm oil blend and diesel-palm biodiesel blend	PO20 Density at 15 °C (kg/mm^3): 845 Viscosity at 40 °C (mm^2/s): 3.4	diesel	Different load and constant speed	BSFC ↑, BTE ↓	CO ↓, HC ↓, NOx ↑	NA	[46]
1-cylinder diesel engine	Calophyllum inophyllum–palm oil methyl ester and CIME	CPME Density at 15 °C (kg/m^3): 884 Viscosity at 40 °C (mm^2/s): 4.8	diesel	Constant load and different speed	BSFC ↑, BTE ↓	CO ↓, HC ↓, NOx ↑	NA	[47]
1-cylinder, 4S, DI diesel engine	Waste cooking-oil	B100 Density at 15.56 °C (kg/m^3): 892.6 CN: 63.63 Calorific value (MJ/kg): 42.835	diesel	Different load and constant speed	BSFC ↑, BTE ↓	CO ↓, HC ↓, NOx ↑	NA	[48]
4-cylinder, turbocharged, HP common-rail diesel engine	Coconut biodiesel	Density at 40 °C (kg/m^3): 866.8 Viscosity (mm^2/s): 4.1 CN: 55.9 Calorific value (MJ/kg): 38.1	diesel	Different load and constant speed	BSFC ↑	CO ↓, NOx ↑	HRR ↓, ID ↓, CD ↑	[49]
1-cylinder, 4S AC and CI engine	Ethyl ester of fish oil	B100 Density (kg/m^3): 885 Viscosity (mm^2/s): 4.741 CN: 52.6 Calorific value (MJ/kg): 40.057	diesel	Different load and injection timings	NA	HC ↓, NOx ↑	ICP ↓, ID ↓, HRR ↓	[50]
1-cylinder, variable compression ratio diesel engine	waste fish oil biodiesel	Density at 15 °C (kg/m^3): 870–880 Viscosity at 40 °C ($>mm^2/s$): 4.142 CN: 51.5	diesel	Different load and constant speed	NA	CO ↓, HC ↓, NOx ↑	ICP ↑, HRR ↑	[51]
1-cylinder, 4S, vertical water cooled VCR engine	Calophyllum inophyllum biodiesel	Density (kg/m^3): 886 Viscosity at 40 °C (mm^2/s): 4.72 CN: 55 Calorific value (MJ/kg): 39.4	diesel	Constant load and speed, different compression ratio	NA	NA	HRR ↓, ID ↓, CD ↑	[52]
1-cylinder research engine	Karanja biodiesel	Density (kg/m^3): 836–856 Viscosity at 40 °C (mm^2/s): 3.04–3.51 Calorific value (MJ/kg): 40.8–43.18	diesel	Different injection mode	BSFC ↑, BTE ↑	CO ↓, HC ↓, NOx ↑	CD ↑	[53]
1 cylinder, 4S, naturally aspirated, WC, and DICI engine.	Mahua biodiesel	Density (kg/m^3): 854 Viscosity (mm^2/s): 5.11 Calorific value (MJ/kg): 40.11	diesel	Different load and constant speed	BTE ↓	C↓, HC ↓, NOx ↑	HRR ↓, ID ↓, ICP ↓, CD ↑	[54]
1-cylinder retrofitted common-rail diesel engine	PODE biodiesel blend	Density (kg/m^3): 1019 Viscosity (mm^2/s): 1.12 CN: 78.4	diesel	Different load and constant speed	NA	CO ↓, HC ↓, NOx ↑	HRR ↓, CD ↑, ID →	[55]

↑: increase, ↓: decrease, →: no changes, CI: compression ignition, DI: direct injection, 4S: 4 Stroke, WC: water-cooled, AC: air-cooled, BP: Brake Power.

3.1. Power

According to researchers, when biodiesel and blended fuels are used in diesel engines, the engine power would be reduced [35–40]. Ilkiliç et al. [36] investigated the performance of safflower biodiesel blends and diesel fuel in one-cylinder diesel engines. They reported that diesel fuel had more power than biodiesel blends, but that at lower engine speeds, B5 had about the same power as diesel fuel. Ileri [38] discovered that the diesel engine brake power was reduced with biodiesel in comparison with diesel fuel. However, it was discovered that as the amount of rapeseed oil methyl ester in the blends increased, brake power dropped. The power reduction is caused by the high density and viscosity, lower heating value (LHV), and the cetane number (CN) of the biodiesel blends. Furthermore, B100's high density and viscosity resulted in poor spray characteristics in the injector, resulting in decreased braking torque and power [38]. Researchers determined that when an engine is running on either biodiesel or diesel fuel, there are no differences in engine power [41]. They discovered that biodiesel had a greater BSFC than diesel, implying that biodiesel provides more fuel to the engine than diesel. Similar findings by Lin [42] found that engine power is the same when using diesel fuel and VOME fuels. Qi et al. [43] evaluated the performance of diesel engines fuelled with soybean crude oil and diesel. They observed that biodiesel engines have almost the same engine power as diesel engines because biodiesel has a higher volume fuel supply and density than diesel.

3.2. Brake Specific Fuel Consumption

The majority of the researchers reported a rise in BSFC as well as an increase in biodiesel concentration in the blended fuel as compared to diesel [44,56–59]. Figure 2 shows the BSFC percentage difference between biodiesel blends and diesel [31,33,43,44,56]. Teoh [45] investigated different BMEP with a constant engine speed of 1600 rpm by using different concentrations of Jatropha methyl ester blends, JB10, JB30, and JB50 in a converted common-rail diesel engine. The engine is modified with the replacement of a common-rail high-pressure injection system. It was reported that at 0.6 MPa BMEP condition, lowest BSFC was found with the use of diesel, and on the other hand, JB50 had the highest BSFC at BMEP 0.6 MPa. Gad et al. [46] investigated a one-cylinder DI engine with varying engine loads (1, 2, 3, and 4 kW) and constant engine speed by using diesel, biodiesel (B100), diesel-palm biodiesel blend (B20), and diesel palm oil blends (PO20). The increase in fuel consumption is influenced by the concentration of biodiesel in biodiesel–diesel blended fuel.

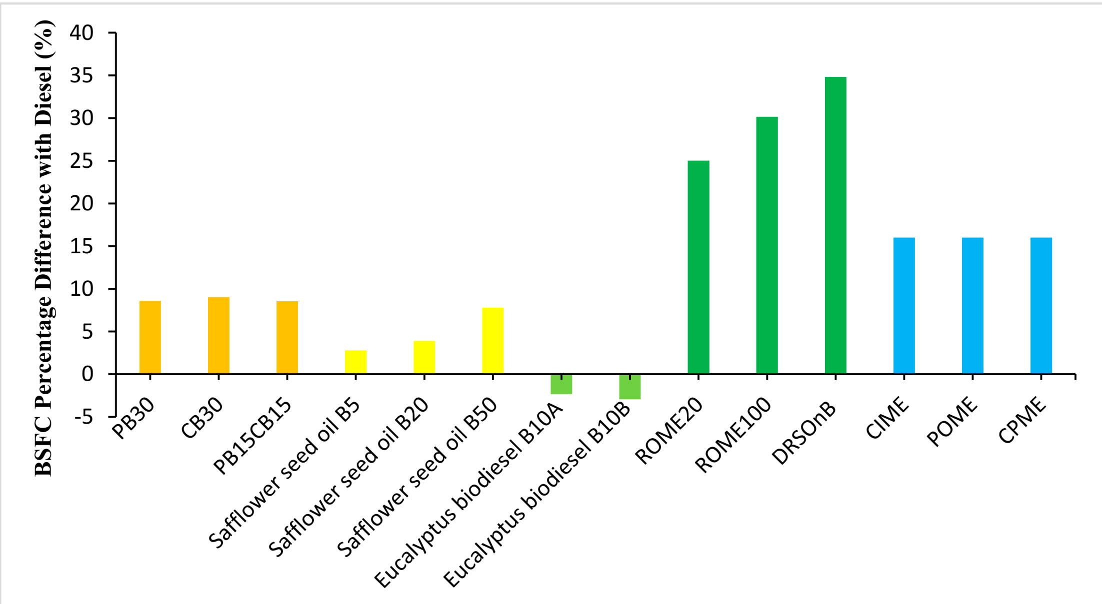

Figure 2. Biodiesel BSFC percentage differences compared with diesel.

According to Gad et al. [46], the rise in BSFC in biodiesel is attributable to the properties of palm biodiesel, such as low calorific value compared to diesel. Many researchers [46,60–64] discovered that the increase in fuel consumption is due to the high density, viscosity, and low heating value and the properties of biodiesel. Habibullah et al. [65] conducted experimental studies on a one-cylinder, diesel engine at full load and various speed conditions in between 1400–2400 rpm by using conventional diesel, palm oil biodiesel blend (PB30), coconut oil biodiesel blend (CB30), and the blend of PB15, CB15 and diesel to form biodiesel–diesel blend (PB15CB15). The result reported that the lowest BSFC occurred at 1800 rpm, and that fuel consumption increases with speed from 1800 rpm to 2400 rpm owing to diminishing volumetric efficiency. When the load is low (105 Nm), Tesfa et al. [66] discovered that BSFC increases with speed from 800 rpm to 2000 rpm.

When the load is large (420 Nm), however, the BSFC drops with speed. Overall, the engine powered by biodiesel BSFC outperforms diesel. Some researchers [67,68] observed that the fuel consumption reduces initially and then increases with increasing speed (1200 to 3600 rpm) at full load conditions. Several researchers [67,68] agreed that when the engine speed increases, which does not consider low engine speed, the consumption of the fuel will increase. Stalin and Prabhu [69] conducted an endurance test to study the performances of IC diesel engines using Karanja biodiesel blend and diesel. The test was performed with nine types of fuel such as diesel and various concentrations of biodiesel blends. They observed that KOME had less BSFC than diesel fuel. The scenario is due to biodiesel's decreased calorific value when compared to diesel. It is possible to determine that the concentration of biodiesel blends, engine speed, and loads influenced fuel consumption.

3.3. *Brake Thermal Efficiency*

The ratio of the engine's braking power to the fuel energy delivered to the engine is known as brake thermal efficiency (BTE) [70]. Many studies [44,46,47,56–59,65] reported that the BTE of biodiesel is slightly lower than conventional diesel fuel. Figure 3 shows the biodiesel percentage differences on BTE against diesel [44,46,56,66]. Gad et al. [46] found that in various engine loads, the BTE of palm oil biodiesel blends, which are PO20, B20, and B100, is lower than diesel due to the biodiesel having poor combustion characteristics compared to diesel fuel. At 4 kW load condition, the BTE value of diesel, biodiesel blend B20, B100, and PO20 fuels are 28.7, 27.7, 24.7, and 26.8%, respectively. Habibullah et al. [65] reported PB30 had the lowest average engine brake power, which is 3.92%. Moreover, the BTE average values of biodiesel are 3.84–5.03%, which are lower than diesel; this is due to biodiesel consists of LHV. Jaichandar et al. [71] investigated the performance of Pongamia biodiesel in a DI diesel engine at a constant speed, 1500 rpm. They found a similar result that biodiesel has lower BTE in comparison with diesel. Teoh [45] found that the BTE is directly proportional to brake mean effective pressure (BMEP). At 0.5 MPa BMEP, BTE observed a 2% improvement with the use of JB50 in the engine.

The improvement was attributable to increased biodiesel concentrations, which caused the combustion to start earlier and resulted in an increase in peak pressures. According to the researchers [46,65,72], biodiesel blends' characteristics such as low heating value and calorific value, low volatility, high density, and high viscosity all have an impact on BTE. Otherwise, engine parameters such as BMEP also impact the BTE [45]. Biodiesel BTE, on the other hand, was determined to be higher or equivalent to diesel fuel [54,61,66,69,73]. Muralidharan et al. [73] studied the performance characteristics of engines with waste cooking oil methyl ester by carrying out an experiment. The experiment is conducted with a constant engine speed, variable compression ratio (CR) multi-fuel engine. The BTE of conventional diesel, B20, and B40 was found to be 34.45%, 37.18%, and 38.46%, respectively. The biodiesel shows a higher BTE value than conventional diesel. Raheman and Ghadge [61] observed the maximum BTE for mahua biodiesel B20 and B40 was 25% and 24%, respectively. The BTE value of biodiesel is comparable to or higher than diesel. The existence of more oxygen content in biodiesel could lead to better combustion in comparison to diesel.

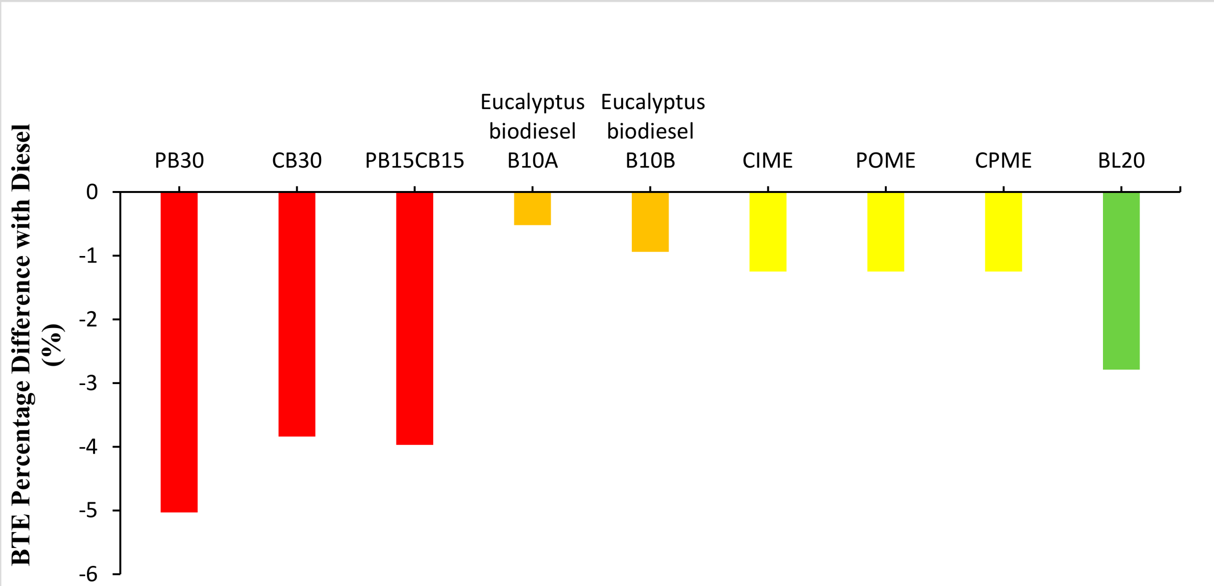

Figure 3. Biodiesel BTE percentage differences compared with diesel.

3.4. Effects of Biodiesel on Performance Characteristics

The power output, BSFC, and BTE are the common characteristics to evaluate the engine performance. The ratio of biodiesel blends, physical and chemical properties of biodiesel, and engine speed and loads had a significant effect on the power out, BSFC, and BTE. The reduction in power output is mainly due to the higher ratio blends in biodiesel, as a higher ratio biodiesel blend contains higher density and viscosity and will result in an increase in the mass of flow injection. Furthermore, the BSFC is also mainly influenced by the properties of biodiesel. While using a similar fuel injection system, more fuel emits with the fuel on high density and results in higher fuel consumption for the engine. They reduce BTE with biodiesel due to the poor combustion characteristics and higher viscosity. However, the BTE with biodiesel can be improved by adjusting the engine parameters such as BMEP.

4. Engine Emissions

In general, diesel engines emit nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Emissions control is an important task for researchers since exhaust emissions impact air quality [74]. Figure 4 shows the concept of engine test setup for emissions. A review of the NOx, HC, CO, and PM emissions characteristics of biodiesel is discussed in this section and the comparison of the results is shown in Table 1.

4.1. Carbon Monoxide, CO

The presence of more CO in exhaust gases indicates incomplete combustion. In terms of exhaust emissions, researchers agree that biodiesel produced fewer CO emissions in comparison with diesel fuel, as shown in Figure 5 [38,47–49,65,71–73,75–77]. Habibullah et al. [65] investigated the emissions with different speed conditions on a one-cylinder diesel engine. The engine speed was controlled within the range of 1400 to 2400 rpm. They discovered that PB30 biodiesel blends reduced CO emissions by 13.75% as compared to diesel fuel use. As the temperature rises, so do the rates of CO_2 conversion, resulting in lower CO emissions at high engine speeds. The fact of decrease in CO emissions was due to the reduced carbon content in biodiesel. Buyukkaya [75] experimented to study the emissions of a six-cylinder direct injection diesel engine with the use of B5, B20, B70, and B100 of rapeseed oil biodiesel blends and diesel fuel. Biodiesel has fewer CO emissions than diesel fuel, with B5, 12%; B20, 25%; B70, 31%; and B100, 35%. Furthermore, it was shown that when engine speed increased, CO emissions reduced. The reduction in CO is explained by the researcher as due to the oxygen content of the biodiesel and its blends.

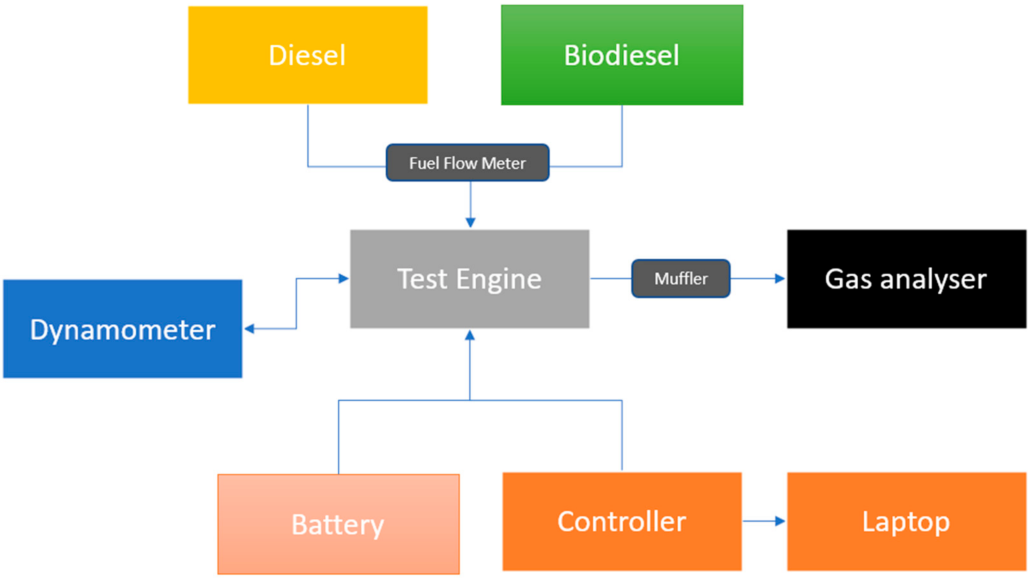

Figure 4. Engine emissions test setup flow chart.

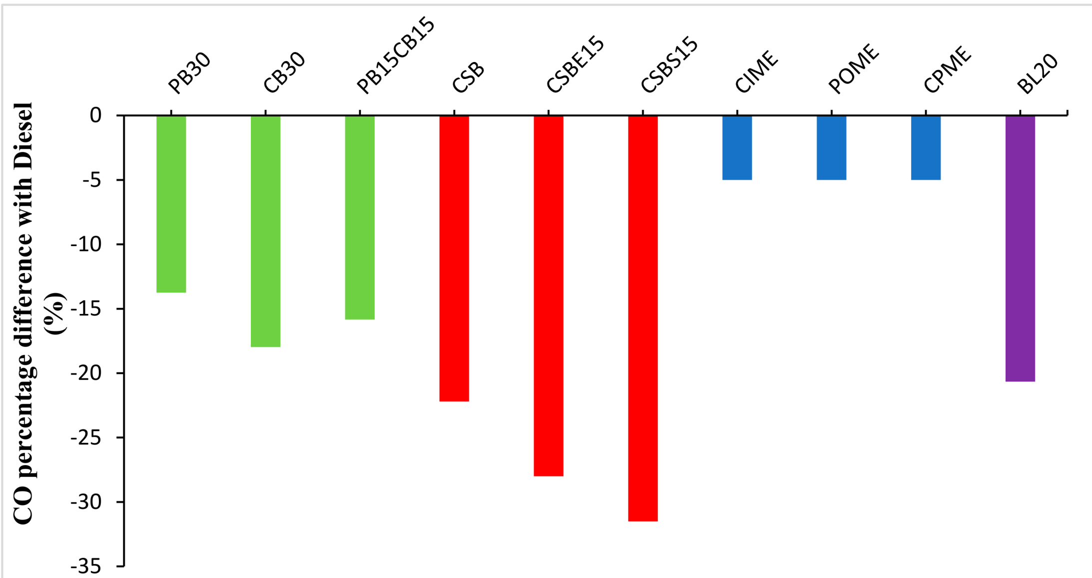

Figure 5. Biodiesel CO percentage different compare with diesel.

Abed et al. [48] investigated the emissions of a diesel engine by using waste cooking-oil biodiesel and diesel. The blends are made in three different percentages, B10, B20, and B30, and performed in the diesel engine with various engine loads of 0 to 4 kW. They discovered that CO emissions were reduced with increasing engine brake power at lower loads. It is explained in the same way: biodiesel–diesel blends have more oxygen molecules and less carbon content than diesel fuel, resulting in better combustion. Researchers discovered that when engine load increases, CO emissions decrease [15,49]. How et al. [49] conducted an endurance test to investigate the engine emissions by using high pressure of common-rail diesel engine with the condition of various engine load (0.17, 0.34, 0.52, 0.69, and 0.86 MPa). The experiment used B10, B20, B30, and B50 of coconut biodiesel blends and diesel fuel. It was observed that, regardless of the fuel used, CO emissions are higher at low load than at high load. The reduction in CO with biodiesel can be explained by a few factors: increase in engine speed, high load condition, more oxygen molecules, and less carbon content.

4.2. Hydrocarbons, HC

Many researchers agreed that hydrocarbon (HC) emissions are reduced when engines operate with biodiesel–diesel fuel blends [15,48,49,65,75,77,78]. Figure 6 shows the reduction in HC with the use of biodiesel and blended fuel [38,44,65,76]. Man et al. [77] investigated the engine emissions of four-cylinder natural aspirated DI diesel engines. The fuels used in the experiment were diesel fuel, waste cooking oil biodiesel blends B10, B20, B30, and B100. HC emissions were determined to be at their lowest when B100 biodiesel was employed. The reduction in HC emissions was also seen on biodiesel blends, which reduced HC emissions by 2% (B10), 7% (B20), 10% (B30), and 23% (B100). In comparison to diesel fuel, biodiesel has a higher oxygen content and a lower carbon content, resulting in reduced HC emissions. Furthermore, when engine load and speed increased, HC emissions decreased. Radhakrishnan et al. [78] found that the HC emissions are lesser found in palm oil biodiesel at different engine loads in comparison with diesel fuel. Similar findings were reported by other researchers, who discovered that HC emissions decrease as load increases [79]. Habibullah et al. [65] observed the HC emissions of biodiesel were reduced significantly by 17.97% as compared to diesel fuel use. The facts of HC reduction are due to increased biodiesel CN and oxygen concentration.

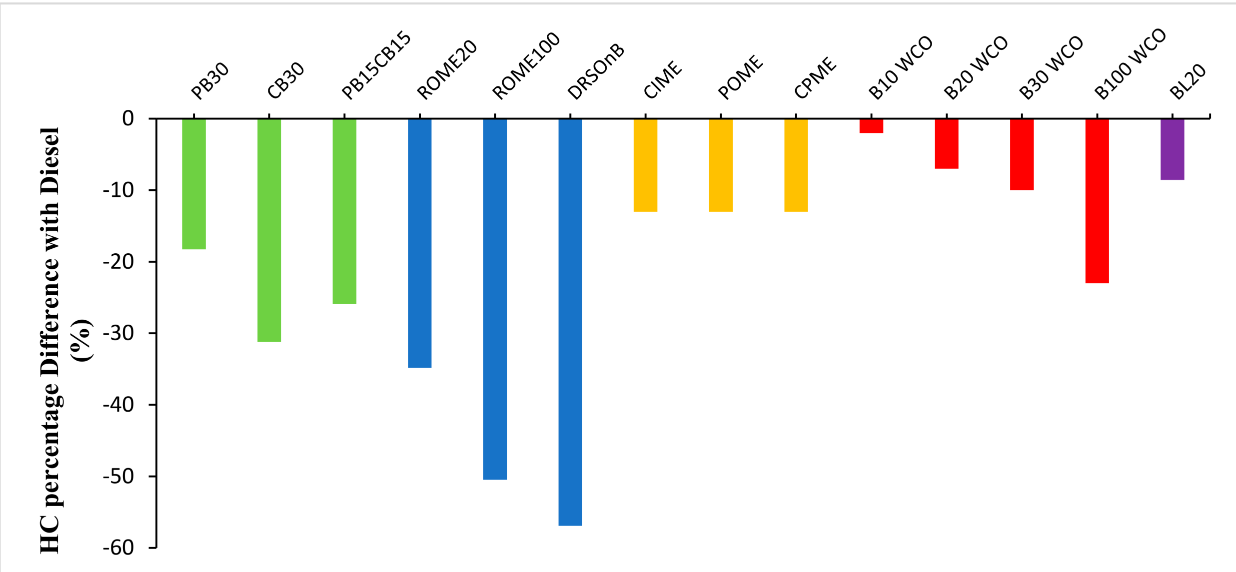

Figure 6. Biodiesel HC percentage differences compared with diesel.

Abed et al. [48] found that increasing the percentage of biodiesel in the blends resulted in reduced HC emissions, and this is due to the high CN and oxygen concentration of biodiesel blends. Engine parameters such as high engine load and high engine speed reduce the HC emissions. Higher CN, oxygen content, and biodiesel blend percentage lead to improved combustion and, as a result, decreased HC emissions. Another study shows higher HC emissions at higher loads [73]. The HC emissions were tested utilising waste cooking oil methyl ester and its blends (20, 40, 60, and 80%) in comparison to diesel fuel. Except for the B20 blends, increasing load results in greater HC emissions. According to the observation, the influence of vegetable oil fuel viscosity and fuel spray quality results in an increase in hydrocarbons. Mahalingam et al. [80] studied the emissions of mahua oil biodiesel by appending octanol in the diesel engine. The mahua oil biodiesel had lower HC emissions than diesel fuel, and adding 10% and 20% octanol to mahua biodiesel lowered HC emissions by 5.1% and 5.7%, respectively. There are similar findings that state that adding additives in biodiesel reduce HC emissions [81].

4.3. Nitrogen Oxide, NOx

The trend of NOx emissions for biodiesel and biodiesel–diesel blends was never agreed upon by the researchers. However, Figure 7 shows that with the use of biodiesel blends in diesel engines, NOx emissions were increased [38,65,76,77]. Another study reported NOx emissions of soybean, palm, and waste frying oils biodiesel–diesel blends [82]. The fuel was put through its paces in a direct injection diesel internal combustion engine at nominal loads of 15, 30, 45, 60, and 75 kW. NOx emissions from all biodiesels were shown to rise as test loads increased. The greatest rise in NOx emissions was recorded in POME20, which was 92.6%. Using Argemone biodiesel–diesel mixes, Singh and Sandhu [83] studied the NOx emissions of a four-cylinder turbocharged common rail DI engine. The engine operates in three load conditions: a low load (15%), partial load (45%), and heavy load (75%), as well as at a fixed rotational speed of 2000 rpm. NOx emissions were measured in three distinct loads. In low-load conditions, argemone biodiesel and its blends emit less NOx than diesel fuel. On the other hand, there was an increase in NOx emissions for AB20 (20% argemone + 80% diesel) under partial load and high load conditions, but a further drop in NOx emissions when biodiesel blending was increased.

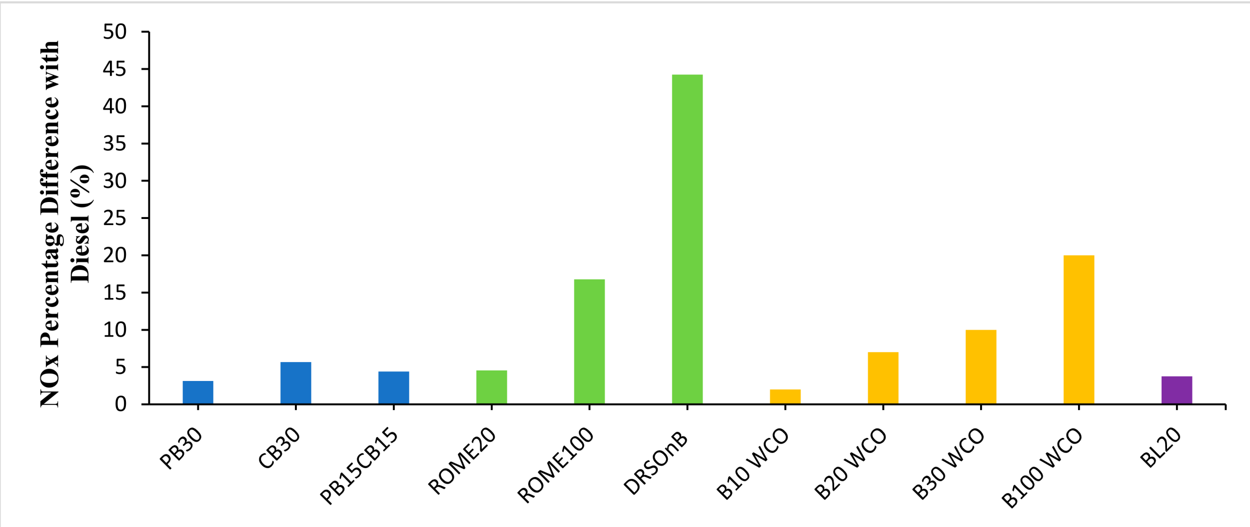

Figure 7. Biodiesel NOx percentage differences compared with diesel.

At partial load and high load conditions, biodiesel–diesel blends show higher NOx emissions. Furthermore, the presence of unsaturation and molecular oxygen in biodiesel blends produces higher in-cylinder temperature and, therefore, increased NOx emissions. Similar findings were reported by other researchers [15,58,70,84] who agreed that the increase in engine load will influence the NOx emissions to increase. Chauhan [58] observed the NOx emissions increased with the increased engine load, stating that the rise was caused by a greater combustion temperature. Some researchers discovered that the engine operated with biodiesel blends produces higher NOx emissions than that operated with diesel, due to the higher oxygen content in the biodiesel [44,76]. Mueller et al. [85] observed that the NOx emissions increase depends on specific combustion and fuel characteristics. They observed that the biodiesel NOx rise for biodiesel-containing fuels is closer to stoichiometric during ignition and in the standing premixed autoignition zone. This will result in greater in-cylinder temperatures, reduced radiative heat losses, and increased NOx emissions. Furthermore, higher-cetane fuels tend to yield lower NOx emissions, implying that NOx emissions at high loads decrease. Overall, NOx emissions are affected by combustion characteristics such as combustion duration (CD) and in-cylinder pressure. Additionally, engine load, engine speed, biodiesel oxygen concentration, and biodiesel CN all have an impact on biodiesel NOx emissions.

4.4. Particulate Matter, PM

PM of an engine can be stated as microscopic solid or liquid debris [86]. It was observed by the researchers that reduction in PM emissions with the use of biodiesel [58,77,78,87–90]. Salamanca et al. [87] experimented to investigate the emissions characteristics of pure palm oil biodiesel combined with diesel at 5, 20, and 50% concentrations, as well as pure diesel. When pure biodiesel and its blends are going through combustion, they produce less soot than regular diesel. When 100% palm biodiesel was utilised in the diesel engine, a decrease of around 65% in PM was found. Furthermore, as the concentration of palm biodiesel increases, particle matter emissions are reduced. Su [90] discovered a reduction in PM emissions with the used waste cooking oil biodiesel in a diesel engine. The comparison of biodiesel PM emissions to ultra-low sulphur diesel (ULSD) indicates that E20 biodiesel blend had the greatest reduction in PM emissions. The PM emissions reduction was caused by higher oxygen content in the biodiesel, a lower stoichiometric air-fuel ratio, and lower aromatic content, which reduces carbonaceous soot. It was noticed that the presence of high oxygen content in its composition, as well as the lack of aromatic compounds, inhibits particle nucleation. There are similar findings found by the researchers [58,77,78,87–89] in agreement with the facts.

Moreover, PM emissions are influenced by engine load, engine speed, and fuel consumption. Ye and Boehman [91] investigated the impact of engine injection strategy on emissions with soybean methyl ester (SME) biodiesel blends and ULSD. The PM emissions are substantially influenced by engine load. PM emissions have decreased at low load, according to their findings, and this was attributable to increased fuel injection pressure and biodiesel fuelling. Li and Wang [92] investigated the PM emissions of diesel and five distinct types of biodiesel from various sources. The diesel engine ran on diesel, B100, B50, and B20, with an engine speed of 2000 r/min and torque of 12.27 Nm. PM emissions are reduced by 7.9, 17.2, and 24.2% when the biodiesel blend's blend ratio is increased from B0, B20, and B50, to B100, respectively. Abed et al. [48] discovered that in a biodiesel–diesel blend, PM emissions rose with engine power output for all fuels, indicating that the rise in emissions is attributable to an increase in BSFC with engine output power. Devarajan [81] discovered that for all test fuels, PM emissions increase with load. The experiment was performed with the Calophyllum inophyllum (Punnai) biodiesel and its blend and various loads. As engine load increases, it impacts the fuel-air mixture, resulting in incomplete combustion.

4.5. Effect of Biodiesel on Emissions Characteristics

For engine emissions, the utilisation of biodiesel reduces CO, HC, and PM. The significant reduction in the CO, HC, and PM emissions is mainly due to higher oxygen content and lower carbon content in the biodiesel blends. Moreover, the reduction in emissions can be improved by optimising the engine parameters such as engine speed and load. However, the exhaust of NOx emissions was still high with the use of biodiesel blends, mainly due to the oxygen content of biodiesel. NOx formations are responsible for high oxygen content and high in-cylinder temperature. By controlling the engine load and ratio of biodiesel blends, NOx emissions can be maintained at a lower exhaust rate.

5. Combustion Characteristics

Combustion is one of the critical processes in engines that has a considerable impact on performance and emissions [93]. The ignition delay, cylinder pressure, CD, and heat release rate are important parameters that indicate the efficiency of the combustion process [94]. This section discusses the comparison of combustion characteristics between biodiesel and blended and diesel fuel in various engines. This section reviews combustion characteristics such as ignition delay (ID), cylinder pressure (CP), and heat release rate (HRR). The combustion characteristics of diesel and biodiesel blended fuels are compared and stated in Table 1.

5.1. Ignition Delay, ID

Ignition delay is one of the most significant elements in combustion characteristics and is defined as the time gap in crank angle degrees between the beginning of injection and the start of combustion [95]. Many researchers [50–52,94–99] discovered that with the use of biodiesel and its blends in diesel engines, the ignition delay is shorter than that of a diesel-fuelled engine. Gumus [94] investigated the combustion characteristics of a DICI engine running with diesel fuel, hazelnut kernel oil methyl ester (HOME) biodiesel, and blended fuel. The engine was performed with various engine loads, 10 Nm and 20 Nm, and the percentages of biodiesel blends were 5, 20, 50, and 100%. They determined that biodiesel had a shorter igniting delay than diesel fuel. The reduction in ignition delay is caused by increasing the CN with higher biodiesel concentrations in blends with diesel fuel. According to certain researchers [96–99], the high CN of biodiesel had a significant influence on ignition delay. In comparison to diesel, Gnanasekaran [50] found that using biodiesel blends in diesel engines resulted in a shorter ignition delay. They tested the fish oil biodiesel on a one-cylinder 4S, AC, and constant DI diesel engine with various engine loads.

Mehmet [98] studied the influence of canola oil biodiesel blends (10, 20, and 50%) and Eurodiesel on combustion characteristics in a one-cylinder diesel engine. The engine performed with a full load and various speeds (1500, 2000, 2500, and 3000 rpm). They observed that the low quantity of aromatic components in biodiesel influenced ignition delay reduction. Furthermore, with the increase in concentration in biodiesel, the ignition delay was reduced. Shelke et al. [97] discovered the reduction in ignition delay for cotton seed methyl ester biodiesel (COME) and its blend as compared to diesel fuel. Ignition delay reduced from 11 to 9.5, 8.5, 7.5, and 6.5 °CA for B5, B10, B15, and B20 blends, respectively. The short ignition delays are caused by the biodiesel's higher bulk modulus. Nayak et al. [52] observed an increase in ignition delay with increasing concentration of COME in the diesel engine. The blends' percentage of COME increase will cause the viscosity and density to increase and lower the heating value and result in increased ignition delay. Furthermore, the ignition delay of COME biodiesel blends is reduced by increasing the CR. Engine parameters and biodiesel properties, such as biodiesel oxygen content, fuel atomisation, cylinder pressure, bulk modulus, CN, and CR, can all affect ignition delay.

5.2. In-Cylinder Pressure, ICP

In-cylinder pressure is an important parameter for the engine, which offers vital information on the processes occurring in the combustion chamber [100]. Shehata [101] investigated the comparison on cylinder pressure of a one-cylinder diesel engine running on biodiesel blended fuel of cotton seed oil, palm oil, and flax oil and diesel. The engine performed at 1000, 1200, 1400, and 1600 rpm. They discovered the biodiesel blends had higher peak cylinder pressure than diesel. The high pressure of biodiesel blends is due to the high oxygen concentration. Furthermore, peak pressure rises with increasing engine speed until it reaches 1400 rpm, after which it falls with increasing engine speed. Biodiesel fuels have a high viscosity and little volatility, resulting in poor atomisation and mixing with air. As a result of the poor burning rate of biodiesel fuels during the ignition delay interval, peak pressure decreases as engine speed increases. Nantha and Thundil [102] observed that the cylinder pressure is influence by the engine loads. Among the biodiesel blends, PME20 had a 2–3% higher peak pressure. The maximum cylinder pressure increases as the load increases for all types of fuels in the test.

Dhar and Agarwal [53] tested diesel fuels, Karanja biodiesel, and its blends in a one-cylinder CRDI research engine with the multiple injection mode. In multiple injection modes at both 500 and 100 bar FIP, the reduction in maximum in-cylinder pressure was observed. Can et al. [103] study the combustion properties of B5, B10, B15, and B20 of Canola biodiesel blends and diesel fuel at different engine loads in a DI engine. The AVL 8QP500c water-cooled quartz pressure transducer was used to measure the in-cylinder pressure. They discovered that the concentration of canola biodiesel influenced the in-cylinder pressure. For each load condition, the maximum in-cylinder pressure values decrease by up to 1.35 bar as the amount of canola biodiesel increased. At low load, the highest drop in maximum in-cylinder pressure readings was recorded to be 0.55 bar. Shrivastava [104] discovered pure Lal ambari biodiesel (LA100) exhibited the lowest peak pressure of 56.3 bar when compared to diesel, which is due to biodiesel consist of higher viscosity and lower calorific value than diesel fuel. The pressure increases when the engine load is higher. The in-cylinder was influenced by the CN of biodiesel was observed by Shelke et al. [97]. They observed that the in-cylinder pressure increased higher for biodiesel, 55.61 bar, in comparison with diesel fuel, 52.28 bar.

5.3. Heat Release Rate, HRR

The biodiesel and blended fuel were agreed by most of the researchers that had a lower heat release rate than diesel fuel [95,105–108]. Fang et al. [109] investigated the low-load engine combustion characteristics of several biodiesel blends. Four fuels were used, which were European low-sulphur diesel, and B100, B50, B20 of soy biodiesel blends to run the one-cylinder DI engine. The heat release rates of biodiesel blends were compared to diesel fuel to investigate the effects. They discovered that higher concentration biodiesel blends had a lower HRR, which is related to the higher boiling point of biodiesel. Gumus [94] experimented to investigate the rate of heat release of a one-cylinder CI engine running with diesel, HOME biodiesel, and the blends of 5, 20, and 50%. Some studies demonstrated the HRR for the diesel, HOME biodiesel, and its blends at different engine loads (10 and 20 Nm), IP of 20 and 24 MPa, and CR of 18 and 20. Because of the lower premixed burning and lower calorific value of biodiesel, the maximum heat release rate was reported to be lower than that of diesel fuel. Furthermore, the heat release of biodiesel was shown to rise with the amount of biodiesel in the blends. Similar findings are reported in the literature [105,106], which agreed that heat release rate increases from low load to high load condition.

According to Ashok et al. [107], the peak heat release rate of Calophyllum inophyllum methyl ester (CIME) biodiesel is lower than diesel fuel due to the shorter ignition delay and higher CN of biodiesel. They discovered that viscosity, surface tension, and poor spray atomisation all had a substantial impact on the heat release rate of biodiesel. The heat release rate was influenced by viscosity, surface tension, poor spray atomisation, biodiesel oxygen concentration, and engine parameters such as engine load. Gautam et al. [108], on the other hand, observed the inverse result. They reported that the heat release was higher than diesel fuel. Moreover, Radhakrishnan et al. [110] studied combustion on diesel engines with neat biodiesel water blends. The results revealed that water particles aid in the increase in the heat release rate of neat biodiesel, which is related to the larger surface area to volume ratio of water particles. Aalam et al. [111] investigated the combustion parameters of a CRDI system-aided diesel engine utilising diesel with ZJME25 (Zizipus jujube methyl ester). In mass fractions, they added ZJME25 aluminium oxide nanoparticles as an additive. They stated that adding the additive to biodiesel enhanced the value of heat release rate, that biodiesel blends with additive had higher calorific value than diesel, and that the value of heat release rate is 154.727, 178.818, and 197.928 kJ/m^{3}deg for ZJME25, AONP25, and AONP50, respectively.

5.4. Combustion Duration, CD

Combustion duration is defined as the duration it takes for the fuel to completely burn. Benjumea [112] observed the combustion characteristics of an HSDI diesel engine running on diesel fuel (B0) and palm oil biodiesel (B100) at two different altitudes above sea level, 500 m and 2400 m. When altitude increases, combustion duration increases for both fuels, but diesel fuel increases combustion duration more than palm oil biodiesel. Agarwal et al. [113] studied the combustion duration by conduct an endurance test with CRDI one-cylinder diesel engine running on diesel and different Karanja biodiesel blends

(10, 20, and 50%) at fuel injection pressures of 300, 500, 750, and 1000 bar. At 300, 500, and 750 bar, KOME10 and KOME20 had shorter combustion durations than diesel fuel. However, at 1000 bar fuel injection pressure, KOME50 indicated a longer combustion duration than diesel. An increase in fuel injection pressure decreases the combustion duration, whereas increasing the blend percentage of biodiesel enhances the combustion duration due to the higher fuel viscosity and lower volatility of biodiesel. On the other hand, An et al. [114] found a different trend in the combustion duration influenced by the percentage of biodiesel blends. The combustion duration was shorter with an increase in the biodiesel blend ratio. A similar observation reported by Santhoshkumar [54] was that the combustion duration was influenced by the ratio of biodiesel blends.

The engine speed influenced combustion duration was found by Wang [115]. In a diesel engine fuelled with diesel and FAME100 biodiesel at 4500 m altitude, varied engine speeds, and high load conditions, the CD for each fuel was found to be almost the same at low (1200 r/min) and high (1800 r/min) speeds. However, it was discovered that the combustion duration rises as engine speed increases. There is research comparing neat biodiesel and its blends on combustion duration; for instance, Anand et al. [116] examined the CD of a Karanja biodiesel blend with methanol in a turbocharged, multiple cylinder DI truck diesel engine. They evaluated the CD of B100 and B90M10 under different load conditions. For both fuels, it was discovered that the combustion duration rises as the load increases. Because the oxygen concentration of the biodiesel–methanol blends rises, the methanol blends into biodiesel and assists to reduce combustion duration. The addition of methanol to biodiesel mixes reduces viscosity and increases the burning rate. Similar findings by Liu [55] found that the combustion duration increases with the engine load. However, the B100 biodiesel shows a shorter combustion duration than diesel at high load conditions due to the highest diffusion combustion rate. Dhar and Agarwal [53] observed different trends in combustion duration for biodiesel at 500 bar and 1000 bar fuel injection pressure. The proportion of biodiesel in the test fuel increased; the combustion duration for KOME50 and KOME20 increased compared to diesel, owing to significantly worse mixing properties and the necessity of a higher fuel amount in comparison to mineral diesel.

5.5. Effect of Biodiesel on Combustion Characteristics

Biodiesel and biodiesel blends have a major impact on the combustion characteristics of engines. In general, higher CN will result in a short ignition delay. The ignition delay was shorter with the use of biodiesel than diesel fuel in a diesel engine. This may be attributed to higher CN in biodiesel than diesel fuel. Higher in-cylinder pressure was discovered with the use of biodiesel blends due to the higher oxygen concentration found in the biodiesel blends. A higher biodiesel blend ratio will have higher in-cylinder pressure. Furthermore, the in-cylinder pressure is also influenced by the engine load and speed. The increase in engine speed decreases the pressure due to the low burning rate of biodiesel during the ignition delay interval. The HRR is affected by engine speed, load, and biodiesel oxygen content. A higher concentration of biodiesel blends has a higher boiling point which results in lower HRR. The high oxygen concentration in biodiesel influences the combustion duration. The combustion duration was shorter with the increase in the biodiesel blend ratio. This is mainly due to the increase in oxygen concentration in biodiesel as the concentration increases. The biodiesel properties can be stated as the main factors that affect the combustion characteristics.

6. Endurance Characteristics

In general, endurance characteristics of an engine are determined by the lubricating oil, carbon deposits, and wear measurement of in-cylinder engine components. In terms of operation, the characteristic is to show the durability of an engine run on biodiesel. While diesel engines operated with biodiesel and blended fuel contributes to some findings, such as carbon deposition, lubricating oil dilution, deterioration, injector coking, fuel filter blockage, and engine wear issues [117]. Investigating lubricating oil will yield the complete history of engine components' wear. In addition, the viscosity of lubricating oil is a significant factor in determining an engine's endurance. Furthermore, combustion efficiency is determined by the carbon deposits of an engine. It has been established that engine combustion and endurance are determined by these characteristics. During engine operation, fuel is regarded as a primary influencing aspect for engine oil conditions. This section covers the review on lubricating oil analysis, carbon deposits, and engine wear analysis. Table 2 shows the overview of the comparison results of endurance tests on lubricating oil analysis.

6.1. Lubricating Oil Analysis

The study of the impact of fuel on lubricating oil contamination is critical for determining its compatibility with an engine. The purpose of the analysis is to determine the effect of biodiesel on lubricating oil by determining various characteristics. The following subsection provides the comparative results of each study related to lubricating oil analysis of biodiesel and diesel fuel in different engines.

Lubricating Oil Properties

Lubricating oil properties include viscosity, density, flash point temperature, moisture content, and ash content. For the whole life of the lubricating oil, the viscosity of the lubricating oil should be appropriate since this influences the lubrication efficiency, engine efficiency, and engine life. Pipitone and Costanza [118] studied the long-term compatibility and durability issue of large stationary compression ignition engines with a different preheated temperature of crude palm oil and diesel fuel. After the engine ran for the first 100 h, lubricant samples were taken and tested for both fuels, and then every 50 h until the engine ran for 300 h. The lubricant viscosities measured for both diesel and CPO80 (crude palm oil warmed to 80 °C) dropped with comparable patterns until 300 h of operation, but CPO60 (crude palm oil preheated to 60 °C) caused a significant reduction immediately after 150 h of operation. The lubricant viscosity decreased owing to the dilution of both fuels, with increased dilution seen at lower CPO preheating temperatures. Liaquat et al. [119] conducted a 250 h endurance test for a one-cylinder CI engine. The used fuels were PB20 (20% palm biodiesel and 80% diesel fuel) and diesel. The lubricating oil was determined using an Anton Paar (SVM 3000) viscometer. They found the reduction in viscosity of lubricating oil and engine oil density was greater with PB20. The deterioration of the lubricant caused an increase in viscosity.

Table 2. Endurance tests on different lubricating oils.

Engine	Test Duration (h)	Test Condition	Biodiesel	Reference Fuel	Lubricating Oil Properties	Wear Metals Particles	Test Method	References
1-cylinder DI engines	1000	Different load	SME100 (Soy methyl ester) and CME100 (Castor oil methyl ester)	diesel	Viscosity ↓, TAN →, TBN →, Flash point →	Si, Zn, Ca, Mg, Mo, Al, Cr, Pb, and Cu	Atomic Absorption Spectroscopy	[31]
1-cylinder, naturally aspirated, WC, horizontal type, 4S DI diesel engine	24	Different load and speed	Rubber seed oil biodiesel B100, B5	diesel	Viscosity ↑, TBN ↑	Fe, Cu, Al, and Cr	NA	[32]
1-cylinder, naturally aspirated, 4S, AC, DI diesel engine	100	Different load and constant speed	JMETPO20 (Jatropha methyl ester)	diesel	Flash point ↓, Moisture content ↑, Ash content ↑	Fe, Cu, Zn, Cr, Mg, and Pb	Atomic Absorption Spectroscopy	[34]
Large multi-cylinder stationary CI engine, Scania DC16 44A	300	Constant speed	Preheated crude palm oil, CPO60, and CPO80	diesel	Viscosity ↓	Fe, Cu, Pb, Al	Atomic Absorption Spectroscopy	[118]
1-cylinder, 4S diesel engine	250	Constant load and speed	PB20 (Palm biodiesel)	diesel	Viscosity ↓, Density ↑	Fe, Cr, Al, Cu, Pb, Mg, and Mo	Anton Paar viscometer and multi-element oil analyser	[119]
1-cylinder 4S CI engine	250	Constant load and speed	JB20 (Jatropha biodiesel)	diesel	Viscosity ↓, Density ↑	Fe, Cr, Al, Cu, Pb, Si, Mg, and Mo	Energy dispersive Xray spectroscopy	[120]
14-hp Kubota RT140 DI diesel engine	800	Constant load and speed	B100 (Palm biodiesel)	diesel	Viscosity ↑, TBN ↑	Fe, Cr, Pb, Cu, Sn, Al, Ni, Ag, Mo, and Ti	Full laboratory analysis	[121]
4-cylinder indirect-injection engine	20	Constant speed	POD (Palm oil diesel) and POD90 (emulsified POD)	diesel	Viscosity →, TBN →	Fe and Cu	NA	[122]
1-cylinder, WC, DICI engines	512	Different load and constant speed	K10 (Karanja oil)	diesel	Viscosity ↓, Density ↑, Flash point ↓, Ash content ↑	Fe, Zn, Cr, Pb, and Al	Atomic Absorption Spectroscopy	[123]
1-cylinder WC portable diesel engine	512	Different load and constant speed	LOME20 (Lin seed oil methyl ester)	diesel	Density ↑, Viscosity ↓, Ash content ↑, Flash point ↓, Moisture content ↓,	NA	Atomic Absorption Spectroscopy and Fourier transform infrared spectroscopy	[124]

Table 2. *Cont.*

Engine	Test Duration (h)	Test Condition	Biodiesel	Reference Fuel	Lubricating Oil Properties	Wear Metals Particles	Test Method	References
4S, AC, DI diesel engine	150	Different load and constant speed	COME10, COME20 (Canola oil methyl ester)	diesel	Viscosity ↓, Density ↑, Flash point ↓, Moisture content ↓, TAN ↓, TBN ↑	NA	Plasma-Atomic Emission Spectroscopy and Inductively Plasma-Mass Spectroscopy	[125]
4-cylinder, 4S, variable speed, medium duty, transportation CI engine	200	Different load and speed	KOME20 (Karanja biodiesel)	diesel	Viscosity →, Density ↑, Ash content ↑, Flash point ↓, TBN ↓	Fe, Al, Cu, Cr, Ni, Zn, Pb, and Mg	Coupled plasma optical emission and Spectro-photometer	[126]
1-cylinder 4S vertical WC diesel engine	512	Constant load and speed	Lin seed methyl ester (5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, and 70%)	diesel	NA	Fe, Cu, Zn, Cr, Mg, Co and Pb	Atomic Absorption Spectroscopy	[127]
1-cylinder, 4S, WC DI diesel engine	100	Different load	PB20S10W (water emulsified biodiesel–diesel blend) and B20 (palm biodiesel)	High-speed diesel (HSD)	NA	Fe, Cu, Zn, Mn, and Mg	Atomic Absorption Spectroscopy	[128]
1-cylinder, variable compression ratio diesel engine	512	Different load and constant speed	T20 (Thumba vegetable oil)	diesel	Viscosity ↓	Fe, Al, Cr, Cu, Pb, Sn, and Si	ISO-accredited laboratory	[129]
1-cylinder, 4S, air cooled, DICI engine	256	Different load and constant speed	PME20 (Pongamia oil methyl ester)	diesel	Viscosity ↓, Flash point ↓, Density ↑, ash content ↑	Fe, Cu, Ni, Pb, Zn, Pb, Cr, and Mg	Plasma-Atomic Emission Spectroscopy	[130]

↑: increase, ↓: decrease, →: no changes, CI: compression ignition, DI: direct injection, 4S: 4 Stroke, WC: water-cooled, AC: air-cooled.

Furthermore, the dilution of lubricating oil viscosity was discovered due to un-burnt biodiesel blends passing into the crankcase. Reksowardojo [32] also found the lubricant oil viscosity decreased due to the dilution by the biodiesel fuel. Dilution of the lubricating oil by biodiesel might lead to viscosity decreases. The addition of biodiesel to the lubricant may result in a decrease in viscosity. While the engine operates, biodiesel will pass through the components and eventually dilute the protecting layer of lubricant on the components, thus reducing the viscosity. Pereira et al. [131] noticed a similar trend in the engine lubricant oil viscosity on a mono-articulated bus with biodiesel and diesel fuel, with biodiesel reducing the lubricant oil owing to poorer oxidation stability and increased hygroscopicity in contrast to diesel fuel. The service-life mileage of the engine lubricant oil charge was reduced by biodiesel fuel from 20,000 to 13,000 km for mono-articulated buses and from 15,000 to 10,000 km for bi-articulated buses. Two primary variables contribute to variations in the viscosity of the lubricant. Higher viscosity means that either oxidation or contamination causes deterioration of the lubricant, whereas decreased viscosity typically means that the lubrication oil is diluted [31,120,132]. Fuel contamination caused oil dilution, which resulted in reduced viscosity, deteriorated additives, a thinner oil layer, and higher adhesive wear on engine components [121]. There are different observations found by Kalam and Masjuki [122]. They compared the lubricant oil deterioration with an unmodified diesel engine running at 2500 rpm for 20 h for each fuel system with palm oil diesel emulsions (POD) and diesel fuel. They discovered that emulsified POD had superior viscosity performance than base OD fuel because emulsified fuels can maintain a more consistent viscosity level than OD fuel.

Density is an important lubricating oil property since it informs about the addition of wear metals and fuel dilution in lubricating oil. Agarwal and Dhar [123] conducted two direct injection compression ignition engines for 512 h on Karanja oil blends with diesel fuel, K10, and diesel fuel. They discovered that the engine fuelled with K10 biodiesel blends had a quicker rate of density change due to the increased wear rate and chemical deterioration of the lubricating oil in comparison to the diesel-powered engine. According to Liaquat et al. [119], there are few factors, such as engine part wear and dilution, that impact the rate of rising in density in engine oil while running on PB20. Agarwal [124] observed that the addition of wear debris to lubricating oil, fuel dilution in the case of biodiesel-fuelled engines, and the addition of moisture to lubricating oil all had a substantial impact on the density of lubricating oil. Furthermore, flash point temperature is also considered an important property of lubrication oil. Agarwal [124] and Sharma [34] discovered that the flash point of lubricating oil decreased with usage.

Sharma et al. [34] observed that the lubricant's flash point with the use of JMETPO20 biodiesel is reduced more than diesel fuel after 100 h of engine operation. The flash point was decreased from 220 to 205 °C with the use of JMETPO20, whereas diesel was only reduced from 220 to 208 °C. It was suggested that the drop in flash point is due to the presence of increased moisture and free fatty acid in the blends. Moreover, the ash content of lubricant can be defined as the proportion of the unburned carbon content after the fuels have been entirely burnt. The ash content of the lubricating oil may cause clogging on the engine filters and reduce the life of the engine. The ash content for engines fuelled with JMETPO20 was found to be greater than that of diesel fuel. A similar finding on the ash content was found in the literature [123–126]. The high ash content found in the lubricant with biodiesel is caused by increased wear debris accumulation in the engine.

6.2. Engine Wear Analysis

Engine wear occurs as a result of extended engine usage, or engine running. The engine wear analysis gave sufficient information regarding wear rate, wear metal source, and engine conditions. The engine wear analysis, which included assessing wear debris or metal particles from lubricating oil and surface wear, was used to determine the durability of biodiesel in diesel engines.

6.2.1. Lubricating Oil Properties

The concentration of wear metals in lubricating oil can be utilised to predict the wear of engine components that contain such metals. When biodiesel, which is composed of oxygen and unsaturated fatty acids, comes into contact with the metal surfaces, this oxidises the metal and produces wear debris [133]. As a result, metal analysis on engine lubricant offers a good assessment of wear on important engine components. According to the authors of [32,120,121,127–129,134], the metal particles found are dependent on engine component material since the particles are formed by the wear of engine components. Metal particles such as Fe, Cr, Al, Cu, Pb, and Mg were found from the engine lubricating oils with biodiesel stated in Table 2 [130,135,136]. Iron (Fe) particles in lubricating oils are derived from the cylinder liner, piston, rings, shafts, crankshaft, and bearings. Chromium (Cr) wear debris are from the cylinder liner, compression rings, gears, crankshaft, and bearing. Aluminium (Al) in lubricating oil is caused by the piston, bearing, dirt, additives, and thrust washer wear. Copper (Cu) in wear debris is derived from bearings, bushes, and valve guides. Lead (Pb) in lubricating oil is caused by the wear of bearings, paints, and grease. Magnesium (Mg) in wear debris can result from additive depletion, cylinder liner surface wear, bearing wear, and gear box housing wear.

Agarwal [130] carried out a long-term endurance test on a one-cylinder, 4S, vertical WC system diesel engine that was operated with diesel fuel, Lin seed oil methyl ester (LOME), and biodiesel blends. The lubricating oil was extracted and analysed using Atomic Absorption Spectroscopy (AAS) to determine the quantity and quality of wear metal particles in the oil. The results showed that the B20-fuelled engine had a lower increase in Fe, Cu, Zn, Cr, Mg, Co, and Pb content, which indicates that lesser wear occurred, and this is due to better lubricity of biodiesel in comparison with the diesel-fuelled engine. Kumar and Raheman [128] investigated the durability of a one-cylinder DI diesel engine using PB20S10W (89% palm biodiesel 20 + 10% water + 1% surfactants), PB20 (20% palm biodiesel and 80% diesel), and High-Speed Diesel (HSD) after 100 h engine operation. They discovered that while using PB20S10W and PB20, the quantity of all metal particles such as Cu, Fe, Mn, Zn, and Mg in lubricating oil was 0.48–28.57% and 6.71–47.6% less than when using an HSD-fuelled engine, respectively.

A different trend was discovered by Reksowardojo et al. [32], Fe was found to be at the high level, 26 ppm in engine lubricating oil with biodiesel due to the reduction in the viscosity of lubricating oil. In another research by Liaquat et al. [119], lubricating oil contamination was collected and analysed every 20 h operation. The result indicated that most of the metal particles such as Fe, Cr, Al, Cu, Pb, Mg, and Mo have a higher concentration in the lubricating oil when fuelled with PB20 due to the rust and wear of engine components.

Jain et al. [129] tested the durability of a compression ignition engine with B20 Thumba vegetable oil over 512 h. Fe, Al, Cr, Cu, Si, Pb, Sn, and Ni was observed from lubricating oil with the use of biodiesel. Copper and silicon were determined to be 66 mg/kg and 112 mg/kg in that sample, respectively, although the referenced critical limit of these material depositions is 50 mg/kg and 25 mg/kg. Dhar et al. [128] reported higher amounts of Fe, Al, Mg, Cr, and Cu debris in the lubricant of a diesel engine operated with biodiesel and blended fuels than a diesel-fuelled engine, thus indicating substantial lubricating oil degradation. Sharma and Murugan [34] observed that JMETPO20 biodiesel blends had higher zinc and chromium concentrations than diesel fuel due to the wear of numerous moving engine components. The increased percentage of zinc on biodiesel was most likely owing to the depletion of additives in the lubricant. The friction of the engine and the dilution of the lubricating oil had an effect on the wear of the engine component.

6.2.2. Surface Wear

Pandey [137] compared engine wear in a military diesel engine between diesel, Karanja, and jatropha methyl ester biodiesel. For all three fuels, the engine was driven for 100 h at varying speeds, 1200–2000 rpm at full load. The engine was collected and performed comparison on wear performance through Scanning Electron Microscopy (SEM) analysis. It was observed that biodiesel-fuelled engines such as the KOME and JOME cause less damage to crosshatched honing marks than diesel-fuelled engines and the honing marks are not removed. Because biodiesel provides better combustion, lower peak in-cylinder temperature, less soot generation, and greater lubricity and biodiesel causes less damage. On the SEM analysis of engine wear with KOME20 and diesel-fuelled engines, Dhar and Agarwal [138] had comparable findings, as shown in Figure 8. They reported seeing white spots on the KOME20-fuelled engine lining, which were most likely caused by corrosive wear. The surface roughness of the cylinder liners in both diesel and KOME20 fuels was satisfactory even after a 250 h endurance test. Large white markings were also detected in the optical micrographs by Reddy et al. [139], owing to heat and abrasive stresses produced in the fuel injection equipment components during the long-term endurance test.

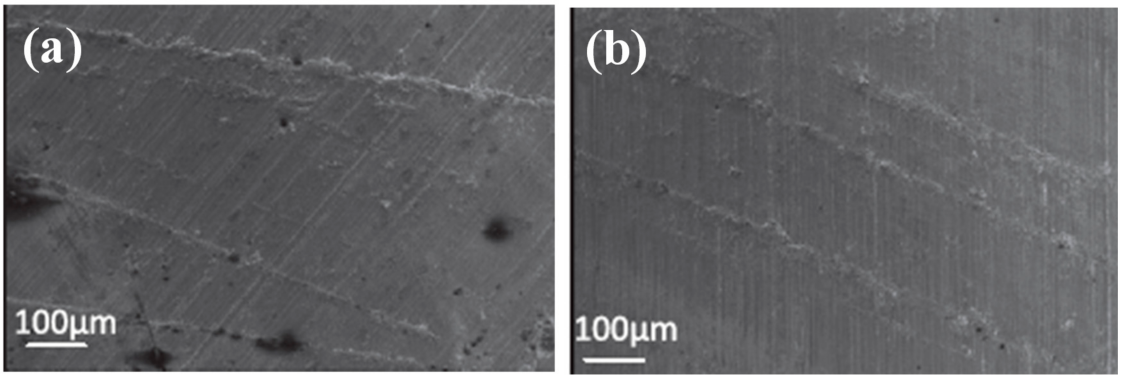

Figure 8. SEM 300X of a (**a**) diesel and (**b**) KOME20 engine cylinder liner at BDC after 250 h [138].

Furthermore, KO100 and KOME100 had lower wear of the fuel injection equipment components than diesel fuel. By using electronic microscopes to analyse the pump plunger surface and nozzle needle surface, Kumar, Varun, and Chauhan [33] discovered that biodiesel had reduced abrasive wear due to better lubricity than diesel fuel, which created a monolayer coating on mating surfaces to preserve the metal surface. A comparison of injection pump between biodiesel and petroleum diesel after a 200 h engine test was observed by Celik [133]. Through SEM studies, a substantial reduction in metal cutting traces on the piston of a biodiesel-fuelled injection pump was discovered. The biodiesel piston had a rabbet height of 1.1 mm, whereas the petroleum diesel piston had a rabbet height of 1.12 mm. However, in terms of wear rate, Gulzar et al. [140] observed that the wear rates of diesel fuel, palm biodiesel (PB20), and Jatropha biodiesel (JB20) were almost equivalent, although diesel fuel had the lowest wear rate due to its high viscosity and minimal fuel residue. Moreover, B20 biodiesel increases fuel residue that lowers lubricant viscosity, and therefore, increases the wear rate.

6.3. Carbon Deposit

Deposition in the engine happens primarily because of the incomplete combustion of fuel, ineffective scavenging, and lubricating oil deterioration. Carbon deposits are most commonly formed on the injector nose, which has the lowest temperature in the combustion chamber, followed by the other engine components such as the cylinder head and piston crown [141]. Carbon deposition was influenced by engine operating conditions, fuel type, and lubricating oil composition [128]. The carbon deposits on the fuel injector, piston top, and cylinder head will be the main focus of this section. The following subsection also covers the carbon deposits comparison of diesel and biodiesel.

6.3.1. Fuel Injector

Reksowardojo et al. [32] observed that rubber seed oil biodiesel B5 and B100 fuels have the highest carbon deposit accumulation on injector liners. The injector surfaces were found dirty with the use of B5 and B100 in comparison with diesel. Greasy carbon deposits were discovered on the injector of a diesel-fuelled engine, whereas dry deposits were discovered on the nozzle of a JB20 blend-fuelled engine, according to Liaquat [120]. Patidar et al. [128] also observed more deposits found on fuel injector tips when operated with PB20S10W and B20, as shown in Figure 9, due to the higher viscosity of biodiesel and blended fuels. Chourasia et al. [142] discovered high carbon deposition in almost all components of the diesel-fuelled engine, including the fuel injector, piston, and cylinder head, in comparison to diethyl ether blend, B20A4, after 512 h of operation. The higher carbon deposition was observed due to incomplete combustion of diesel fuel in the engine. Kalam and Masjuki [122] found that with the usage of POD emulsions, there are fewer carbon deposits discovered in injector tips. The POD emulsions exhibit encouraging results in terms of wear resistance and carbon deposit reduction.

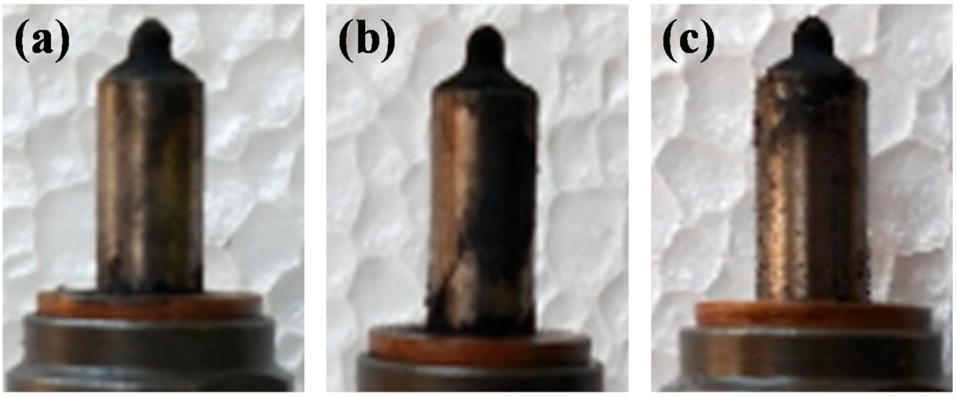

Figure 9. Carbon deposition on fuel injector after 512 h test: (**a**) HSD, (**b**) PB20, and (**c**) PB20S10W [128].

6.3.2. Piston Top

Agawal et al. [124] discovered that carbon deposits on the piston top of a K10-fuelled engine were greater than those on a mineral diesel-fuelled engine after a 512 h endurance test. Suthisripok and Semsamran [121] also observed dry black deposits on the pistons after operated for 100 h and 700 h with palm biodiesel, B100. The carbon deposit on the piston crown with PB20S10W and B20 was found to be lower by Kumar and Raheman [128], as shown in Figure 10. Carbon deposits on the piston crown of a PB20-fuelled engine were found to be 28.16% lower than on a PB20S10W-fuelled engine, but 40.67% lower on an HSD-fuelled engine. The quantity of carbon deposits in the biodiesel is significantly proportional to the oxygen availability in the biodiesel. Chourasia et al. [142] examined carbon deposits on pistons in engines powered by diesel fuel and B20A4 fuel. Less carbon deposition was found on the piston and cylinder head, which was attributed to the addition of oxygenated additives in B20A4, which resulted in less carbon deposit on the piston and cylinder head. On the other hand, with the use of COME10 fuel in the engine, higher carbon deposition on the second piston ring was observed by Temizer [143]. It was stated that the unburned fuel deposited on the piston ring surface was due to the increase in carbon ratio. Wander et al. [31] also observed that carbon deposits and gum formation were higher on the piston ring with the use of CME100 and SME100 in comparison to diesel.

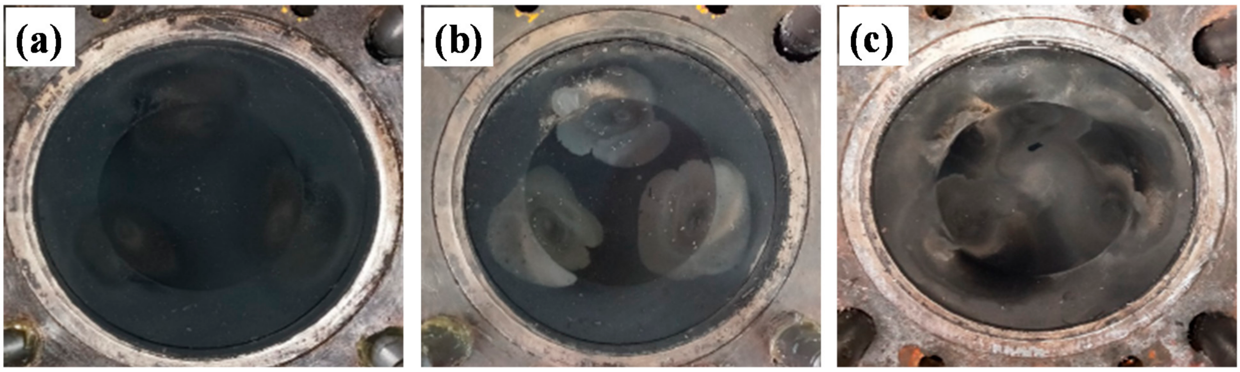

Figure 10. Carbon deposition on piston top after 512 h test: (**a**) HSD, (**b**) PB20, and (**c**) PB20S10W [128].

6.3.3. Cylinder Head

Kumar and Raheman [128] visually inspect the cylinder of the engine after a 100 h endurance test with PB20S10W, B20, and high speed diesel fuel. As indicated in Figure 11, they compared the cylinder head before and after the endurance test with three different types of fuels. Carbon deposits on the cylinder head were found to be lower with PB20S10W and B20 than with HSD. The number of carbon deposits on the cylinder head in the case of a PB20-fuelled engine was found to be 18.36% less than that of a PB20S10W fuel operation, respectively, but it was 32.2% less in the case of an HSD-fuelled engine. Dhar and Agarwal [138] investigated engine wear and a 250 h endurance test using KOME20 and diesel fuel in a direct injection compression ignition engine. They discovered that the carbon layer generated on the cylinder head of the KOME20 engine was thicker. Furthermore, Dhar and Agarwal claim that greater carbon deposition in the combustion chamber with a KOME20-powered engine is owing to KOME20 having a larger carbon residue than diesel fuel and incomplete combustion of the fuels.

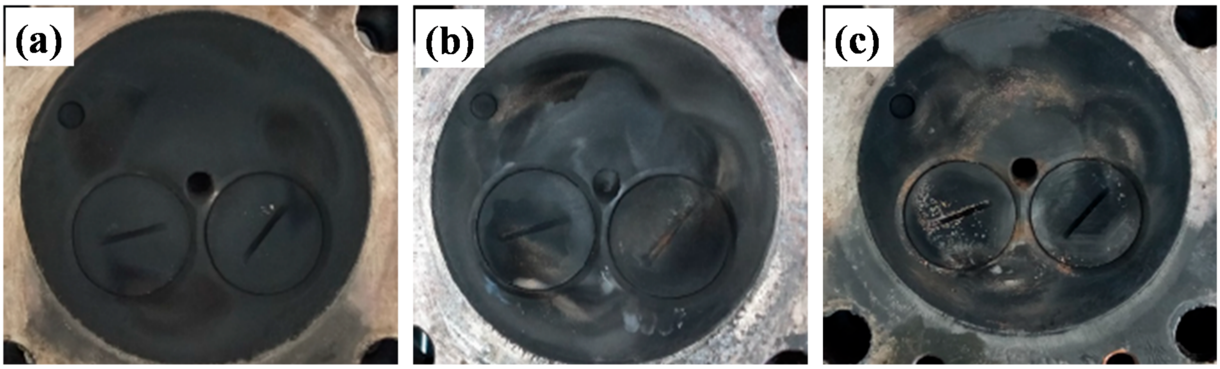

Figure 11. Carbon deposition on cylinder head after 512 h test: (**a**) HSD, (**b**) PB20, and (**c**) PB20S10W [128].

Kumar et al. [33] discovered that in diesel-fuelled engines, thicker carbon deposits were produced on the surfaces compared to when biodiesel-fuelled engines was used. Carbon deposits on diesel-fuelled engines were found to be greasy, but the carbon deposits on biodiesel-fuelled engines were dry. The reduction in carbon deposits for B40 is due to biodiesel contributing to better combustion by providing necessary oxygen to fuel, particularly in locally fuel-rich zones. Pipitone and Costanza [118] investigated cylinder head deposits with diesel, CPO60, and CPO80 after 300 h of operation. CPO60 usage resulted in a 53% rise in in-cylinder deposits as compared to diesel, however, CPO80 usage resulted in a 12% decrease in deposit development when compared to diesel. The increase in the preheating temperature of CPO to 80 °C decreased fuel viscosity, resulting in better fuel jet nebulisation and fewer deposits in the cylinder. However, the low preheating temperatures might result in significant ash content increases in the in-cylinder deposits.

6.4. Effect of Biodiesel on Endurance Characteristics

The chemical properties of biodiesel show significant effects on engine lubricants. During the operation of the engine, the rate of dilution on lubricant with biodiesel was higher than diesel fuel due to poor oxidation stability of the biodiesel, which results in an increase in lubricant viscosity. By this matter, the density of lubricant will be found high due to an increase in wear rate and chemical deterioration. The wear debris in the lubricant then will accumulate and form ash content in the fuels. Furthermore, the flash point of lubricant was decreased with the use of biodiesel mainly due to the increase in moisture content and free fatty acid. The amount of carbon deposited in engine components is directly proportional to the amount of oxygen available in the biodiesel. An increase in oxygen availability will result in a lesser carbon deposit formed in the engine components. However, biodiesel generated a lesser carbon deposit than conventional diesel.

7. Conclusions

In this paper, the performance, emissions, combustion, and endurance characteristics of different operating conditions diesel engines running on diesel, biodiesel, and its blends have been reviewed and summarised. The endurance test duration for evaluating the endurance characteristics after engine running was also highlighted. Furthermore, the various lubricating oil measuring procedures were discussed. The following conclusions can be stated.

- Biodiesel and blended fuel lowered power and thermal efficiency while increasing brake-specific fuel consumption reported in the review.
- The researchers concurred that biodiesel and blended fuel produces less CO, HC, and PM than diesel. The NOx trend with biodiesel varied according to engine speed, engine loads, and biodiesel properties. When compared to diesel fuel, biodiesel and its blends had a shorter ID and a lower HRR. The ICP was marginally higher than that of diesel fuel. The CD of biodiesel–methanol was found to be lower than pure biodiesel and diesel fuel.
- Among the endurance tests, reductions in the lubricating oil's viscosity and density were mostly impacted by fuel dilution, whereas the increase in ash content with biodiesel was caused by the accumulation of wear debris in the engine.
- Biodiesel and blended fuel resulted in less wear and carbon deposits after a long-term endurance test. A high concentration of wear debris was found inside the lubricating oil while operated with a biodiesel-fuelled engine.

Furthermore, this study revealed that biodiesel with various blends provides a significant improvement in the performance, emissions, combustion, and endurance characteristics of the diesel engine. Finally, the addition of alcohol fuels in biodiesel blends shows better combustion characteristics and reduces PM emissions, and subsequently, may improve the carbon deposition in the diesel engine. However, further research on biodiesel blends with alcohol fuels in long-term endurance tests is required to obtain a better understanding of endurance characteristics about engine wear of the diesel engine.

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Nomenclature

AONP 25	25 ppm aluminium oxide nanoparticles
AONP 50	50 ppm aluminium oxide nanoparticles
B10	10% biodiesel + 90% diesel
B100	100% biodiesel
B15	15% biodiesel +85% diesel
B20	20% biodiesel + 80% diesel
B30	30% biodiesel + 70% diesel
B40	40% biodiesel +60% diesel
B5	5% biodiesel + 95% diesel
B50	50% biodiesel +50% diesel
B70	70% biodiesel + 30% diesel
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CD	Combustion duration
CO	Carbon monoxide
COME10	10% Canola oil methyl ester + 90% diesel
COME20	20% Canola oil methyl ester + 80% diesel
CPME	Calophyllum inophyllum-palm oil methyl ester
CR	Compression ratio
CRDI	Common rail direct injection
CSB	Canola oil+ Safflower oil biodiesel
CSBE15	85% CSB+ 15% Ethanol
CSBS15	85% CSB+ 15% Solketal
DICI	Direct injection compression ignition
DRSOnB	Diesel-rapeseed oil-n-butanol
E20	20% ethanol
HC	Hydrocarbon
HOME	Hazelnut kernel oil methyl ester
HRR	Heat release rate
ICP	In-cylinder pressure
ID	Ignition delay
JMETPO20	20% Tyre pyrolysis oil + 80 % Jatropha methyl ester
KO100	100% Karanja oil
KOME	Karanja oil methyl ester
NOx	Nitrogen oxide
PB30	30% palm biodiesel + 70% diesel
PM	Particulate matter
PO20	20% palm oil + 80% diesel
POME	Palm oil methyl ester
ppm	Part per million
rpm	Revolution per minute
VOME	Vegetable oil methyl ester

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