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Analysis of Engine Parameters of High Composition Palm Oil Biodiesel in CRDI System

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ABSTRACT

The heavy reliance on fossil fuels has serious consequences, particularly regarding increased greenhouse gas emissions that contribute to global warming. In order to obtain cleaner fuel resources and reduce fossil fuel dependence, palm oil biodiesel is added to fossil diesel by volume ratio resulting in B50 and B55 blends. Combustion characteristics, performance, fuel consumption, and emissions were performed in a diesel engine with a 4-cylinder common rail direct injection (CRDI) at different engine speeds (1500, 2000, 2500, and 3000 rpm). Compared to fossil diesel, biodiesel blends exhibit higher density at 855.9 kg/m³ (B55), kinematic viscosity with a value of 5.1 mm²/s (B55), and cetane index of 58 (B55). As biodiesel composition increases, the calorific value of fuels decreases (B55 = 48.73 MJ/kg) which positively correlated with the fuel consumption increase. Combustion analysis indicates that B0 generates a higher peak cylinder pressure and heat release rate due to a higher calorific value compared to the diesel/biodiesel blend. Performance test result shows B0 delivers superior torque (180 Nm) and peak power (80.6 HP) at high engine speeds, whereas B50 and B55 improve low-engine-speed combustion efficiency due to enhanced oxygen compound and cetane index. Based on findings, biodiesel blends are better suited for emission reduction and low-speed applications, while B0 remains optimal for high-power demands, highlighting a performance and emission trade-off that depends on engine operational requirements.

Keywords: *Biodiesel, CRDI, Emission, Performance*

I. Introduction

Fossil fuel is a major world energy source, around 88% of which is expected to rise along with population growth. The global energy crisis has become a major concern over the past decade due to fossil fuels scarcity [1]. A steady rise in fuel oil consumption is projected in the near future, based on the significant expansion in crude oil production between 2010 and 2023 [2]. This heavy reliance on fossil fuels has serious consequences, particularly regarding increased greenhouse gas emissions that contribute to global warming [3]. Especially in recent years, the sharp decline in urban air quality has been reported to be directly related to transportation sector. The main harmful air pollutants emitted by fossil-fueled vehicles are CO, HC, NOx, and PM. Compared with gasoline engines, diesel engines emit less CO and HC, but more NOx and PM. These emissions are posing a danger to human health [4]. At present, electric vehicles (EVs) are often described as an effective way to

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reduce environmental impact. However, high capital and maintenance costs, immature technology, and small scale are restricting EVs development. The conventional vehicles combined with exhaust after-treatment equipment can reduce emissions, but increase the cost of the vehicle and maintenance [5]. Therefore, the search for environmentally friendly alternative fuels has become essential. One promising solution is biodiesel.

Biodiesel has become the best alternative fuel for diesel because it is green, renewable, and biodegradable. Most importantly, its basic properties are similar to diesel fuel and offer minimal engine modification requirements [6]. Biodiesel can be derived from a variety of vegetable oils, from algae, and from animal fats via simple transesterification, which is the most effective method for biodiesel production [7]-[9]. There are four main vegetable oils, which consist of palm oil, soybean, rapeseed, and sunflower, that account for 85% of the total market share. Palm oil is the largest shareholder of 35% or 56,233,000 tons compared to others. The estimated oil content (highest) and market price as of May 2018 (lowest) for palm oil are 5000 kg of oil/ha and 660 USD/ton [10]. Indonesia is currently the world's largest producer of crude palm oil (CPO), contributing 45.5 million tons annually, or 59% of global production [11]. Although palm oil biodiesel has major advantages compared to other feedstocks, the overall quality is lower than that of fossil diesel. On the other hand, potential alternative fuels should improve combustion and emission performance without sacrificing engine performance, and fundamentally alleviate energy shortages and realize carbon neutrality as early as possible [12]. Blending biodiesel with diesel is one of the easiest and most effective ways to reduce the negative effects of biodiesel and biodiesel blending significantly improves the fuel's physicochemical properties [13]. Liu *et al.* [14] reveals that a high composition palm oil biodiesel blend of 50 vol% (B50) reduces soot emission by 14% compared to fossil diesel. Meanwhile, Ge *et al.* [15] conducted combustion characteristics analysis of palm oil biodiesel blend, where maximum cylinder pressure (CP) and heat release rate (HRR) of B20 blend are higher compared to fossil diesel, mainly due to the presence of oxygen in biodiesel, which can improve combustion characteristics. CP and HRR increased while using argemone biodiesel (B50)[16]). However, Kodate *et al.* [17] reported that B50 blend utilization reduces CP and HRR, which is attributed to the high viscosity of Vateria indica methyl ester. A similar result was also reported by Nema *et al.* [18] which uses soybean methyl ester blend (B55). Engine operational parameters also affect combustion characteristics. El-Kasaby *et al.* [19] pointed out that engine speed positively correlated with CP value until it reached the engine's maximum rated torque. However, there is a limited study of engine parameter effect on engine performance, along with combustion and emission characteristics of a high composition palm oil biodiesel blend.

Based on these findings, this study investigates diesel and palm oil biodiesel blend (B50 and B55) characteristics. These blends are chosen to provide insight for high biodiesel composition fuel, as the Indonesian Ministry of Energy and Mineral Resources projected higher biodiesel blends in the near future [20],[21]. In the present study, the effect of fuel blend and engine speeds (1500, 2000, 2500, and 3000 rpm) on combustion behavior, engine performance, and exhaust emissions was investigated in a CRDI 4-cylinder diesel engine to find optimal engine operational parameters using high composition palm oil biodiesel.

II. Material and Methods

1. Material

Palm oil biodiesel was selected as the renewable basic fuel. Palm oil biodiesel was purchased from the Wilmar CPO processing plant in Gresik, Indonesia. Pertamina Dex is used to represent diesel oil (B0), which was obtained from Pertamina Fuel Station in Madiun, Indonesia. Diesel/biodiesel blend of B50 (volumetric ratio of 50% Pertamina Dex and 50% Palm oil biodiesel) and B55 (45% Pertamina Dex and 55% Palm oil biodiesel). The blending process was carried out using a mechanical stirrer operated at 750 rpm for 5 minutes to ensure proper homogeneity [22]. Afterward, the blended fuels were stored in air-tight glass containers to avoid contamination, oxidation, or evaporation prior to engine testing.

2. *Fuels Characterization and Experimental Procedure*

Physicochemical properties of the diesel/biodiesel blends were characterized. Calorific value was obtained using the Labtron LBC-C20 bomb calorimeter. Fuel density assessment was carried out using a Pycnometer. The NDJ-8S viscometer is employed to measure fuel viscosity. Anton Paar ADU 5 is employed to calculate the fuel's cetane index. Flash point of the sample was measured using the Pensky-Martens closed-cup method on Anton Paar PMA 5.

Diesel/biodiesel blend combustion was performed using 4-cylinder common rail diesel engine as listed in Table 1, which served as the testing platform for evaluating the performance and emissions of the fuel blends. The experiment was conducted at engine speeds of 1500, 2000, 2500, and 3000 rpm as testing conditions. In addition, ambient air conditions were measured and controlled using a temperature and humidity meter. Inlet air pressure into the cylinder was measured using a scanner under standard conditions. Meanwhile, the temperatures of intake, ambient air, coolant, and exhaust gas were monitored using K-type thermocouples. The effect of diesel/biodiesel blend on combustion characteristics, fuel consumption, engine performance, and exhaust gas opacity was also measured, as visualized in Figure 1. Combustion characteristics were analyzed using KiBox To Go 2893B to obtain cylinder pressure and heat release rate for combustion quality assessment. OPA-102 opacity smoke meter was employed to measure exhaust gas opacity. This experimental test was conducted three times for each parameter, and then the average was calculated. The specifications of measuring instruments and the uncertainties were given in Table 2.

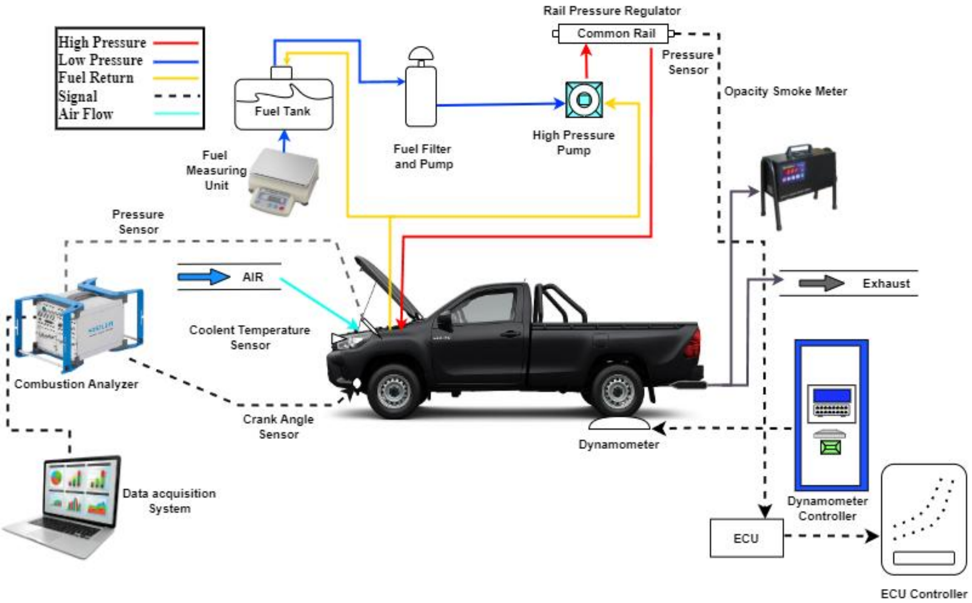

Fig. 1. Scheme of research

Table 1. 2KD-FTV engine specification

Specification	Detail
Engine type	2KD-FTV
Number of cylinders & configuration	4 cylinders, In-line
Gas exchange system	Turbocharger
Fuel type	Diesel
Valve mechanism	16-valve DOHC
Displacement	2494 cm^3
Fuel system	Direct injection 4-stroke common rail
Bore × stroke	92 × 93.8 mm
Firing order	1-3-4-2
Compression ratio	18.5:1
Maximum output	75 kW / 3400 rpm
Maximum torque	200 Nm / 2400 rpm

Table 2. Accuracy and uncertainty of measured parameters

Instrument	Measured parameters	Range	Accuracy	Uncertainty
Fuel measuring unit	Fuel mass flow	0.1 g – 15kg	0.1g	0.3g
Combustion analyzer	Combustion characteristic	1/min	0.1 °CA	Approx. 5ms (<< 1 combustion cycle)
Dynamometer	Performance	Max. 965 kW/ 1295 hp	0.1%	max. torque 3.800 Nm
Opacity smoke meter	Emission/ smoke opacity	0.0-100 %	0.1%	Within ±1% (rpm: ±80rpm)

III. Results and Discussions

1. *Fuel Properties*

Table 3 shows a comparison of the physicochemical properties of diesel/biodiesel blends. Generally, Palm oil biodiesel addition increases density, kinematic viscosity, cetane index, and flash point. Biodiesel physicochemical properties are varied due to its different fatty acid (FA) composition. Saturation degree and unsaturation type (mono- or polyunsaturated) of FA directly affect viscosity and density. Calorific value of fuel decreases with enhanced biodiesel concentration. B0 has a density of 833.1 kg/m^3, which increases to 853.6 kg/m^3 and 855.9 kg/m^3 in B50 and B55, respectively. Palm oil biodiesel has a lower density compared to roselle biodiesel (879 kg/m^3) [23]. Biodiesel has a higher density due to its unsaturated compounds [24]. Density is influenced by the number of double bonds (unsaturation degree) and heavy atom content [25]. Verdusco *et al.* [26] found that molecular weight has a more prominent effect on density value, where the molecular weight of Methyl caprylate ($C_9H_{18}O_2$) is 158.2 g/mol, while Methyl palmitate ($C_{17}H_{34}O_2$) is 270.45 g/mol. Fuel density directly influences injection spray pattern, amount of injected fuel, and brake-specific fuel consumption [26]. Higher density will increase fuel droplets, thus reducing their atomization degree. On the other hand, fuel with lower densities is desired for cleaner and efficient combustion [27].

Table 3. Fuel physicochemical properties

Type of fuel	Density (kg/m³) ASTM D4052 / D1298 at 15°C	Kinematic viscosity (mm²/s) ASTM D445 at 40°C	Calorific value (MJ/kg) ASTM D240	Cetane index	Flash point (°C) ASTM D93-A
B0	833.1	4.69	59.79	48	61.5
B50	853.6	5.09	51.26	59	82.5
B55	855.9	5.10	48.73	58	85.5
B100	875.5	5.77	45.23	67	164.5

The kinematic viscosity of B0 is recorded at 4.69 mm²/s, which reaches a maximum for the fuel blend at B55 (5.1 mm²/s). Higher biodiesel content increases kinematic viscosity. However, all values remain within the ASTM D6751 standard (1.6 and 6.0 mm²/s). Carbon chain length, level of unsaturation, number and position of methyl ester double bonds, and temperature are affecting the kinematic viscosity of biodiesel [28]. Viscosity increases as the number of random intermolecular interactions from long chain length and degree of saturation [29]. Due to its straight chain structure, saturated FA has an efficient packing, which prevents greater molecular movement and increases resistance to flow. While unsaturated FA has a double bond tail that has less efficient packing, it increases flowability [30]. Double-bond configuration of unsaturated FA reduces viscosity, where the cis double bond configuration gives a lower viscosity than the trans bond [25]. Biodiesel has higher viscosity compared to fossil diesel due to its long ester chain nature; FA molecules have higher resistance to flow, thus increasing their viscosity [31]. Palm biodiesel is dominated by saturated palmitic acid ($C_{16}H_{32}O_2$) and monounsaturated oleic acid ($C_{18}H_{34}O_2$) with percentages of 37.9% dan 43.9%, respectively. However, compared to beef tallow biodiesel, palm oil biodiesel has a lower viscosity due to the lower amount of saturated FA [32]. Fuels with too high viscosity result in injection delay, reduced injection volume, longer spray penetration, narrow spray cone angles, and poor atomization characteristics [27], [33], [34].

Calorific value is a very important property of fuel, which represents the amount of heat transferred into combustion chamber through chemical reactions during ignition and indicates the fuel's available energy [35]. The highest calorific value is found in B0 at 59.79 MJ/kg. As biodiesel content is added, the calorific value gradually decreases, where B55 has a calorific value of 48.73 MJ/kg. Palm oil biodiesel has a higher calorific value compared to roselle biodiesel (39.12 MJ/kg). There is a direct relationship between the calorific value and the size of the ethyl ester carbon chain in biodiesel. Longer ethyl ester chains possess a higher calorific value, which is attributed to a greater number of carbon-carbon and carbon-hydrogen bonds available for oxidation during combustion [27], [36]. If the activation energy of a chemical compound is achieved due to a work input or ignition source, the fuel chemical chain will break and oxidize, resulting in the formation of CO_2, water vapor, and heat. Jameel et al [37] compiled several fuel combustion enthalpy databases, where *n*-Decane is one of the lighter fractions of fossil diesel, with a ΔH of 1620 kcal/mol [38]. While a longer carbon chain, such as n-Hexadecane, has much higher ΔH of 2557.64 kcal/mol. That theory also applies to the FA compound, where C10 methyl ester ΔH is 1625 kcal/mol, while C14 is 2254 kcal/mol [39]. However, oxygen content in biodiesel originates from the FAME double bond, which negatively affects its calorific value [40]. Fuel having low calorific value can worsen fuel consumption and lower brake power in a diesel engine [23]. Several studies reveal that a high density of biodiesel helps compensate for its low calorific value. Biodiesel supplies a larger mass per cycle (e.g., 1 m^3 biodiesel = 875.5 kg vs. 1 m^3 diesel = 833 kg), increasing injected fuels, while the oxygen content of biodiesel (10-12%)

increases the combustion efficiency, compensating for the lower calorific value [16], [25], [27]. However, biodiesel brake-specific fuel consumption is higher compared to diesel fuel.

B0 has the lowest cetane index at 48, which rises to 58 at B55. Longer carbon chains and higher saturation degree of palm oil biodiesel typically contribute to a higher cetane index, improving ignition quality, but also increase kinematic viscosity, which can negatively impact the fuel flow system [32]. Low Cetane index will increase exhaust gas emissions, due to incomplete combustion [27]. Flash point of B0 is the lowest at 61.5°C. B50 and B55 have higher flash points at 82.5°C and 85.5°C, respectively. The highest value is shown by B100 at 164.5°C. The flash point of biodiesel will always be much higher than that of diesel fuel, which reflects the volatile nature of the fuel. Flash point is affected by the chemical composition of biodiesel, including the number of double bonds, the number of carbon atoms, water content, and the heavier molecular structure of biodiesel [41]. Although this property does not directly affect combustion, it is important when it comes to storage, fuel handling, and transportation [27].

2. *Combustion Characteristic*

2.1 *Cylinder Pressure*

CP is the amount of pressure generated inside the combustion chamber when the fuel burns, which pushes the piston and connecting rod to do mechanical work. Therefore, the cylinder pressure is expected to be high as combustion has occurred [42]. Cylinder pressure comparison at various engine speeds is shown in Figure 2. Peak pressure depends on the rate of combustion in the initial stage, which in turn is influenced by the amount of fuel burning in the premixed phase [43]. Fuels with higher cetane numbers and oxygen content enhance maximum CP (CPmax). However, lower calorific values and high viscosity lead to poor atomization and mixing with air, ultimately reducing CPmax [27].

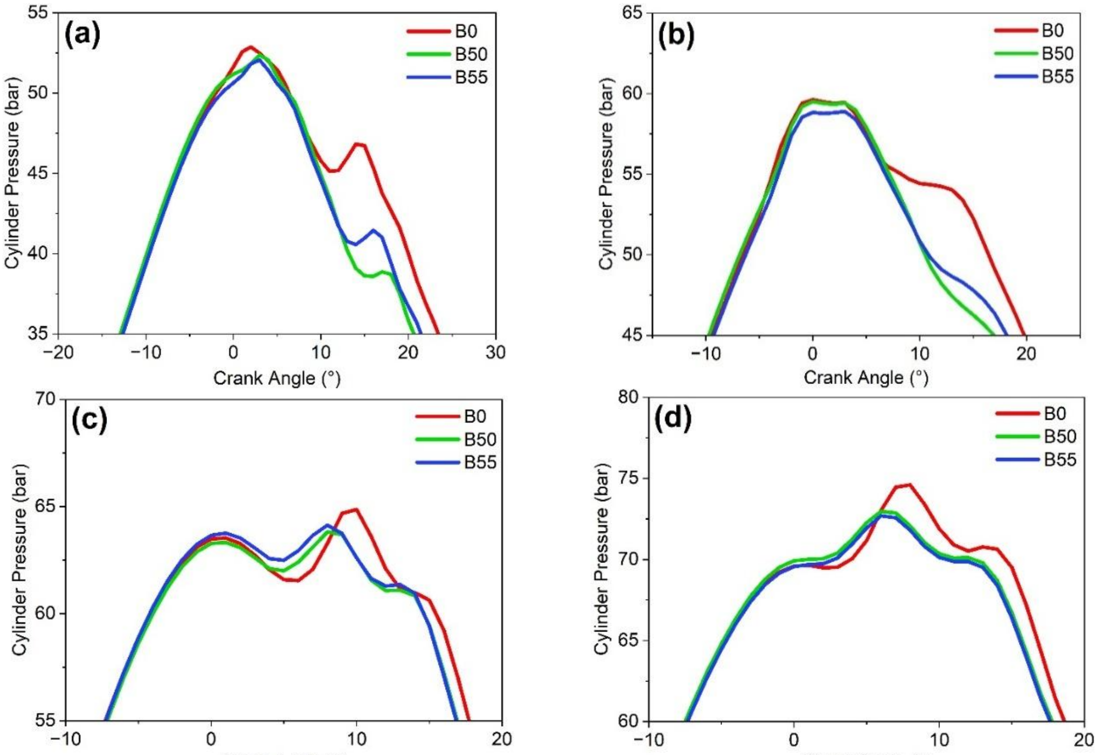

Fig. 2. Cylinder pressure comparison at (a) 1500, (b) 2000, (c) 2500, and (d) 3000 rpm

2.2 *Heat Release*

HRR indicates fuel's chemical energy released during the combustion process. The heat release rate is affected by viscosity, density, calorific value, fuel latent heat, combustion speed, and combustion temperature [46]. Referring to Figure 3, B0 has the highest maximum HRR compared to diesel/biodiesel blend at every engine speed. The HRR pattern shows that B0 generates greater heat release during the initial combustion phase. However, compared to diesel/biodiesel blend, B0 has slower and more intense combustion characteristics due to the absence of oxygenate compounds. Nevertheless, all types of fuel exhibit a similar HRR pattern except at 1500 rpm, where B0 has the earliest maximum HRR compared to diesel/biodiesel blend, which might be due to B0's high calorific value [46]. The difference in maximum HRR between the fuels is not significant, and the peak HRR still occurs within 10–20°CA after TDC, indicating that the injection system is capable to control combustion timing, resulting in a stable combustion process even with variations in fuel blend composition. In addition, the presence of more than one HRR peak suggests the occurrence of multi-stage combustion, which is commonly found in diesel fuel combustion at medium to high engine speeds, where premixed and diffusion combustion phases occur sequentially [47]. Heat release of diesel/biodiesel blend shifted into earlier crank angle compared to B0, which correlates with the high cetane index of biodiesels, leading to shorter ignition delay [48] In addition, the lower calorific value of biodiesel contributes to energy release reduction during the combustion process [40].

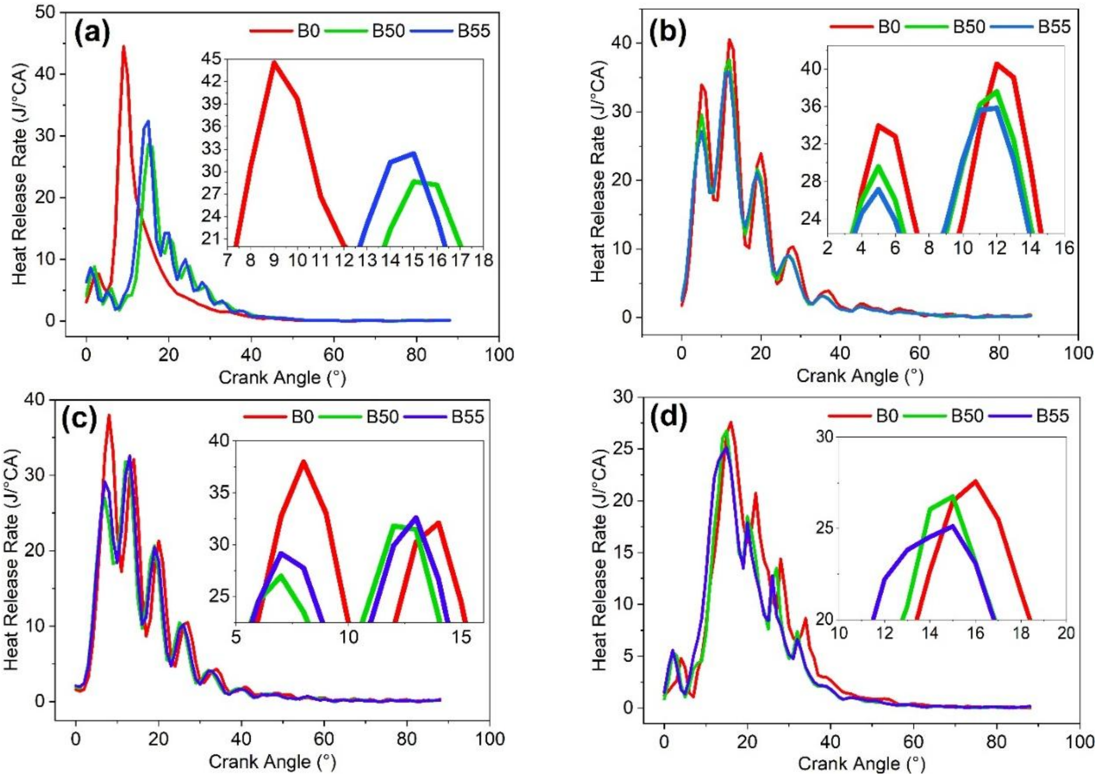

Fig. 3. Heat release rate comparison at (a) 1500, (b) 2000, (c) 2500, and (d) 3000 rpm

Table 4 shows the engine speed effect on CPmax and HRRmax. Generally, B0 has a higher maximum CP and HRR compared to B50 and B55. The differences in pressure among the fuels remain relatively small, even at high engine speeds. Ge *et al.* [48] found that the fuel combustion process is improved as engine speed increases, which is indicated by cylinder wall temperature increase that leads to an improved charging temperature during injection and the shortening of ignition delay, resulting in high CPmax [19]. Besides that, total combustion duration per minute gradually increases along with higher engine speed, where more fuel is injected into the cylinder, resulting in higher CPmax and engine power output at higher engine speed [49]. The maximum value of HRR for each test fuel gradually decreases with the increase of engine speed, and the location of the max HRR occurs away from the top dead center (TDC), except for B0, which fluctuates between engine speed variations. However, B0 demonstrates the highest max HRR at 44.5 J/°CA within 1500 rpm. In addition, for each test fuel, the amplitude of the crankshaft angle corresponding to HRR increases gradually with the increase in engine speed [50]. Biswakarma *et al*. [51] found that the HRR of waste cooking oil biodiesel is decreased as engine speed increases; this reduction is attributed to limited time for fuel and air mixing, resulting in shorter combustion duration.

Table 4. Effect of engine speed on CPmax and HRRmax

Fuel Type	CPmax (bar)				HRRmax (J/°CA)			
	1500rpm	2000rpm	2500rpm	3000rpm	1500rpm	2000rpm	2500rpm	3000rpm
B0	52.87	59.62	64.86	74.6	44.5	40.52	37.96	27.57
B50	52.37	59.5	63.81	73.03	28.65	37.58	31.79	26.75
B55	52.05	58.88	64.13	72.69	32.41	35.82	32.6	25.11

3. *Performance*

Based on Figure 4a, B0 exhibits the highest peak torque, reaching nearly 180 Nm in the 2000–2500 rpm range. A higher proportion of biodiesel in the fuel blend tends to reduce torque [52]. Biodiesel and its blends tend to lower engine torque due to their lower calorific value than conventional diesel, reducing combustion energy [27], while biodiesel with high viscosity and density reduces effective brake power and torque by increasing the momentum of the air-fuel mixture, which deepens penetration into the cylinder. The high surface tension also inhibits optimal atomization during injections, causing incomplete combustion that leads to diminished combustion efficiency, which ultimately reduces engine torque [27]. On the other hand, B50 and B55 show more consistent and evenly distributed torque characteristics across the rpm range due to their higher cetane index, although their maximum torque is lower than that of B0. Higher engine speed positively correlates with shorter combustion duration [51]. HRRmax significantly reduced at 3000rpm (Table 3), which was followed by a decrease in torque due to insufficient heat energy.

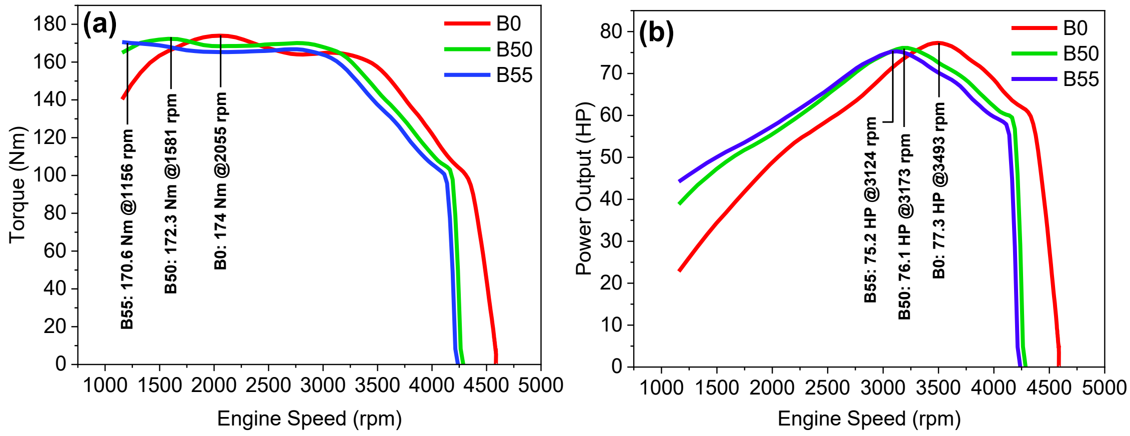

Fig. 4. Engine (a) Torque and (b) Power output comparison of B0, B50, and B55

Power output of every test fuel increases with engine speed (Figure 4b). Peak output power occurs around 3200–3400 rpm. B50 and B55 fuels produce higher power at lower engine speeds (<2500 rpm), compared to B0. This indicates that biodiesel blends exhibit more efficient combustion at low to mid-range engine speeds. Similar results were observed by several studies [53], [54], where peak torque and power of biodiesel occur at slightly lower engine speed compared to fossil diesel, that phenomenon might be linked with higher CI of biodiesel which enhances the initial combustion process and reduces ignition delay [25], [55]. However, B0 outperforms the diesel/biodiesel blends at peak power at 80.6 HP. Lozano *et al*. [56] found that Fossil diesel showed higher total enthalpy generation than biodiesel, resulting in higher adiabatic flame temperature. Meanwhile, biodiesel contains less carbon and hydrogen, which reduces the power generation of this fuel, as indicated by a lower ΔH of combustion due to the oxygen-functional group in FA that reduces the generated heat during the combustion process, ultimately decreasing its overall torque and power [37]. Under high load and high-speed conditions, B0 has higher cylinder pressure resulting in high power output, due to its lower oxygen content and higher calorific value compared to biodiesel [40]. Therefore, B50 and B55 perform better at low to mid-range rpms, making them suitable for low-end torque applications, whereas B0 excels in peak power output at higher rpms. Significant power drop occurs beyond 4000 rpm due to lack of torque, with B0 showing the steepest decline, while B50 and B55 tend to decrease more gradually because of the prolonged combustion effect from biodiesel [57].

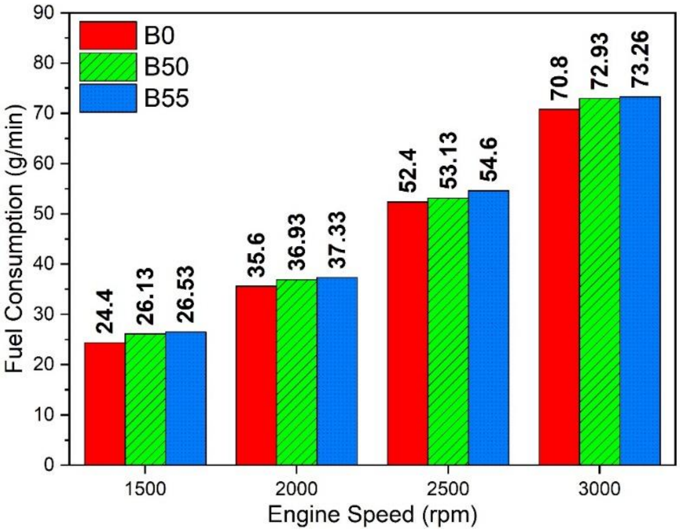

Fig. 5. Fuel consumption comparison under various engine speeds

Fuel consumption (FC) rises proportionally with increasing engine speed (Figure 5). Generally, a diesel/biodiesel blend has a greater FC compared to B0 [58]. This is due to the lower calorific value of biodiesel compared to pure diesel, which means more biodiesel fuel must be burned to achieve the same power output of B0 [44]. Energy per mole of biodiesel is relatively lower compared to fossil diesel. A major component of palm oil biodiesel is palmitic acid [32]; its methyl ester form ($C_{16}H_{32}O_2$) has an energy of 2384.7 kcal/mol [59], [60]. Fossil diesel comparable component is n-Hexadecane ($C_{16}H_{34}$) with an energy of 2557.67 kcal/mol [37], which signifies higher fuel consumption in biodiesel. This phenomenon also explains why a longer ester chain has more calorific value compared to its shorter counterpart. High density and viscosity of palm oil biodiesel worsen the fuel consumption, where high viscosity causes poor atomization and incomplete combustion, as well as greater mass per injection volume due to biodiesel's high density, which also negatively affects FC. However, a high cetane index can lower FC by shortening the combustion delay. Nevertheless, the differences between B0 and diesel/biodiesel blend remain within a reasonable range, generally at 2-25% due to biodiesel's lower energy density [27]. Higher engine speed enhances air-fuel mixing due to greater turbulence inside the cylinder. However, engine speed increase negatively affects FC due to shorter time available for heat transfer, which also reduces brake thermal efficiency [51].

4. *Emission*

Figure 6 shows the effect of fuel type and engine speed on smoke opacity values. Generally, B0 has the highest smoke emission across all engine speed ranges. In contrast, diesel/biodiesel blend emits lower smoke compared to B0. Smoke formation usually occurs in fuel-rich areas at high temperatures without sufficient oxygen concentration. Fuels containing hydrocarbons undergo pyrolysis in a high-temperature and anoxic environment inside the cylinder, which will produce soot precursors as well as unsaturated hydrocarbons, polyacetylene, and polycyclic aromatic hydrocarbons [61]. Biodiesel significantly reduces smoke opacity compared to diesel due to its oxygen content, which improves combustion completeness. The main factors affecting PM emissions include ester chain length (C18:0 > C16:0 > C12:0) and saturation rate (C18:1 < C18:0), which act as soot precursor [62]. Higher cetane index reduces smoke and soot formation through shortening of ignition delays that minimize rich zones [61]. B50 and B55 have a higher cetane index and oxygen content compared to B0 [63], which explains reduced smoke emission in all engine speed ranges.

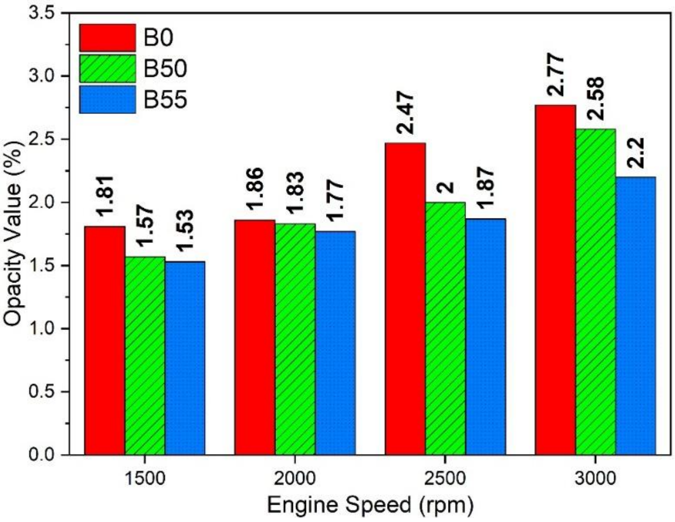

Fig. 6. Smoke Opacities of B0, B50, and B55

Table 5 shows a comparison of various high-composition biodiesel blends. CPmax and HRRmax are negatively affected when biodiesel blend is used. However, argemone and jatropha biodiesel blends have higher CPmax and HRRmax compared to fossil diesel. Those phenomena might be correlated with low viscosity and densities of argemone (3.9mm^2/s; 856kg/m^3) and jatropha (3.51 mm^2/s; 843.5 kg/m^3). Every biodiesel feedstock has unique FA that affects its physicochemical properties. Viscosity is influenced by carbon chain length, degree of unsaturation, number and position of double bonds of methyl esters, and operational temperature [28]. While density is dependent on the FA composition and purity of the biodiesel [64]. High viscosity and density negatively affect injected fuel atomization, which leads to clogged injectors and seized piston rings [65]. Wang *et al.* [66] reported that the high viscosity of biodiesel leads to a small spray angle, poor spray atomization and air entrainment, longer injection delay, and spray tip penetration. Ultimately reduces CPmax and HRRmax. Low calorific values of *Vateria indica* methyl ester blend (38.17MJ/kg) resulting in the lowest HRRmax.

Table 5. A summary and comparison of the current results with those from previous publications

Ref	Fuel Type	CPmax (bar)		HRRmax (J/°CA)		Torque (Nm)		Power (HP)		FC (g/min)		Emission (Smoke Opacity%)	
		1500 rpm	2000 rpm	1500 rpm	2000 rpm	1500 rpm	2000 rpm	1500 rpm	2000 rpm	1500 rpm	2000 rpm	1500 rpm	2000 rpm
This Study	B0	52.9	59.6	44.5	40.52	163.3	174	34.3	50.2	24.4	35.6	1.81	1.86
	B50	52.4	59.5	28.7	37.58	171.9	168.4	47.2	56.5	26.13	36.93	1.57	1.83
	B55	52.1	58.9	32.4	35.82	168.9	165.3	50	58.3	26.53	37.33	1.53	1.77
[16]	B0	-	106.5	-	73	-	-	-	-	-	0.235 kg/kWh	-	7.25 HSU
	B50 (Argemone biodiesel)	-	107	-	77.5	-	-	-	-	-	0.245 kg/kWh	-	7.45 HSU
[17]	B0	60	-	24.5	-	-	-	-	-	12 MJ/kWh	-	42.5	-
	B50 (*Vateria indica* methyl ester)	52.5	-	15.2	-	-	-	-	-	13 MJ/kWh	-	34.5	-
[69]	B0	72	-	115 kJ/m³	-	-	-	-	-	0.32 kg/kWh	-	-	-
	B50 (Karanja biodiesel)	71	-	110 kJ/m³	-	-	-	-	-	0.337 kg/kWh	-	-	-
[19]	B0	54	55	-	-	18.4	21.2	3.9	6.1	0.375 kg/kW.hr	0.395 kg/kW.hr	-	-
	B50 (Jatropha oil biodiesel)	61	62	-	-	17.5	19.6	3.7	5.6	0.415 kg/kW.hr	0.47 kg/kW.hr	-	-
[18]	B0	61	-	54	-	-	-	-	-	-	-	-	-
	B55 (Soybean Methyl Ester)	59	-	44	-	-	-	-	-	-	-	-	-

Engine torque and power output are generally reduced as biodiesel blend is used, which is attributed to the low calorific value. Jatropha biodiesel blends have very small engine torque and power output due to different types of engines (1-cylinder; 582cm^3). FC of biodiesel blend is mostly higher due to higher density compared to fossil diesel. Biodiesel blend emissions mainly decreased due to the high cetane index and oxygen content that inhibited its formation soot [27].

Based on a comparison with previous research, viscosity and density of biodiesel palm oil blends can be improved to increase CPmax and HRRmax values by adding oxygenate and non-oxygenate additives, or modifying the fuel injection system with preheaters. This is proposed solution to reduce the density and viscosity of biodiesel mixtures [17], [67], [68].

V. Conclusions

The comparative analysis of diesel and diesel/biodiesel fuel reveals distinct changes in physicochemical properties, combustion characteristics, engine performance, and emissions. Biodiesel blends exhibit higher density (B55 = 855.9 kg/m³ and B0 = 833.1 kg/m³), kinematic viscosity (B55 = 5.1 mm²/s and B0 = 4.69 mm²/s), and cetane index (B55 = 58 and B0 = 48). However, the calorific value has decreased (B55 = 48.73 MJ/kg and B0 = 59.79 MJ/kg), which leads to increased fuel consumption. Combustion analysis indicates that B0 generates higher peak cylinder pressure and heat release rate due to its higher calorific value, while biodiesel blends exhibit earlier combustion, which indicates reduced ignition delay, while soot emissions are decreased due to higher oxygenated compounds and cetane number. Based on performance test, B0 generates the highest torque (180 Nm) and peak power (80.6 HP) at high engine speeds, whereas B50 and B55 improve low-rpm combustion efficiency due to shorter ignition delay. Consequently, biodiesel blends are advantageous for soot reduction and low-speed applications due to their bound-oxygen content, whereas B0 remains optimal for high-power demands, highlighting a trade-off between performance and emission that depends on engine operational requirements. To enhance its viability as a fuel, the viscosity and density of biodiesel are required to be comparable with those of fossil diesel, through the use of additives or the application of fuel preheating.

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