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## **Abstract:**

Biodiesels from coconut and palm cooking oil are viable alternatives to diesel fuel due to their environmental sustainability and similar physicochemical properties compared to diesel. In the present study, these fuels were tested separately in a diesel engine by blending with fossil diesel in proportions of 10%, 20%, 30% and 40% by volume. Experiments were conducted under a constant brake mean effective pressure (BMEP) of 400 kPa and at 2000 rpm. The results revealed similarities in engine performance, emissions, combustion and engine block vibration for used palm cooking oil methyl ester (UPME) fuel blends and coconut methyl ester (CME) fuel blends. Most blends resulted in slight improvements in brake specific energy consumption (BSEC) and brake thermal efficiency (BTE). A maximum reduction of 54%, 89% and 16.8% in pollutant emissions of brake specific hydrocarbons (BSHC), brake specific carbon monoxide (BSCO) and brake specific nitrogen oxides (BSNOx), respectively, was observed with UPME and CME in the blends. The cylinder pressure profiles when UPME-diesel and CME-diesel blends were used were comparable to a standard diesel pressure trace, however, some deviations in peak pressure were also noticed. It was also apparent from the results that engine vibration was influenced by the type of methyl ester used and its blend composition. Notably, the rate of pressure increase was maintained within an acceptable limit when the engine was fueled with both of the methyl ester blends.

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Article

# Performance, Emissions, Combustion and Vibration Analysis of a CI Engine Fueled with Coconut and Used Palm Cooking Oil Methyl Ester

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**Abstract:** Biodiesels from coconut and palm cooking oil are viable alternatives to diesel fuel due to their environmental sustainability and similar physicochemical properties compared to diesel. In the present study, these fuels were tested separately in a diesel engine by blending with fossil diesel in proportions of 10%, 20%, 30% and 40% by volume. Experiments were conducted under a constant brake mean effective pressure (BMEP) of 400 kPa and at 2000 rpm. The results revealed similarities in engine performance, emissions, combustion and engine block vibration for used palm cooking oil methyl ester (UPME) fuel blends and coconut methyl ester (CME) fuel blends. Most blends resulted in slight improvements in brake specific energy consumption (BSEC) and brake thermal efficiency (BTE). A maximum reduction of 54%, 89% and 16.8% in pollutant emissions of brake specific hydrocarbons (BSHC), brake specific carbon monoxide (BSCO) and brake specific nitrogen oxides (BSNO<sub>x</sub>), respectively, was observed with UPME and CME in the blends. The cylinder pressure profiles when UPME-diesel and CME-diesel blends were used were comparable to a standard diesel pressure trace, however, some deviations in peak pressure were also noticed. It was also apparent from the results that engine vibration was influenced by the type of methyl ester used and its blend composition. Notably, the rate of pressure increase was maintained within an acceptable limit when the engine was fueled with both of the methyl ester blends.

**Keywords:** non-edible oil; combustion; vibration; coconut; waste cooking oil; emissions

## 1. Introduction

The rapid increase in population, development and industrialization growth over the last century has led to a concurrent rise in global energy demand. Currently, non-renewable energy source like fossil fuels are still the backbone of human activities. Unfortunately, these resources are estimated to diminish in less than ten decades [1]. This scenario has initiated worldwide alarm with regard to energy security and the need to avoid prolonged reliance on limited fossil fuels. Another undeniable fact is

that the world population today is threatened by climate change, global warming and pollutions. Since transportation has been identified as the largest source and contributing more than 25% of greenhouse gases (GHG) and pollutant emissions, reducing exhaust emissions from engines has become one way of moving towards a cleaner environment [2]. As a consequence, stringent engine emission standards have been issued and enforced in countries all around the world, thus imposing a challenge to automobile manufacturers and researchers to come up with solutions for both environmental pollution and oil shortage issues.

One of the many proposed solutions over the past decades is the use of biofuel as a replacement for fossil fuels. Biofuels, mostly derived from plants and animal fats, are one of the most prominent alternative energy resources that have been introduced as a replacement of diesel. Fatty acid methyl ester (FAME) is one form of biodiesel derived through a reversible transesterification process that converts triglycerides in oil into ester and glycerol. Biodiesel is a non-toxic, clean, biodegradable and carbon neutral fuel that can be readily used in modern diesel engines with little or no alteration [3,4]. Applying biodiesel blends as a diesel engine fuel has been reported to have benefits, especially in engine emissions. Biodiesel blends generally exhibit comparable engine performance in terms of brake thermal efficiency (BTE) and brake power when compared to pure diesel [5,6]. Substantial reductions in harmful emissions such as carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), unburned hydrocarbon (HC), and particulate matter (PM) were found in engines fueled with biodiesel blends [7].

However, overall, small drawbacks with regard to fuel consumption have been reported when biodiesel is used due to the lower heating value and a marginal increase in nitrogen oxide (NO<sub>x</sub>) emission [8,9]. The rise in NO<sub>x</sub> may not be solely caused by changes in a single fuel property, instead, it is more likely to be due to the effect of coupled mechanisms. The mechanisms of NO<sub>x</sub> formation tend to strengthen or terminate one another under various combustion conditions, and they also depend on the fuel properties such as the degree of unsaturation of the fatty acids [10,11]. Besides, the physicochemical properties of biodiesel vary with its fatty acid composition and are considerably different compared to standard diesel. These properties include the fuel density, kinematic viscosity, flash point, heating value and cold filter plugging point. Since fuel combustion traits such as ignition delay, cylinder pressure and heat release rate are strongly associated with fuel properties, dissimilarities arise in the resultant combustion characteristics when biodiesel is employed in diesel engines [12].

Coconut oil is a first-generation biofuel usually derived from the edible flesh of *Cocos nucifera* (copra) that is widely available in Asian coastal areas. Generally, CME exhibits advantageous properties in terms of its cold flow properties such as a lower cloud point and pour point because it consists of mainly short saturated fatty acid chains compared to biodiesels from other feedstocks. Also, CME demonstrates a relatively higher cetane index and oxidation stability due to its chemical composition, which results in superior fuel flammability that persists in the longer term [13,14]

Suryawanshi employed CME produced through the transesterification process in a compression ignition (CI) engine. The density and viscosity were found to be very close to those of diesel despite a higher flash point was observed. The use of the CME showed similarities in BTE, brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) when compared to using diesel only. The author also observed a significant decrease in smoke, HC and CO<sub>2</sub> along with comparable NO<sub>x</sub> emission levels [15]. Nakpong et al. investigated biodiesel processed from high free fatty acid coconut oil by two-step transesterification. They revealed the potential of the low cost coconut oil as biodiesel feedstock, and the biodiesel product offered high oxidative stability and viscosity similar to diesel [16].

In an investigation of the diesel combustion traits of esters based on coconut oil, palm oil and rapeseed oil, Kinoshita et al. showed that CME was a more favorable alternative for diesel fuel than other biodiesels. CME was found to have similar thermal efficiency and superior volatility compared to other biodiesels and achieved the most reduction in HC, smoke and CO emissions [17]. A study conducted by Yusuke et al. also revealed improved ignition timing for engine cold starts when early increases in combustion chamber wall temperature were noticed with the use of CME. The authors pointed out the potential of CME as an alternative for diesel as it exhibited superior compression ignition characteristics and a reduction in exhaust gas emissions [18].

Biodiesel production from edible feedstocks has been the subject of controversy and debate since it affects human food resources and causes surges in food prices due to increasing demands. Hence, biodiesel production from non-edible feedstocks such as *Calophyllum inophyllum*, *Ceiba pentandra*, *Karanja* and *Jatropha curcas* have been proposed and studied by many researchers. On the other hand, some researchers have also proposed the utilization of waste oils as biodiesel feedstocks.

Producing third-generation biodiesel from waste cooking oil is a very effective solution for waste oil disposal problem, and hence, waste cooking oil biodiesel production is highly recommended to resolve water or agricultural land shortage issues. Moreover, it does not interfere with food supplies and can be done at relatively low cost since it requires no land or water use [19–21]. Even though production of methyl esters from waste cooking oil involves pretreatment processes to remove debris in the oil, the overall cost of the used cooking oil biodiesel production is to 45% lower than direct biodiesel production from virgin oils [22]. Nonetheless, the biodiesel properties of used palm cooking oil methyl ester (UPME) are usually influenced by the quality of its stock, that is, the condition of the fresh waste cooking oil.

Attia and Hassaneen investigated diesel engine performance and emissions with waste cooking oil (WCO) blends. The authors concluded that best fuel economy was achieved with 10% WCO, while best emissions resulted from blends with 30–50% WCO. Simultaneous lower CO, HC, NO<sub>x</sub> and EGT can be achieved with the expenses of higher HC and fuel consumption when the recommended blend ratios were used [23]. Hwang et al. also studied WCO biodiesel in a direct injection (DI) diesel engine. The researchers noticed a slight reduction in peak in-cylinder pressure and longer injection delay for WCO biodiesel due to its lower heating value and higher viscosity. WCO biodiesel also exhibited reduced flame luminosity and visible flame duration. In short, advantages with regard to CO, HC and smoke emissions were recorded with the use of WCO biodiesel [24].

On the other hand, Abed et al. researched diesel engine performance and emissions using waste cooking oil biodiesel with variable load conditions. The authors observed an increased exhaust gas temperature for the biodiesel compared to the unadulterated diesel. They recorded benefits in CO, smoke and HC despite higher CO<sub>2</sub> and NO<sub>x</sub> [25]. Next, a study by Anand et al. revealed generally similar combustion characteristics for WCO-diesel blends. Lower peaks in the heat release rate and cylinder pressure were observed for WCO blends when compared to diesel [21]. Besides, Muralidharan et al. conducted performance, emission and combustion traits analyses with blends of palm methyl ester (PME) and diesel at various compression ratios. The biodiesel blend ratio, engine load and compression ratio were identified as influential parameters in the engine performance and combustion. The authors also found reductions in CO and HC but with increased NO<sub>x</sub> emission when PME-diesel blends were employed. The B40 blend was reported to give the maximum thermal efficiency [26].

Zareh et al. performed an analysis on the uses of castor-, CME- and WCO-based biodiesels in a turbocharged direct injection diesel engine. The authors found notable reductions in CO, CO<sub>2</sub> and PM, increased brake specific fuel consumption (BSFC) and NO<sub>x</sub> with lower output brake power with biodiesel blends. They reported that favorable performances and emissions were achieved with blends of diesel with either WCO or CME. The performance and emission results with CME blends and WCO blends were generally comparable and they varied under different engine speeds and loads [27].

### *Purpose of Study*

Currently, the main challenges to further utilization of biodiesel in transportation is the economic viability and availability of raw materials for fuel production. Many researchers have reported that the raw materials account for nearly 60–80% of the total cost of biodiesel production [28–30]. As a consequence, the cost of raw materials must be carefully considered as the cost directly affects the production feasibility and final selling price of biodiesel. Recently, many studies have suggested that the cost of biodiesel production could be lower by using waste as well as improving the quality of the environment. Therefore, to support this initiative, this paper focused on the utilization of used palm cooking oil as the raw material for biodiesel production. Another motivation was that

most of the previous studies conducted on used palm cooking oil and coconut oil biodiesel have mainly concentrated on engine performance and the fuel emission characteristics. Additionally, the research on combustion characteristics on both biodiesels when blended at different proportions with diesel is still insufficient, and there is also a lack of research on engine vibration using CME and UPME. Thus, the main aim of this study was to undertake a comprehensive investigation of a single-cylinder, water-cooled direct injection diesel engine fueled with UPME-diesel and CME-diesel blends. Tests including factors ranging from engine performance, emissions, combustion to vibration characteristics were carried out and analyzed in an effort to understand the impact of the fuels on the engine.

## 2. Experimental Methods

### 2.1. Test Fuels and Engine Operating Conditions

In the existing study, the UPME and CME were purchased from local commercial suppliers. The UPME used in this study was manufactured through a transesterification process that used palm-based cooking oil collected from the food industry. The physiochemical fuel properties of the neat UPME, CME, diesel and the methyl ester-diesel fuel blends are shown in Tables 1 and 2. The UPME and CME fuels were selected to represent a moderate to high level composition of saturated-unsaturated fatty acids with ratios of 46.1:53.9 and 86.8:13.2, respectively.

**Table 1.** Physiochemical properties of the methyl ester and diesel fuel.

Properties	Test Method	Diesel	UPME	CME
Carbon chain length distribution (wt. %)				
C 8:0	Gas Chromatograph-Flame Ionization detector (GC-FID)	-	<0.01	10.56
C 10:0		-	<0.01	8.38
C 12:0		-	0.69	43.11
Saturated fatty acid C 14:0		-	1.35	14.01
C 16:0		-	38.91	7.86
C 18:0		-	4.75	2.84
C 20:0		-	0.4	<0.01
Monounsaturated fatty acid				
C 16:1		-	0.48	<0.01
C 18:1		-	42.27	9.7
Polyunsaturated fatty acid				
C 18:2		-	10.42	3.51
C 18:3		-	0.76	<0.01
Fatty acid saturation/unsaturation ratio (wt. %/wt. %)		-	46.1/53.9	86.8/13.2
Cetane index	ASTM D976	52	59	56
Flash point, °C	ASTM D93	92	184	162
Density (40 °C), kg/m <sup>3</sup>	ASTM D7042	838.4	862.35	880.5
Kinematic viscosity (40 °C), mm <sup>2</sup> /s	ASTM D7042	3.815	5.199	6.692
Heating value, MJ/kg	ASTM D4809	45.31	39.74	37.85

**Table 2.** The properties of methyl ester-diesel fuel blends.

Property	Units	UPME				CME				Test Method
		B10	B20	B30	B40	B10	B20	B30	B40	
Heating value	MJ/kg	44.82	44.14	43.59	42.94	44.39	43.73	42.96	42.20	ASTM D4809
Kinematic viscosity (40 °C)	mm <sup>2</sup> /s	3.971	3.916	4.100	4.337	4.176	4.372	4.616	4.860	ASTM D7042
Dynamic viscosity (40 °C)	mPa·s	3.331	3.293	3.461	3.676	3.513	3.701	3.937	4.163	ASTM D7042
Density (40 °C)	kg/m <sup>3</sup>	838.7	841.1	844.1	847.5	841.3	846.5	852.8	856.6	ASTM D7042

The diesel engine's speed was kept at a constant 2000 rpm and it experienced a constant load as brake mean effective pressure (BMEP) of 400 kPa. Initially, the diesel fuel was prepared as a standard for evaluation. Then, blends of diesel and methyl ester with 10%, 20%, 30% and 40% by volume of

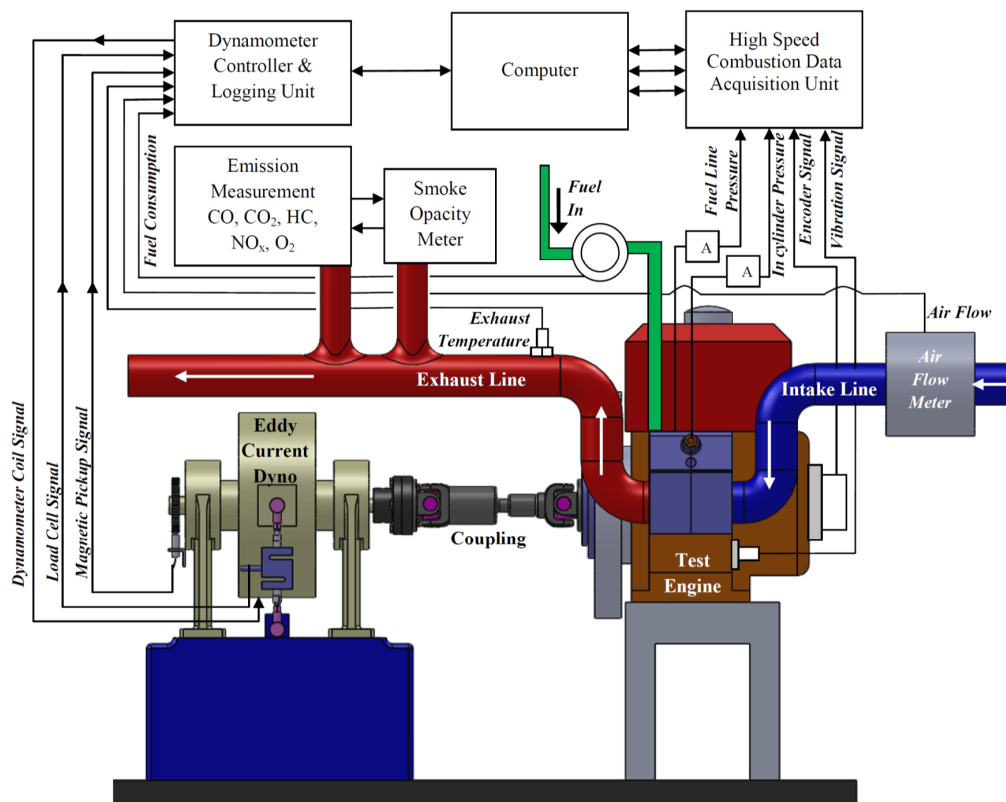
UPME and CME were used and named as B10, B20, B30 and B40, respectively. Hence, a total of nine types of fuel including neat diesel fuel were prepared and evaluated. During the test of the engine fueled with methyl ester fuel blends, the engine was run at a room temperature of 25 °C and pressure of 1 atm, and the engine worked well until the end of the test. Notably, no changes were made to the diesel engine although different fuel blends were used in this study. The exhaust gas temperature was warmed up adequately and the water coolant temperature was appropriately maintained throughout the test under steady-state condition. The readings were taken twice for each test in order to obtain an accurate and precise average value.

## 2.2. Test Engine

The tests were performed in a single-cylinder, four-stroke direct injection compression ignition engine. The test engine specifications are listed in Table 3. The fuel was injected with 196 bar pressure and was timed at 17 °BTDC (degree before top dead center). The experimental setup in the present study is illustrated in Figure 1.

**Table 3.** Engine specifications.

Parameter	Specification
Engine model	Single cylinder, water cooled 4-stroke DI diesel
Bore	92 mm
Stroke	96 mm
Displacement	638 cm <sup>3</sup>
Compression Ratio	17.7:1
Continuous Rating Output	10.5 hp @ 2400 rpm
1-Hour Rating Output	12.0 hp @ 2400 rpm
Injection Timing	17 °BTDC
Injection Pressure	196 bar or 200 kg/cm <sup>2</sup>
Connecting Rod Length	149.5 mm



**Figure 1.** Schematic representation of the test rig. Note: “A” indicates the item is a charge amplifier.

### 2.3. Test Bed Configuration and Instrumentation

The engine load applied was controlled by using the SAJ SE-20 model 20 kW eddy current dynamometer. An air flow meter with a range of 50 CFM (cubic feet per min) and a K-type thermocouple were also employed for the measurement of the intake airflow and the exhaust gas temperature, respectively. The fuel flow rate was measured with a DOM-A05H flow meter that connected to a ZOD-Z3 flow rate totalizer. Multiple sensors were installed for this test, such as the Kistler 6125B pressure sensor for the measurement of in-cylinder gas pressure. The signal was captured and amplified by a Kistler 5041 charge amplifier. For the identification of the position of crank angle, a 632-00685-1 Leine & Linde incremental encoder was employed. Furthermore, a PCB 108A02 dynamic pressure sensor and a PCB 480E09 signal conditioner were installed for the measurement of the fuel injection pressure and signal conditioning purpose.

A generic piezoelectric type of automotive knock sensor with a calibration specification of nominal sensitivity of 25.11 mV/g and dynamic range of 50 g was used to measure the engine vibration signals. The calibration was carried out following the Singapore Test Services (STS) in-house calibration procedure T-WI-CMD-004-16. The knock sensor was set horizontally on the side wall of the engine block for measuring vibration in the lateral axis and was firmly fixed by means of an M-8 through-hole mounting bolt. Moreover, the sensors were connected to a computer with an ADLink DAQe-2010 simultaneous sampling data acquisition card. The mean pressure data was obtained from 100 consecutive combustion cycles to minimize the variation between every cycle. The noise effects were lowered with the aid of Savitzky-Golay smoothing filtering. The pressure data, combustion parameters as well as the vibration data was analyzed using the MATLAB software. The engine-out emissions were measured using the AVL DICOM 4000 5-gas analyzer and AVL DiSmoke 4000 smoke analyzer. The details of the instruments used are as shown in Table 4.

**Table 4.** Measuring components, ranges and resolution of the AVL DICOM 4000 gas analyzer and DiSmoke 4000 smoke analyzer.

Equipment	Measurement Principle	Component	Measurement Range	Resolution
Gas analyzer	Non-dispersive infrared	Carbon monoxide (CO)	0–10% Vol.	0.01% Vol.
	Non-dispersive infrared	Unburned hydrocarbon (HC)	0–20,000 ppm Vol.	1 ppm
	Electrochemical	Nitrogen oxides (NO <sub>x</sub> )	0–5000 ppm Vol.	1 ppm
	Electrochemical	Oxygen (O <sub>2</sub> )	0–25% Vol.	0.01% Vol.
	Calculation	Excess air ratio ( $\lambda$ )	0–9999	0.001
Smoke opacimeter	Photodiode detector	Opacity (%)	0–100%	0.10%

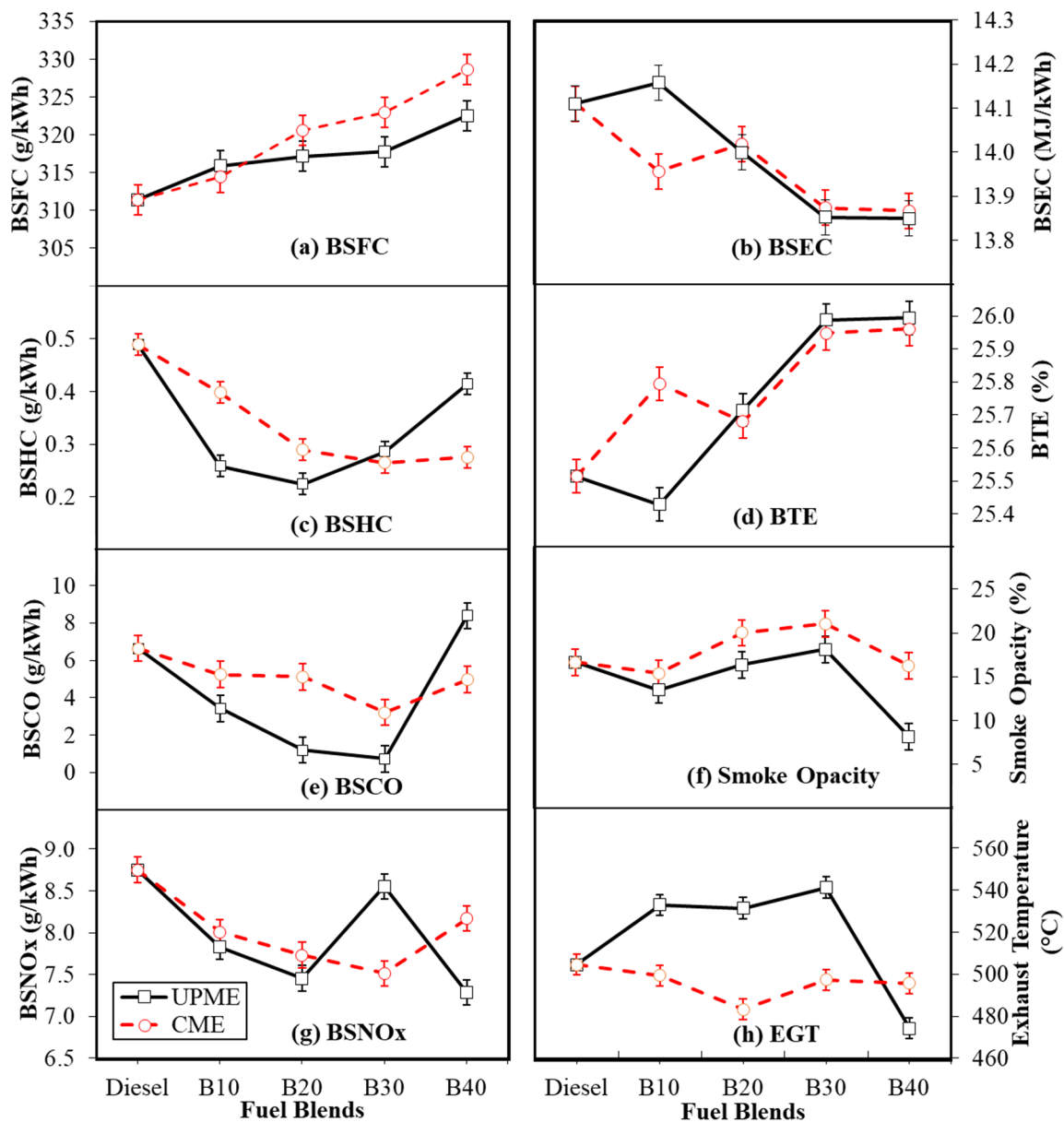
## 3. Results and Discussion

### 3.1. Engine Performance Characteristics

#### 3.1.1. Brake Specific Fuel Consumption

Generally, brake specific fuel consumption is the ratio of the mass flow rate of fuel to the brake power output. The BSFC for UPME and CME at various blend proportions with reference to the standard diesel is depicted in Figure 2a. Based on the results obtained, it is clear that all the UPME and CME fuel blends exhibit larger BSFC when compared to standard diesel. With UPME fuel blends, the BSFC showed a similar trend to that when CME fuel blends were used. The BSFC of B10, B20, B30 and B40 with respect to diesel fuel increased by 1.4%, 1.8%, 2.0% and 3.6% for UPME and 1.0%, 2.9%, 3.7% and 5.5% for CME, respectively. Interestingly, the higher the blend fraction of biodiesel, the greater the BSFC. As shown in Table 2, the heating value decreased with the biodiesel blend fraction. Therefore, more fuel is consumed when the heating value drops in order to produce the same amount of torque for higher-level blends [31]. Also, the variation in BSFC was more prominent and higher for

CME fuel blends compared with the UPME fuel blends, except for B10. This may be caused by the lower density of the UPME fuel blends, thus less fuel is needed due to the lower mass flow rate [32].



**Figure 2.** Performance and emission characteristics of various fuel blends compared with diesel fuel.

The results obtained were in alignment with other research done by many authors. A similar study was done by Abed et al. on engine performance when using WCO biodiesel. They concluded that all the blends of WCO biodiesel increased the specific fuel consumption with respect to the standard diesel at all engine loads. Also, the greater the WCO biodiesel blend fraction, the larger the specific fuel consumption [25]. Furthermore, Zareh et al. conducted a study to evaluate engine performance and exhaust emissions using three different biodiesels from castor oil, coconut oil and used palm cooking oil. They found that the used palm cooking oil biodiesel had slightly lower specific fuel consumption as compared to the coconut oil biodiesel [27]. In addition, this situation aligns with the research carried out by B. Tesfa et al. on the performance of a diesel engine for biodiesel from rapeseed oil, waste oil and corn oil. It was reported that the variation in BSFC between the biodiesels was negligible.



Moreover, the BSFC of rapeseed oil biodiesel increased with the increment in the biodiesel blend ratio at low engine load [33].

### 3.1.2. Brake Specific Energy Consumption

The brake specific energy consumption of a fuel is the product of the BSFC and the heating value of the fuel. Generally, the BSEC drops with the elevation in the efficiency of energy consumption. Figure 2b represents the BSEC of the engine fueled with UPME and CME at various blend ratios. The BSEC value had a tendency to stabilize with higher methyl ester content in the fuel blends. Specifically, the BSEC declined with the increment in the biodiesel blend percentage as compared to the standard diesel. How et al. obtained similar results when they investigated engine performance using coconut oil biodiesel. Their results showed that the BSEC of all blends of coconut biodiesel was lowered with respect to that of standard diesel, which was probably because of the more complete combustion process that is dominated by the rich oxygen molecules in the biodiesel [34].

In Figure 2b, it can be observed that B40 of the UPME blend and CME blend shows the lowest BSEC of 13.85 MJ/kWh and 13.87 MJ/kWh, respectively. This phenomenon may be explained by the higher cetane index of the biodiesel as shown in Table 1, which enhances the combustion process and consequently consumes less energy [32]. Also, the UPME has a higher cetane index compared to the CME. This characteristic may explain the fact that the UPME fuel blends have lower BSEC than the CME fuel blends at all blend ratios, except for B10. The UPME B10 fuel blend demonstrated the highest BSEC among all the tested fuels. This situation aligns with the BSFC of the UPME B10 fuel blend, which has higher fuel consumption than the CME at the same blend ratio.

### 3.1.3. Brake Thermal Efficiency

Engine BTE is dominated by two important parameters, the mechanical efficiency and the net indicated thermal efficiency. To be specific, it can be obtained by dividing the total energy output of the engine by the total energy input delivered to the system [35].

The variations in BTE are shown in Figure 2d for all the fuels. In general, it was observed that the BTE was slightly enhanced with the UPME-enriched blends. The BTE achieved by UPME blends was consistently greater than that for diesel fuel, except for UPME B10. Similarly, all blend ratios of CME fuel showed higher BTE than standard diesel fuel. This improving trend may be due to the richer fuel-bound oxygen molecules in all methyl ester fuel blends, which enhance the combustion efficiency and this results in higher BTE [36]. This result is in agreement with results from research conducted by Man et al. on blends of used palm cooking oil biodiesel. They observed that the BTE was raised when biodiesel was employed as a consequence of richer oxygen content and greater lubricity [37].

Furthermore, another interesting observation found for this test was that at lower methyl ester blend fractions such as CME B10, the BTE was found to be larger than that for UPME B10. This can be caused by the relatively lower energy consumption of CME B10 as compared to UPME B10 discussed previously. Thus, less fuel was consumed and the BTE was improved [38]. In addition, it was also observed that the BTEs were generally higher with larger blend ratios of the biodiesels. For instance, the B40 blends resulted in the highest BTE of 26.0% for both the UPME and CME fuels. This may be explained because the lowest BSEC was attained by B40 blends for both tested fuels as discussed previously.

## 3.2. Exhaust Emissions Characteristics

The combustion of fuel in engines results in HC, CO, NO<sub>x</sub> emissions and soot. These pollutants cause air pollution that has various detrimental effects on human health.

### 3.2.1. Brake Specific Hydrocarbon

As can be seen in Figure 2c, in general, the addition of methyl ester to the fuel blends reduced brake specific hydrocarbon emissions. This suggests that the addition of oxygenated fuels leads to

partial mitigation of HC formation via locally over-rich mixtures [39]. The higher density of the used palm cooking oil biodiesel could be another possible reason for this phenomenon since it improves the air-fuel mixture, resulting in higher fuel consumption and consequently, more soot formation [40]. In a similar study by J. Hwang et al., the researchers found that HC emission for biodiesel was lower than the diesel fuel due to the richer oxygen content in the biodiesel, which promoted a cleaner combustion process [24]. Similar results were also obtained by Habibullah et al. [41].

The greatest reduction in BSHC emission that we recorded was 54% and 45.8% for UPME B20 and CME B30, respectively, when compared to the standard diesel. An opposing effect on the increment of BSHC emission was seen beyond the UPME B20 levels, such as UPME B30 and UPME B40. More unburned HC due to incomplete combustion was possibly caused by the lower combustion temperature as reflected by the relatively lower EGT for higher-level UPME blends. The phenomenon may also be due to the advanced injection timing, which results in a higher degree of fuel spray impingement on the combustion chamber walls [42]. This effect is less apparent in CME, although a slight increase in HC could be observed with B40 compared to B30.

### 3.2.2. Brake Specific Carbon Monoxide

During combustion, the partial oxidation process of the carbon particles in the fuel determines the amount of CO emission (16). Methyl ester is an oxygenated fuel, therefore it is expected to promote better combustion, which results in less CO emission. Various differences in CO emissions between diesel and methyl ester blended fuel have been reported in some studies [43–45]. Authors argue that the principal reason for this is that diesel engines are always operated lean and the CO emissions are low enough to evade identification. In this study, the general trend indicated that there was a reduction in BSCO emissions when methyl ester and standard diesel were mixed, except for UPME B40. This may be mostly caused by the increased oxygen concentration present in methyl ester, which results in cleaner and more complete combustion [46–48]. This result aligns with another study on engine emissions by Akar et al. that evaluated the application of castor oil biodiesel in diesel engine. They deduced that biodiesel has lower CO emissions than conventional diesel fuel due to the oxygenated fuel property [49].

As illustrated in Figure 2e, the variation in BSCO was more noticeable and lower with the substitution of UPME compared with CME. For instance, the decrement in BSCO with respect to the standard diesel fuel was 48.3%, 81.9% and 89% for UPME B10, UPME B20 and UPME B30, respectively. For CME fuel blends, the decrement in BSCO was 21.2%, 23%, 51.6% and 25.3% for CME B10, CME B20, CME B30 and CME B40, respectively. This might be due to the higher cetane index of UPME as compared to CME, which improved the flammability and combustion, thus reducing the CO emission. However, UPME B40 showed an opposite result and increased the BSCO emissions by 26.3%. This may be explained by the larger density and viscosity of the fuel, which results in a slower atomization process, and hence suppresses complete combustion. Notably, the higher content of oxygen in the UPME B40 fuel blend may not be enough to compensate for the influence of the viscosity of the fuel, therefore an opposite trend was recorded.

### 3.2.3. Brake Specific Nitrogen Oxide

Most previous studies have found that there is an increment in  $\text{NO}_x$  emission with fuel blends that contain methyl ester. The oxygenated nature of methyl ester fuels facilitates combustion at higher temperatures and hence promotes the formation of thermal  $\text{NO}_x$  [50–52]. On the other hand, opposite trends have also been reported by researchers [53,54]. This result is well aligned with the outcome of this study.

As seen in Figure 2g, the overall  $\text{BSNO}_x$  emission in this study was found to be lower for the UPME and CME blends compared to that of diesel. Greater reduction effects were recorded with increasing biodiesel concentration in both the UPME and CME blends. In fact, although the unsaturated fatty acid content in UPME is slightly higher than in CME (see Table 1), the variation in  $\text{BSNO}_x$  was consistent

and there was no significant difference between both types of fuel blend. Large reductions in BSNO<sub>x</sub> in the range of 16.8% and 14.1% were observed for UPME B40 and CME B30 compared to standard diesel. The improvement in the NO<sub>x</sub> emission when biodiesel blends were used may be attributed to the relatively lower heating value and higher cetane index of the UPME and CME fuel blends. Besides, the significant increment in NO<sub>x</sub> emission when UPME B30 and CME B40 were employed may be a consequence of an increase in combustion temperature as reflected by the EGT results.

#### 3.2.4. Smoke Opacity

Smoke is emitted as a byproduct of poor hydrocarbon fuel combustion in engines. Overall, the fuel used, the engine operating conditions and the carbon residue content of the fuel are the major factors in soot formation. As seen in Figure 2f, the smoke opacity decreased with most of the methyl ester blended fuel, except for UPME B30, CME B20 and CME B30. Compared to the standard diesel fuel, the maximum reduction observed was 51.1% with UPME B40 and only 7.6% with CME B10. The level of impurities, oxygen and sulfur content are crucial in determining the smoke opacity level [41]. However, a slight increment in smoke opacity could be observed for UPME B30, CME B20 and CME B30 as compared to the standard diesel. The higher viscosity of these fuel blends might explain the negligible rise in smoke opacity, as it can result in less air-fuel mixing, and hence, a leaner combustion process occurs. Also, in this study, there was a similar trend in the variation in smoke opacity for UPME blends and that of CME blends. However, the smoke opacity for UPME fuel blends was slightly lower as compared to the CME fuel blends. This may be explained by the higher level of unsaturation of UPME as double bonds promote the key reaction pathway to soot formation [55].

#### 3.2.5. Exhaust Gas Temperature

The exhaust gas temperature of a diesel engine is normally lower than that of a petrol engine due to the higher proportion of air and expansion ratio. This is unfavorable as it contributes to worsening fuel economy and thermal damage to the engine piston components. Also, EGT plays a critical role in determining the amount of NO<sub>x</sub> emission [12].

In this study, as illustrated in Figure 2h, fueling the engine with methyl ester fuel blends resulted in both higher and lower EGT when compared to diesel fuel. The EGT results for UPME blends indicated that most of the fuel blends except B40 were higher than standard diesel fuel. The EGT for UPME of B10, B20 and B30 was 28.5 °C, 26.9 °C and 36.8 °C, respectively, higher than that of diesel fuel (504.5 °C). This may be due to the higher local combustion temperature caused by the slightly highly unsaturated but oxygenated UPME fuel [55]. A further increase in the UPME fuel proportion in the blend to B40 resulted in a sharp drop in EGT to 474.3 °C, which is relatively lower compared to diesel fuel. This may be attributed to the inherently higher kinematic viscosity and poor fuel atomization, which leads to inferior combustion and a lower combustion temperature [56].

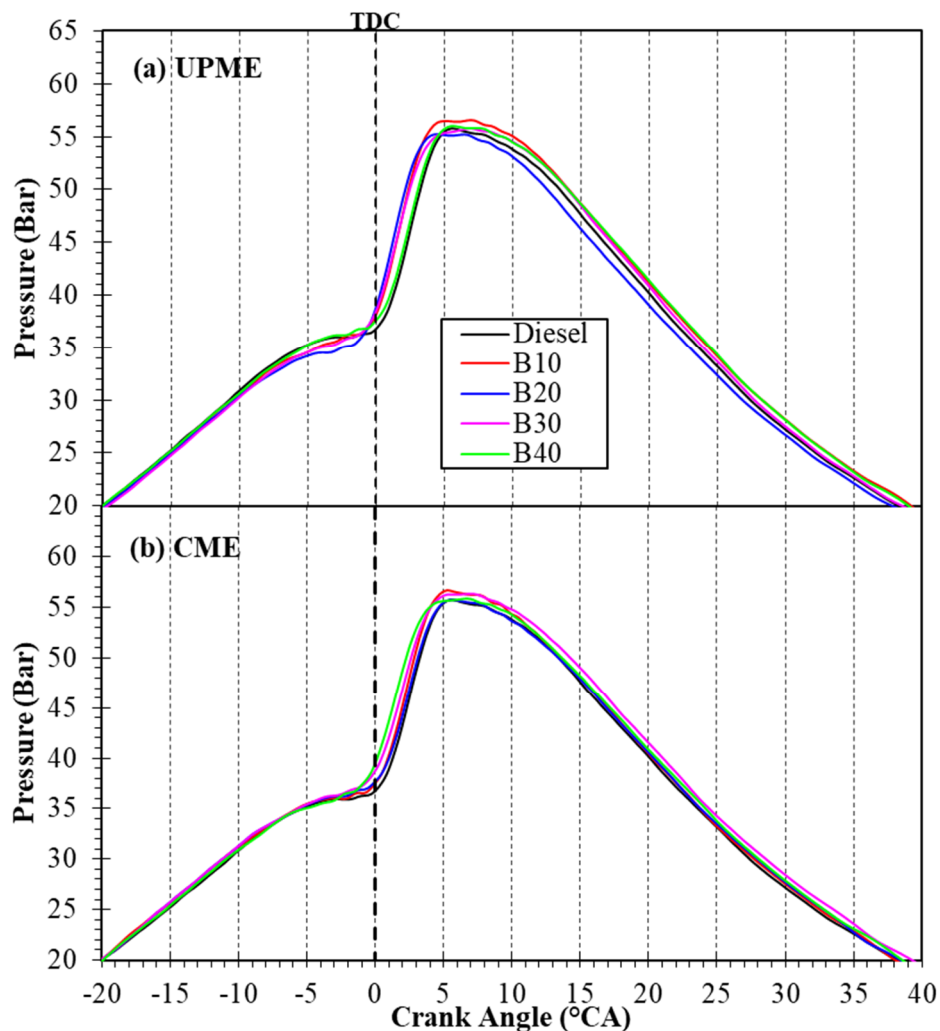
Attia et al. obtained similar results when they evaluated engine performance using blends of used palm cooking oil biodiesel. They noticed that the EGT increased by 1% at B10, there was no significant difference from B20 to B30, and it finally dropped by 2% at B100 [23]. The inconsistency of the results recorded was mostly due to the competition between the effects of the quality of combustion and the fuel atomization process. Unlike the UPME fuel blends, all the CME fuel blends revealed lower EGT than diesel fuel. For instance, CME B20 resulted in the lowest EGT of 483.2 °C. The decrement may be due to the low unsaturated fatty acid content in CME, which might reduce the premix burning and lower the combustion rates, resulting finally in reduced in-cylinder bulk-gas-averaged temperatures.

### 3.3. Combustion Characteristics

#### 3.3.1. In-Cylinder Combustion Pressure

The overlay plots of in-cylinder pressure curves in comparison with standard diesel for UPME fuel blends and CME fuel blends are depicted in Figure 3. In this study, the cylinder pressure profiles for

UPME blends and CME blends were very similar to that of standard diesel despite slight variations in peak pressure and the location of peak pressure occurrence. The combustion of diesel fuel demonstrated a peak pressure of 55.7 bar at 5.50 °ATDC (degree after top dead center). In comparison, most of the fuel blends achieved higher peak pressure than standard diesel except for UPME B20, which recorded 55.2 bar.



**Figure 3.** In-cylinder pressure versus crank angle for (a) UPME and (b) CME fuel blends as compared to standard diesel.

Generally, the ignition delay (ID) for biodiesel fuel blends was shorter compared to standard diesel, which was delayed 16 °CA (degree crank angle) before ignition began. Mathematically, ignition delay is the crank angle interval measured from the time at the start of injection (SOI) to the start of combustion (SOC). As shown in Table 5, the shortest ignition delays were observed to be 15.5 °CA for B20 and B40 UPME blends, while it was determined to be 14.5 °CA for the B40 CME blend. The reduction in ignition delays of biodiesel blends may be attributed to superior ignitability due to high cetane indices [57]. Both UPME and CME blends achieved peak pressure in the range of 55.2–56.5 bar and 55.8–56.6 bar, respectively. Overall, there were decrement trends in peak pressure with a higher percentage of biodiesel in the blends, which were likely due to a decrease in ignition delays of the biodiesel blends compared to diesel [58]. Hossain et al. observed constantly lower peak pressures in used palm cooking oil biodiesel compared to diesel in a three-cylinder engine, while a study by How et al. reported reduced cylinder pressures for most of the coconut biodiesel blends

tested [34,59]. In addition, peak pressure for UPME and CME blends occurred between 4.5 and 7 °CA ATDC for all tested fuels, which were slightly delayed compared to standard diesel. This may be due to poor fuel atomization, fuel-air mixture preparation and combustion, which caused slightly late occurrence of the peak pressure [60].

**Table 5.** Combustion characteristics of the fuels.

Fuel	Start of Injection (SOI) °BTDC	Start of Combustion (SOC) °BTDC	Ignition Delay (°CA)	Pressure		Pressure Rise Rate (dP/dθ)		Heat Release Rate (HRR)		IMEP (Bar)	
				Peak Value (Bar)	Location °ATDC	Peak Value (Bar/°CA)	Location °ATDC	Peak Value (J/°CA)	Location °ATDC		
Diesel	17	1	16	55.7	5.5	5.46	2.75	71.9	3	5.86	
UPME	B10	17.25	1.25	16	56.5	7	5.72	1.75	72.2	2.25	6.37
	B20	17.25	1.75	15.5	55.2	4.5	5.67	1.5	69.9	1.75	5.87
	B30	17.75	2	15.75	55.8	7	5.21	1.75	65.7	2	6.10
	B40	17.5	2	15.5	55.9	5.75	5.37	2.5	71.0	3	5.99
CME	B10	17.25	1.5	15.75	56.6	5.25	5.63	2.5	74.0	2.75	5.93
	B20	17	1.75	15.25	55.8	5.5	5.23	2.5	69.6	3	6.00
	B30	17.5	2	15.5	56.3	7	5.12	2	67.1	2.5	6.21
	B40	17.5	3	14.5	55.9	6.75	5.13	1.5	65.4	2	6.03

The peak pressure achieved by CME-diesel blends was also higher than that of UPME-diesel blends. The variation in peak pressure values between the blends may be due to the complex combined effects of the fuel properties of the blends. Longer ignition delays due to the higher degree of unsaturation of UPME biodiesel generally tend to result in higher peak pressure for its blends since better mixing for premixed combustion can be achieved [61]. The stability provided by the double bond in unsaturated molecules is responsible for the slower ignition, which leads to increases in the ID [55]. Besides, UPME blends exhibited lower viscosities than CME blends, which promote better fuel atomization, and hence higher peak pressures were expected [62]. However, greater oxygen content of CME blends, due to its source biodiesel having lower levels of unsaturation and shorter fatty acid chain length compared to UPME, may be responsible for improved combustion that facilitates an increase in pressure in engine cylinders [63,64].

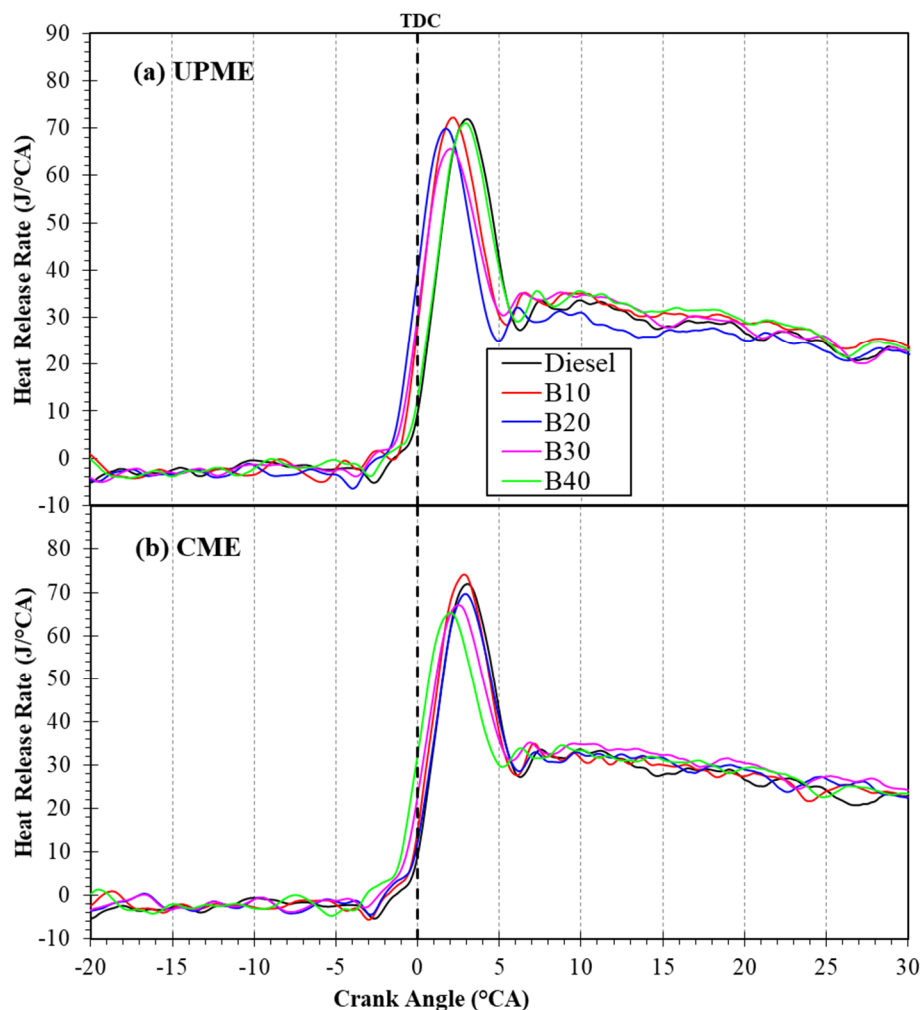
### 3.3.2. Heat Release Rate

The HRR diagrams plotted for UPME and CME fuel blends in comparison to standard diesel fuel are shown in Figure 4. The HRR profiles showed insignificant heat release at the start of the plots. When the piston is near to top dead center (TDC), negative heat releases were observed for all the fuels before the major rise in heat release rate due to the fuel vaporization effect. All the UPME and CME blends demonstrated similar heat release patterns comparable but slightly lower peak HRRs with respect to diesel fuel.

As listed in Table 5, unadulterated diesel fuel used in this study achieved the maximum 71.9 J/°CA peak HRR at 3.00 °ATDC. The peak HRR were in the range of 65.7–72.2 J/°CA and 65.4–74.0 J/°CA for UPME and CME blends, respectively. On the other hand, there were generally decreasing trends found in peak HRR values with increasing portions of biodiesel in blends. For example, maximum reductions of 6.2 J/°CA and 6.5 J/°CA of peak HRRs were noticed for B30 UPME blends and B40 CME blends, respectively. These declines in peak HRRs were likely due to the lower heating value and higher viscosity of the blends, especially for higher-level blends [52,65].

Interestingly, when 10% of diesel fuel was replaced by either UPME or CME biodiesel, a slight increase in peak HRR was observed. This phenomenon may be due to the combined effects of the presence of higher oxygen content compared to diesel and the relatively lower viscosities of B10 blends under the operating conditions. The slightly higher oxygen content in the UPME and CME B10 blends may be sufficient to ensure complete combustion along with better fuel atomization than higher-level blends, which leads to greater peak HRRs. Besides, ignition delays in B10 blends were longer than

that of other higher-level blends, hence they have more time for better fuel-air mixing and superior combustion and heat release rates.

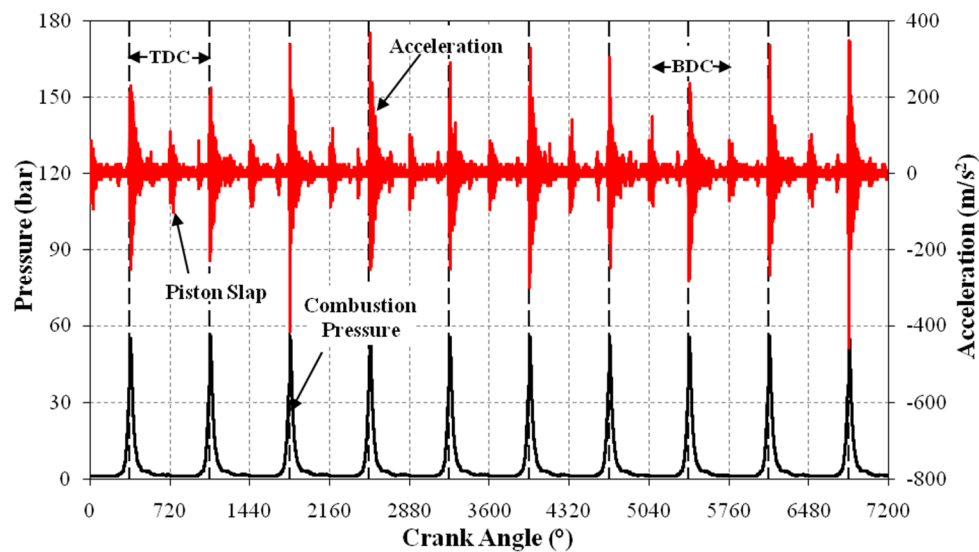


**Figure 4.** Heat release rate in terms of crank angle for (a) UPME and (b) CME fuel blends as compared to standard diesel.

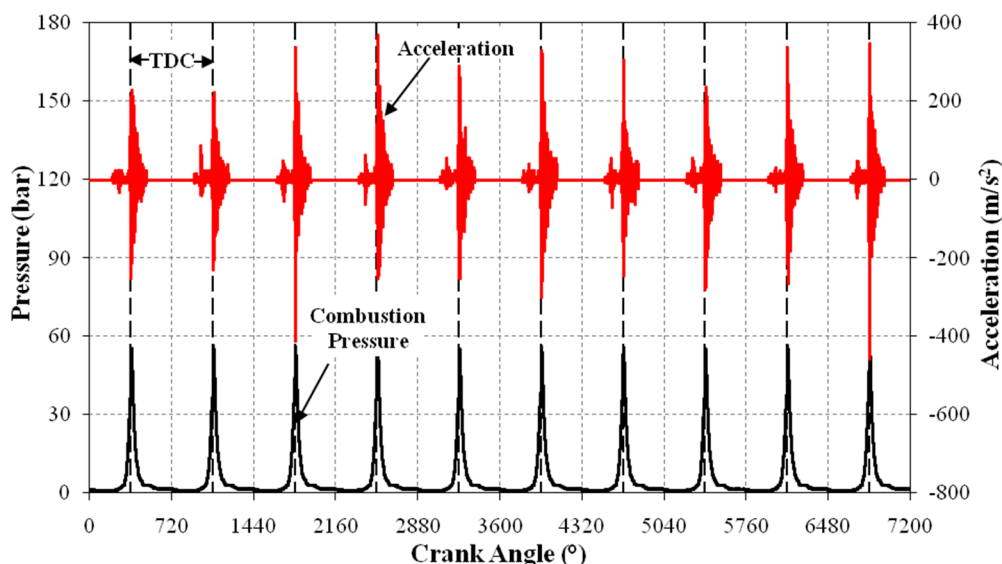
### 3.4. Vibration Analysis

Vibration in an engine arises from piston slap, faults in valves, knocking, piston friction, torsional vibration and the rotation of other engine accessories [66–69]. Vibration signals in an engine can be used as diagnostic data as they allow the engine bearings to be examined for wear and overall engine knock detection.

Figure 5 presents the simultaneously sampled cylinder combustion pressure and vibration acceleration signal profile in the crank angle domain for ten consecutive combustion cycles. These signals were acquired for the engine running with standard diesel, at a constant BMEP of 400 kPa and engine speed of 2000 rpm. Note that the vibration responses due to piston slap (as labeled) that occurred at TDC for an interval of 720 °CA are clearly visible in this figure. To distinguish them from the vibrations due to the combustion process only, signal windowing and filtering was introduced. Figure 6 shows the filtered signal that depicts the vibration signals exclusively due to the combustion process. In fact, the filtering process also provides better accuracy by isolating the root mean square (RMS) of the acceleration signal contributed by fuel combustion [70].



**Figure 5.** Vibration acceleration wave form and combustion pressure as a function of crank angle for 10 consecutive combustion cycles (diesel fuel).

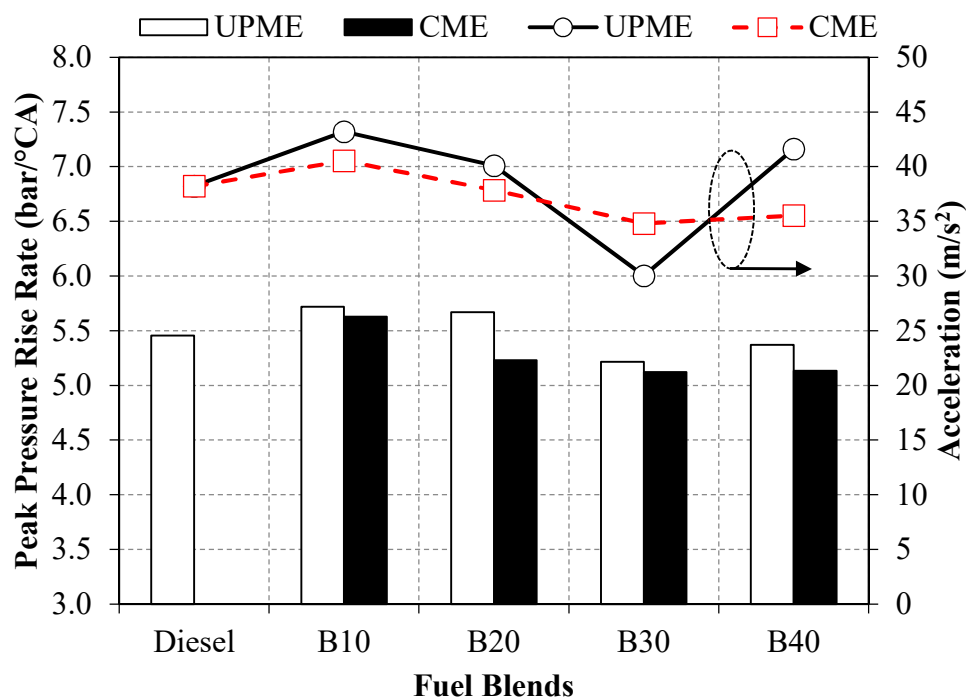


**Figure 6.** Filtered vibration acceleration wave form and combustion pressure as a function of crank angle for 10 consecutive combustion cycles (diesel fuel).

The combined plot of the rate of increase in peak pressure and the RMS acceleration values for UPME and CME fuel blends with respect to standard diesel is shown in Figure 7. In general, it is evident that the feedstock and methyl ester content in the blend have an effect on engine vibration.

In the case of UPME, it was observed that all fuel blends except UPME B30 show higher RMS acceleration values than standard diesel. This trend relates well to their corresponding rate of increase in peak pressure, which were computed from cylinder combustion pressure data. For instance, UPME B10 demonstrated both the largest RMS value of  $43.2 \text{ m/s}^2$  and the highest rate of increase in peak pressure of  $5.72 \text{ bar}/^\circ\text{CA}$ . Conversely, the least vibration was observed for UPME B30 with RMS value of  $30.0 \text{ m/s}^2$  and also the lowest increase in peak pressure of  $5.21 \text{ bar}/^\circ\text{CA}$ . In the case of CME blends, reductions in engine vibration with respect to standard diesel could be observed with most of the fuel blends, except for CME B10. The highest vibration occurred when using CME B10, the maximum RMS value of  $40.5 \text{ m/s}^2$  along with the highest rate of increase in peak pressure of  $5.63 \text{ bar}/^\circ\text{CA}$ . Also,

the lowest RMS value of  $34.8 \text{ m/s}^2$  and lowest rate of increase in peak pressure of  $5.12 \text{ bar/}^\circ\text{CA}$  were recorded for CME B30.



**Figure 7.** Rate of increase in peak pressure and the root mean square (RMS) of acceleration for all UPME and CME fuel blends as compared to the standard diesel.

These results are in good agreement with previous research that suggests a direct linear relationship between in-cylinder pressure and engine vibration level. Chiavola et al. conducted a study to quantify the relationship between in-cylinder pressure and accelerometer traces. The authors reported variation in accelerometer signals that were in tune with changes in in-cylinder pressure such as pressure intensity and location of its maximum values [71]. In fact, accelerometer signals can be utilized as a form of feedback to enhance combustion control strategies such as injection control [72]. It is also worth noting that the lower methyl ester content of UPME B10 and CME B10 tends to cause a higher level of increase in peak pressure and thus engine vibration. These may be attributed to relatively higher premixed combustion phases of the blends as a consequence of higher oxygen contents in the fuels, which leads to better combustion efficiency [73]. In contrast, higher-level blends of UPME and CME generally exhibited a decrease in the peak pressure rate and RMS acceleration, probably because of inferior combustion efficiencies due to higher viscosity of the blends, which leads to poorer fuel atomization [74].

The inconsistencies in the variations in engine vibration characterized by RMS acceleration when using UPME and CME blends are also well aligned with the results of other researchers. Taghizadeh-Alisaraei et al. reported an inconsistent trend in engine vibration with biodiesel blend fraction. The lowest vibrations were noticed for B20 and B40 blends, while B15, B30 and B50 were associated with the highest vibrations. The authors suggested fuel spraying and injection besides blend fuel properties such as cetane index, flash point, viscosity and lubricity as possible causes of the different vibration [69]. On the other hand, the results of filtered accelerometer RMS by Chiatti et al. showed no straightforward trends with different biodiesel blend proportions [70]. However, in another study, Taghizadeh-Alisaraei et al. observed greater vibration with lower-level B20 and B40 blends, while noticing reduced vibration using higher-level B80 blends [75]. Therefore, due to the complex combined effects of biodiesel properties on fuel combustions that can indirectly affect engine vibration



levels, it is not surprising that no consistent vibration variations can be related to biodiesel blend portion in this study. Essentially, it is worth noting that the largest reduction of 21.5% in the RMS of acceleration was obtained with UPME B30 with respect to the baseline diesel.

Another highlight of the present study is that the test engine fueled with either UPME or CME fuel blends did not result in exaggerated rates of increase in pressure. High rates of increase in pressure are undesirable in a normal running engine as this not only produces combustion noise but also imposes stress beyond the limit of the material, especially on the piston rings. For safety purposes, the increase in peak pressure should be kept under the limit of 6 bar/°CA [76]. From the results obtained, the rate of increase in pressure when either UPME or CME was used were within the acceptable threshold.

#### 4. Conclusions

In the present study, tests on an engine fueled with two different methyl esters produced from coconut oil and used palm cooking oil were successfully undertaken. For each fuel type, blends of methyl ester-diesel in different fuel compositions (B10, B20, B30 and B40) were prepared and tested. The results including performance, emissions, combustion and engine block vibration were compared with those using the standard diesel. From the experimental data, the findings can be summarized as follows:

The BSFC for all UPME and CME fuel blends was higher than standard diesel, while most of the blends also recorded lower BSEC than diesel. Also, salient variations and generally slightly higher BSFC were observed for CME fuel blends compared to the UPME fuel blends. Besides, the BTE for all UPME and CME fuel blends were found to consistently show an overall slight improvement when compared to diesel fuel. The BTEs for both of the methyl ester blends are similar to each other except for the B10 blends.

For the emission characteristics, the maximum reduction in BSHC emissions was 54% and 45.8% for UPME B20 and CME B30, respectively, when compared to the standard diesel. Besides, major reductions in BSCO emissions in the range of 21.2–89% with respect to the baseline diesel were obtained for all methyl ester fuel blends except for UPME B40. Furthermore, the BSNO<sub>x</sub> emissions for all methyl ester fuel blends were found to be lower than for the baseline diesel. The largest reductions of BSNO<sub>x</sub> in the range of 16.8% and 14.1% were observed for the UPME B40 and CME B30, respectively, with respect to the standard diesel.

Combustion analyses revealed that the cylinder pressure and HRR traces for UPME and CME fuel blends were comparable with the profiles of standard diesel despite some variations in peak pressure and peak HRR. The peak cylinder pressures for most of the methyl ester blend operations were comparable to that of diesel and occurred at slightly delayed locations. Heat release characteristics showed that the SOC timing for both of the methyl ester blended fuels occurred earlier than for standard diesel, owing to their shorter ID due to the higher cetane index of the fuel blends. Besides, the UPME with a slightly higher degree of unsaturated fatty acid as compared to CME tends to result in a longer ID duration.

The engine vibration was significantly influenced by the fuel blends and methyl ester type. For each of the methyl ester types, it was found that UPME B30 and CME B30 had the lowest vibration, with RMS acceleration values of 30 m/s<sup>2</sup> and 34.8 m/s<sup>2</sup>, respectively. Furthermore, the results showed that an engine fueled with both of the UPME and CME blended fuels had pressure increase rates that were within the acceptable threshold. The largest reduction of 21.5% in RMS of acceleration was obtained with UPME B30 with respect to the baseline diesel.

From this overview it can be concluded that UPME-diesel and CME-diesel blends can be employed safely in the current diesel engine without any modifications since they did not result in unfavorable combustion processes such as excessively high increases in the pressure rate that might contribute to knocking. According to the experimental results, the most suitable fuels employed in this research were CME B30 and UPME B30 blends.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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