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**Original citation & hyperlink:**
Teoh, Y.H., How, H.G., Sher, F., Le, T.D., Nguyen, H.T. and Yaqoob, H., 2021. Fuel Injection Responses and Particulate Emissions of a CRDI Engine Fueled with Cocos nucifera Biodiesel. *Sustainability*, *13*(9), p.4930.
https://dx.doi.org/10.3390/su13094930

DOI 10.3390/su13094930
ISSN 2071-1050

Publisher: MDPI

sustainability

*Article*

# Fuel Injection Responses and Particulate Emissions of a CRDI Engine Fueled with *Cocos nucifera* Biodiesel

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**Citation:** Teoh, Y.H.; How, H.G.; Sher, F.; Le, T.D.; Nguyen, H.T.; Yaqoob, H. Fuel Injection Responses and Particulate Emissions of a CRDI Engine Fueled with *Cocos nucifera* Biodiesel. *Sustainability* **2021**, *13*, 4930. https://doi.org/10.3390/su13094930

Academic Editors: Jose Navarro Pedreño, António Dinis Ferreira, Peter Goethals, Eun-Sung Chung and Vincenzo Torretta

Received: 11 March 2021
Accepted: 16 April 2021
Published: 28 April 2021

**Abstract:** The objective of this paper is to study the effect of coconut oil biodiesel (COB)-diesel blends on exhaust particulate matter (PM) emissions and fuel injection responses in an unmodified turbocharged four-stroke common-rail direct injection (CRDI) diesel engine. Characterization of COB and their blends has been conducted to ascertain the applicability of these fuels for the existing engine. The test fuels used were fossil diesel fuel, COB10, COB20, COB30 and COB50 of biodiesel-diesel fuels. A test cycle which composed of 16 different steady-state modes at various loads and speed conditions was followed. Generally, the results showed a marginally advanced SOI timing and longer injection duration with increasing COB blends at higher load as compared to diesel fuel. Additionally, the lower calorific value (CV) and higher viscosity of the COB fuel blends have resulted in reduced turbo boost pressure and increased common-rail fuel injection pressure, respectively, across all engine speeds and loads. On the aspects of PM emissions characterization, results indicated that the blending of COB with conventional diesel had benefits over diesel in PM reduction. In fact, the largest achievable PM mass reduction of 38.55% was attained with COB50. In addition, it was noticed that the size of PM particles accumulated such that the granular size increased with higher diesel content in the blend. Additionally, the composition analysis on the PM collected by EDX spectroscopy has revealed that the C, O and Si as three main elements that made up the PM particles in descending order. Overall, the results indicated that COB biodiesel is a clean-burning alternative fuel and can be used satisfactorily in an unmodified diesel engine without the needs for engine remapping.

**Keywords:** sustainable fuels; particulate matter; coconut biodiesel; common-rail; biodiesel; combustion and renewable energy

## 1. Introduction

Combustion of petroleum diesel in engines is known to produce emissions such as carbon monoxide, carbon dioxide, nitrogen oxides (NOx), particulate matters and more, which are pollutants that are detrimental to human health if inhaled [1]. Prolong exposure to NOx may contribute to acute lung injury [2] and a direct association is indicated between particulate matter with mortality from cardiovascular and respiratory disease [3]. On the other hand, global oil consumption has continued to grow for three consecutive years from 2015 to 2017 [4] alongside a surge in total world carbon emissions from fuel combustions to 33,444 million tonnes of $CO_2$ in 2017. Over the last few years, researchers have attempted in accessing various energy sources including derivatives from hydrogen, alcohols, vegetable oils as alternatives to petroleum diesel [5–9]. In fact, the inventor of diesel engine, Rudolf Christian Karl Diesel himself had introduced and envisioned the use of pure vegetable oil as fuels to power diesel engines since petroleum was not widely available at that time [10,11]. The idea gained attention in the 1970s when researchers were alarmed by the 1973 oil crisis but their interests soon plummeted when availability and prices of oil stabilized [12].

However, owing to the recent fossil fuel depletion issue besides concerns on climate change due to greenhouse emissions, alternative fuels or substitutes of petroleum diesel have caught the attention they deserve. In 1983, Ziejewski et al. [13] investigated the potential of sunflower oil, safflower oil and their blends as a diesel alternative. They concluded that both tested blends were potential candidates as an alternative fuel but were uncertain about the long-term use of one of the blends. Unfortunately, it was reported later that the use of vegetable oils that exhibit high viscosity in the diesel engine is not a sustainable solution as problems such as poor atomization, increase in wears and carbon deposits would arise in long run. To resolve the problems, biodiesel, derived from vegetable oils with proven better properties than in its raw oil forms comes into the picture as one of the promising alternative fuels [14]. To investigate the particulate matter, SEM scans and element composition of COB diesel performed in the test engine. Therefore, it is necessary to optimize the relationship between biodiesel and engine parameters for optimal performance of the engine.

### 1.1. Biodiesel

Biodiesel is a biodegradable and non-toxic substitute of diesel that consists of mono-alkyl esters of long-chain fatty acids produced from plant or animal oils through processes such as transesterification, emulsification and pyrolysis. Among feedstocks that are used to produce biodiesel all around the world are soybean, palm, jatropha, moringa, rapeseed and more [15]. Biodiesels are known to have superior lubricity than diesel [16] and the use of biodiesel in a diesel engine is known to produce much cleaner burning than petroleum diesel. Babu et al. [17] concluded that both vegetable oil and derived biodiesel demonstrate benefits over petroleum diesel with lower engine noise and emission advantages including less smoke, hydrocarbons and carbon monoxide (CO). However, these produce a slightly higher NOx level than petroleum diesel. In fact, it is reported that the utilization of biodiesel in internal combustion engines could also reduce the release and impact of greenhouse gas (GHG) [18] and improve combustion efficiency [19]. Furthermore, a higher flash point of biodiesel than petroleum diesel has also become a perk of the fuel in transportation matter. Despite their merits, biodiesels have drawbacks such as their general poor low temperature properties and poor oxidation stability [20–23].

The high pour point and cloud point of biodiesels give rise to fuel filter plugging when they are used especially in the cold region while oxidation stability induces changes in biodiesel quality over time. Dominant characteristics of biodiesels which would affect the combustion of the fuel in diesel engine such as density, viscosity and acidity also vary with storage time. Therefore, the storage and distribution of biodiesel should be considered to preserve its quality. In addition, biodiesel material compatibility issues due to their corrosive nature. Studies by Fazal et al. [24] and Cursaru et al. [25] have reported that biodiesel exhibit higher corrosiveness than petroleum diesel. Even though biodiesels are proven to be readily used in the diesel engine without or only with little engine modifications, the use of pure biodiesels directly in diesel engine might cause problems due to the difference between fuel properties. Nevertheless, this issue can be mitigated by using blends of both fuels. Furthermore, other proven approaches of advanced combustion concepts such as dual fuel, partially premixed combustion [26] combined with alternative fuels (natural gas, ethanol-biodiesel blends, etc.) could give a potential boost to the CI engine fuel economy and engine-out emissions reduction [27,28]. In fact, the research and industry are working extensively on fuel design and advanced combustion concepts to improve the $CO_2$ and improving the NOx-Soot trade-offs [29].

### 1.2. Research Gap and Motivation

COB can be derived from *Cocos nucifera* copra which is widely available especially in the Asia region [30]. It contains mainly shorter chain of highly saturated fatty acids compared to other biodiesels. Due to its composition, it is reported that COB has moderate cold flow properties (slightly low pour point and cloud point than other biodiesels). Moreover, research indicates that COB shows density closer to that of petroleum diesel and lower viscosity than other biodiesels that is preferable for engine cold start. Its highly saturated nature has also enabled it to manifest better characteristics such as higher flash point and higher cetane number than petroleum diesel that promotes combustion [31]. In addition, the results from a study by Nakpong et al. [32] shows that COB exhibit lower viscosity than other biodiesels (soybean, rapeseed and rubber seed) and has higher oxidation stability. The authors have also reported that the feedstock, coconut oil which contains high free fatty acids content obtained at a lower cost in Thailand has high potential in biodiesel production.

Moreover, a study by Shahabuddin et al. [33] has revealed the high potential of COB in terms of preserving fuel properties due to higher stability. Despite the urge and stress of the need for alternative fuel, determining suitable biodiesels as diesel substitute is a challenging task as there are numerous types of feedstock with variable biodiesel properties to be investigated. Coconut oil biodiesel with distinctive properties has been noticed by several researchers and COB has been included in their experiments. Prior work on using COB fuel for Naturally Aspirated (NA)/Turbo Charged (TC) and Indirect Injection (IDI)/Direct Injection (DI) engines is described in Table 1. It was found that there was a lack of research on exhaust particulate emissions and fuel injection responses of COB-diesel blends in CRDI engine to date. Additionally, information on the release of particulate matter from the engine under such set up is yet not available.

**Table 1.** An overview of prior work on engines using COB fuels.

| Motive | Engine | Highlights | Reference |
|---|---|---|---|
| Performance and emission characteristics of a diesel engine fueled with coconut oil-diesel fuel blend | Robin DY41D, 412 cc,<br>1 Cylinder<br>21:1 CR, DI | Heating value of coconut oil is about 15% lower than that of diesel fuel and results in 16% decrease in BMEP. Smoke and NOx reduce by 50% and 40%, respectively, pure coconut oil operation. | [34] |
| Effect of coconut biodiesel blended fuels on engine performance and emission characteristics | 638 cc<br>1 Cylinder<br>17.7 CR<br>NA DI | Torque reduced by 2.58% and BSFC increased by 2.11% for COB15 when compared to diesel fuel. The noise level for coconut fuel blend is also noted to decrease. The average reduction in CO, $CO_2$ and HC was 21.51%, 4.64%, 22.88%, respectively, for COB15 at 2200 rpm when compared to diesel. However, NOx increased by 3.19%. | [35] |
| Fuel Properties of Croton megalocarpus, Calophyllum inophyllum and Cocos nucifera methyl esters and their performance in a multi cylinder diesel engine | Mitsubishi<br>2500 cc<br>4 Cylinder<br>21:1 CR<br>IDI | Use of COB10 and COB20 result in NOx increase by 1.55% and 6.16%, Reduction in HC by 3.89%, and 15.58% and CO by 15.44% and 34.72%. COB10 gave the highest BP value of 36.48 kW at 3500 rpm as compared to 36.99 kW with diesel fuel and lowest BSFC value of 338.5 g/kWh at 1500 rpm as compared to 488 g/kWh for diesel. | [36] |
| Performance and emission characteristics of a CI engine fueled with Cocos nucifera and Jatropha curcas B20 blends accompanying antioxidants | 2500 cc<br>4 Cylinder<br>21:1 CR<br>TC IDI | Addition of antioxidants to blends reduces BSFC by 0.55–0.79% and BTE by 0.60–0.77% depending on that feedstock. | [37] |

**Table 1.** *Cont.*

| Motive | Engine | Highlights | Reference |
|---|---|---|---|
| Biodiesel production and performance evaluation of coconut, palm and their combined blend with diesel in a single cylinder diesel engine | TF 120 M<br>683 cc<br>1 Cylinder<br>NA DI | Compared to diesel fuel, the average NOx emissions were 3.13–5.67% higher for all the tested biodiesel blends while CO and HC emissions were reduced by 13.75–17.97%. | [38] |
| A comparative analysis on engine performance of conventional diesel fuel and 10% biodiesel blends produced from coconut oils | 497.8 cc<br>1 Cylinder<br>17.7:1 CR | A 62% reduction in CO and HC emission was noticed with COB10. The lowest smoke/NOx emissions are found for COB10 (Produced from Biological Catalyst) fuel at 20% EGR rate, which shows 9% opacity and 4 g/kWh NOx emissions compared to 8% opacity and 5.8 g/kWh NOx emissions measured diesel at 0% EGR rate. The BMEP of coconut oil COB10 fuels appear to be higher than that of petroleum diesel. | [39] |
| Production of Coconut Methyl Ester (CME) and glycerol from coconut oil and the functional feasibility of CME as biofuel in diesel engine | TATA<br>702 cc<br>2 Cylinder<br>NA IDI | CME provides a power of 16 bhp at 3000 rpm and a torque of 38.5 Nm at 2000 rpm compared to 16 bhp at 3200 rpm and 38 Nm torque at 2000 rpm using diesel. CME increased the mileage of the vehicle to 22.5 km/L from the 16 km/L for diesel fuel. | [40] |

This information is crucial due to the fact that PMs of the exhaust engine could adversely affect the health of human being as it is very dangerous to the human respiratory system and cannot be jeopardized, which also being highlighted by most of the researchers [41,42]. Thus, a research gap exists in these fields which are assessed in this research study. Therefore, the present work is intended to provide a better understanding of the application of coconut oil biodiesel-diesel blends in diesel engines, additionally aimed to contribute as one of the many efforts to determine more sustainable alternative fuels. Hence, in this work, the study of the use of COB biodiesel-diesel blends in a multi-cylinder high-pressure common-rail turbocharged diesel engine is studied in light of the current lack of comprehensive research on this matter. This includes the key investigations of fuel injection parameter response characteristics and exhaust particulate matter (PM) emission.

## 2. Methodology

### 2.1. Fuel Properties and Preparations

Tests were carried out for both neat coconut oil biodiesel and petroleum diesel to determine their physicochemical properties including density, kinematic viscosity, cold temperature properties, calorific value and chemical compositions. These properties were important to characterize the suitability of the fuels to be run in diesel engines. All tests were conducted according to ASTM and EN standards that were commonly referred to the fuel quality and specification tests. The results of the fuel properties tests are presented in Table 2. In this study, 4 blends of different proportion of COB with petroleum diesel were among the test subjects besides unadulterated petroleum diesel. In addition, all the blends were also subjected to similar fuel properties tests that were conducted to their sources. A few key fuel properties for the COB-diesel blends are shown in Table 3. It was unsurprising that the blends exhibited properties that were in-between that of neat COB and diesel. From the results, COB-diesel blends exhibited lower calorific values, greater densities and higher kinematics viscosities than diesel. The difference between the blends and diesel in property values increased for a higher percentage of COB in the blends.

**Table 2.** Key physicochemical properties of petroleum diesel and COB.

| Properties | Units | Standards | COB | Diesel |
|---|---|---|---|---|
| Kinematic viscosity at 40 °C | $mm^2/s$ | ASTM D445 | 4.10 | 3.63 |
| Density at 40 °C | $kg/m^3$ | ASTM D1298 | 867.00 | 834.30 |
| Flash point | °C | ASTM D93 | 182.50 | 71.50 |
| Cloud point | °C | ASTM D2500 | 4.00 | 3.00 |
| Pour point | °C | ASTM D97 | 3.00 | 0.00 |
| CFPP | °C | ASTM D6371 | 7.00 | 5.00 |
| Cetane number | - | ASTM D6890 | 56.70 | 52.40 |
| Calorific value | MJ/kg | ASTM D240 | 38.70 | 45.21 |
| Acid value | mg KOH/g | ASTM D664 | 0.05 | - |
| Oxidation stability | h | EN ISO 14112 | 7.00 | >100.0 |
| Conradson carbon residue (100% sample) | m/m | ASTM D4530 | 0.021 | 0.125 |
| Carbon (C) | wt% | ASTM D5291 | 73.20 | 86.10 |
| Hydrogen (H) | wt% | | 12.50 | 13.80 |
| Nitrogen (N) | wt% | | <0.10 | <0.10 |
| Oxygen (O) | wt% | | 14.30 | 0.10 |
| C/H ratio | - | - | 5.86 | 6.24 |

**Table 3.** Fuel properties for biodiesel blends.

| Properties | Units | Diesel | COB10 | COB20 | COB30 | COB50 | Test Method |
|---|---|---|---|---|---|---|---|
| Calorific Value | MJ/kg | 45.21 | 44.67 | 43.91 | 43.22 | 41.70 | ASTM D240 |
| Density @ 40 °C | $kg/m^3$ | 834.3 | 834.9 | 838.1 | 841.4 | 848.3 | ASTM D1298 |
| Kinematic Viscosity @ 40 °C | $mm^2/s$ | 2.99 | 3.28 | 3.35 | 3.43 | 3.62 | ASTM D445 |

### 2.2. Experimental Setup and Methods

Figure 1 depicts the arrangement and experimental set up of the apparatus used in this study. A turbocharged direct injection diesel engine with a common-rail injection system was used as the test engine in this study. The specifications of the test engine are displayed in Table 4. The common-rail injection system operated at a maximum of 140 MPa injection pressure, while the engine was rated to run at a maximum power of 48 kW and maximum torque of 160 Nm. All the tests for all fuels were accomplished in the unmodified test engine at room temperature of 25 °C. The operating boundary conditions of the test engine are shown in Table 5. The variable of the engine ECU was recorded through an on-board diagnostic (OBD) connection. The following parameters were consistently recorded (with 4 Hz of sampling rate) throughout the engine testing: the engine speed, accelerator pedal position (load demand), intake air pressure (boost pressure), intake air temperature, fuel rail pressure and engine coolant temperature. To determine the timing and duration for fuel injection, the injector voltage supply was tapped and channeled to a high-speed data acquisition system.

**Table 4.** Details of test engine parameters.

| | |
|---|---|
| Type | Four-stroke, diesel turbocharged, DI engine |
| Fuel injection system | Common-rail with 140 MPa max. of injection pressure |
| Cylinder number | 4 |
| Valve per cylinder | 2 |
| Bore × stroke | 76.0 × 80.5 mm |
| Total cylinder volume | 1.461 L |
| Ratio of compression | 18.25:1 |
| Maximum power/torque | 48 kW/160 Nm |

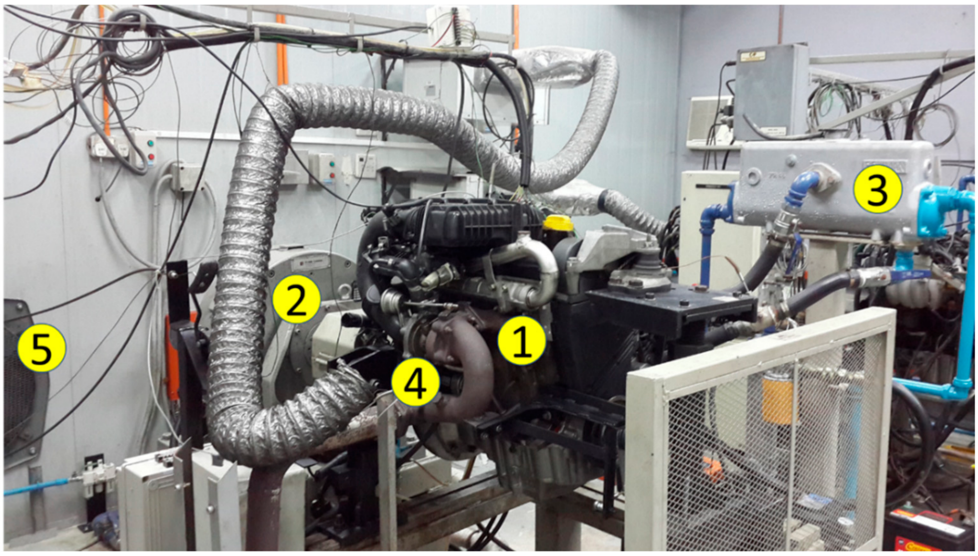


**Figure 1.** The arrangement of experimental setup: (1) test engine, (2) eddy current dynamometer, (3) engine coolant heat exchanger, (4) turbocharger and (5) ventilation fan.

**Table 5.** Engine operating boundary conditions.

| Parameter | Units | Boundary Condition |
|---|---|---|
| Intake temperature | °C | 28–30 |
| Boost pressure | kPa | 110–200 |
| Injection quantity | mg/stroke | 9.5–31.5 |
| Injection strategy | - | Pilot + Main |

### 2.3. Particulate Matter (PM) Sampling

As shown in Figure 2 is the exhaust PM flow diagram employed in the present study. As can be seen, there were two solenoid valves labelled as A and B, respectively, that were used to control the PM sampling state. In the present study, collection of the particulate sample was carried out by passing a known volume of exhaust gas through a PALL Tissuquartz filter. This was followed by further analysis and calculation of concentrations of compounds trapped by the filter. All filters were prepared by heat treatment in a furnace at 900 °C for 2.5 h continuously and followed by a drying process in a desiccator for 24 h before PM samplings. Before a filter was installed into the cleaned filter holder for each sampling, the filter was weighed by an electrical balance. Then, the raw exhaust from the test engine was directed to subsequently flow through a cooling oil, the particle filter holder, a 3-way fitting and rotameter before reaching the sampling pump. The flow rate was maintained at 15 L/min throughout the experiment using the adjustable rotameter, which was calibrated using a BIOS DEFENDER air sampling calibrator before the sampling was carried out for each operating point.

In the present study, PM was sampled through a 16-point steady-state test cycle, which took sufficiently wide ranges of engine operating points into account. As shown in Table 6, the collection for one PM sample involved operating the test engine under 16 combinations of load and engine speed conditions. The engine was left running at each operating point for 60 s duration consecutively in the ordered sequence with 10 s delays between transitions for flow stabilization. After the 16-operating point-run, the filter was then removed. The filter holder was cleaned with detergent to remove residues from it for repeated use. The filter was placed and conditioned in a desiccator for another 24 h before weighed. The mass agglomerated on the filter was calculated as the difference between the mass of the filter before and after the sampling processes. If the mass accumulated was not sufficient at the end of the sampling or if there was a change in fuel type, the procedures were repeated. In the case of successful sampling, the filter sample was examined under a

Scanning Electron Microscope (SEM) at 500× magnification, while its chemical composition was also investigated by Energy-dispersive X-ray (EDX) spectroscopy.

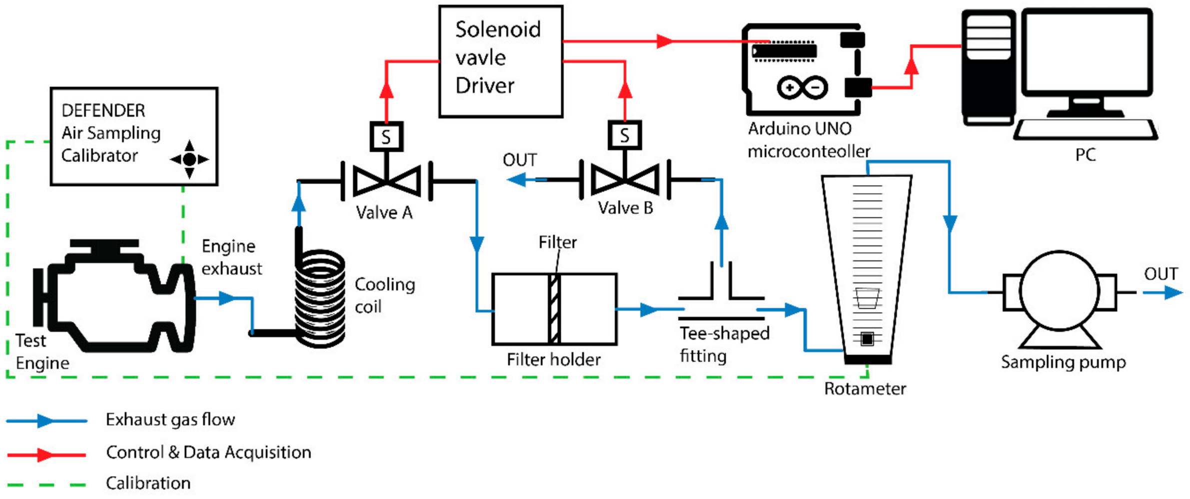


**Figure 2.** Exhaust particulate sampling process flow diagram.

**Table 6.** Sequence of test modes for the comparison of fuels.

| Mode | Engine Speed (rpm) | Load (%) | Torque (Nm) | Power (kW) | Duration (s) |
|---|---|---|---|---|---|
| 1 | 3850 | 100 | Maximum * | Maximum * | 60 |
| 2 | 3850 | 75 | 75 | 30.20 | 60 |
| 3 | 3850 | 50 | 50 | 20.20 | 60 |
| 4 | 3850 | 25 | 25 | 10.10 | 60 |
| 5 | 3100 | 100 | Maximum * | Maximum * | 60 |
| 6 | 3100 | 75 | 90 | 29.20 | 60 |
| 7 | 3100 | 50 | 60 | 19.50 | 60 |
| 8 | 3100 | 25 | 30 | 9.70 | 60 |
| 9 | 2350 | 100 | Maximum * | Maximum * | 60 |
| 10 | 2350 | 75 | 120 | 29.50 | 60 |
| 11 | 2350 | 50 | 80 | 19.70 | 60 |
| 12 | 2350 | 25 | 40 | 9.80 | 60 |
| 13 | 1600 | 100 | Maximum * | Maximum * | 60 |
| 14 | 1600 | 75 | 105 | 17.60 | 60 |
| 15 | 1600 | 50 | 70 | 11.70 | 60 |
| 16 | 1600 | 25 | 35 | 5.90 | 60 |

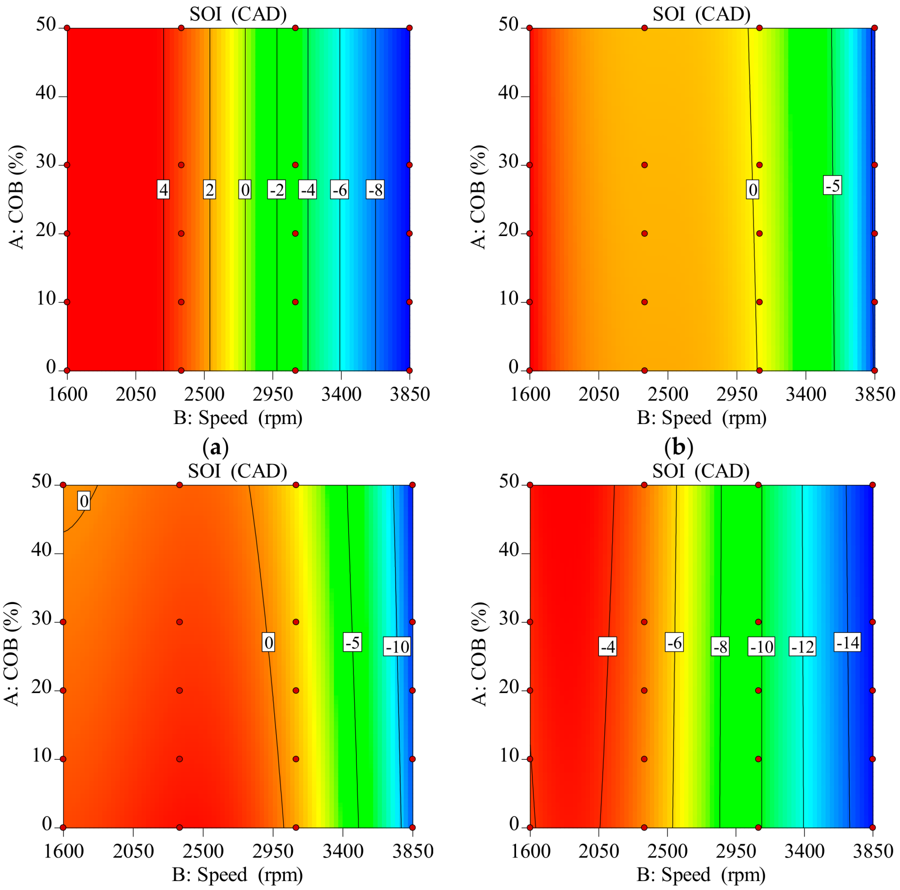
* Note: maximum torque and power value depend on fuel type.

## 3. Results and Discussion

### *3.1. Engine Response Characteristics*

### 3.1.1. Start of Injection (SOI)

The effect of load, speed and COB blends on SOI timing as shown in Figure 3 is observed to be advanced with increasing COB blends at higher loads. At 75% load and speed of 3850, 3100, 2350 and 1600 rpm, SOI timing advances by a maximum change in the value of 5.8, 10, 95 and 130% that is −12.7°˙, −1.1°, 0.1° and −0.3° CA for COB50 compared to diesel operation at −12°, −1°, 2° and 1° CA, respectively. Unlike mechanical fuel injection (MFI) systems with a tendency to advance fuel injection timing due to several factors such as bulk modulus, viscosity, fuel density and sound velocity which is well explained by Breda Kegl [43], the advancement of fuel injection timing in CRDI system is mainly due to its characteristics of the programmed fuel injection map in ECU based as a function of engine speed and load demand. The load demand is measured by mass air flow (MAF) sensor by comparing the actual air intake to the theoretical air intake. In order to gain performance like diesel fuel, the ECU with higher throttle actuation input signal and diesel fuel calibrated fuel map compensates for lower torque produced when running with COB blends by advancing the SOI timing along with higher injection duration that rises to better combustion and performance. Since the CV of COB blends is less when compared to diesel, power delivery is decreased. The advance of SOI also is one of the factors along with increased oxygen content in fuel resulting in higher combustion temperatures for the rise in NOx emission especially with biodiesels, which is evident from the results of this research and results from previously conducted research by Devan et al. [44] and its reduction strategies discussed by Szybist et al. [45].

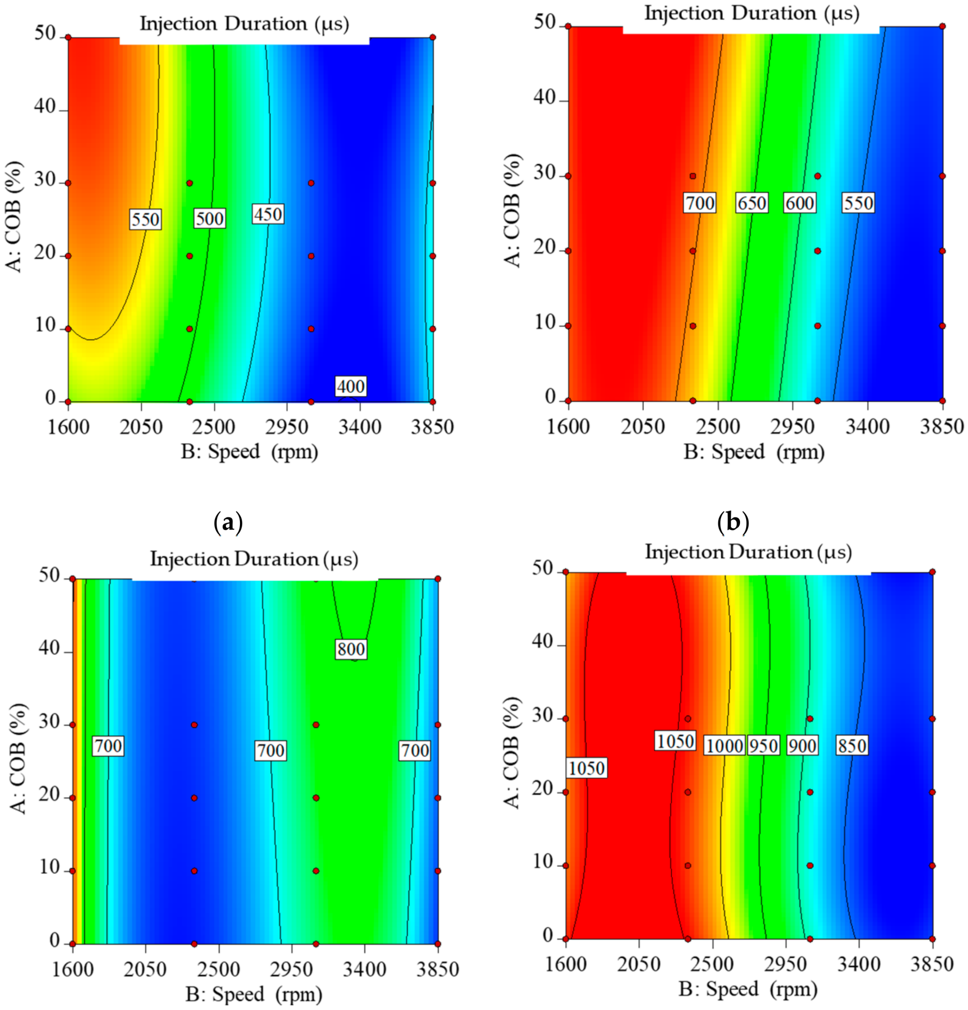


(**a**) (**b**) (**c**) (**d**)

**Figure 3.** Interactive effect of speed and COB blends on SOI timing at various engine loads; (**a**) 25%, (**b**) 50%, (**c**) 75% and (**d**) 100%.

### 3.1.2. Injection Duration

Injection duration is observed to rise significantly with increasing COB blends at high loads and is shown in Figure 4. At 75% load and speed of 3850 rpm, 3100 rpm and 2350 rpm, fuel injection duration increases substantially by 4.6%, 7.2% and 4.1% that is 659, 789 and 637.6 µs for COB50 compared to pure diesel operation at 630, 736 and 612 µs, respectively. Injection duration when using COB blends is increased due to increased load demand; throttle actuation is coupled with the programed injection map of standard diesel fuel stored in the ECU. Higher BSFC values correlate well with higher injection duration, as it is required to supply more fuel to achieve similar performance characteristics of diesel fuel when actually running with COB blends. A similar trend was noticed with research done by Subash and Subramanian [46], where they report that duration of in-cylinder fuel injection is higher with biodiesel-diesel blends and an increased fuel flow rate is required to maintain the same power output as diesel.



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

(**c**) (**d**)

**Figure 4.** Interactive effect of speed and COB blends on injection duration at various engine loads; (**a**) 25%, (**b**) 50%, (**c**) 75% and (**d**) 100%.

### 3.1.3. Turbo Boost Pressure

As illustrated in Figure 5, the changes in values of turbo boost pressure while running COB blends is observed to be in the negative trend but negligible. At 100% load and speed of 3850, 3100, 2350 and 1600 rpm, turbo boost pressure reduces slightly by a value of −0.2%, −0.65%, −1.67% and −4.40% that is 195.5, 196.7, 188.2 and 140.9 kPa for COB50 compared to diesel operation at 195.9, 198, 191.4 and 147.4 kPa, respectively. The reduction in turbo boost pressure is well attributed to a low CV of COB blends compared to diesel due to reduced combustion peak pressure which itself can be denoted from decreased PHRR subsequently reducing overall power delivery. Particularly at a low engine speed of 1600 rpm and COB50 blend, the turbo boost pressure is reduced by −4.40% due to turbo lag which can overshoot NOx emissions. A similar trend is reported by Constantine et al. [47] when using *n*-butanol-diesel fuel blend.

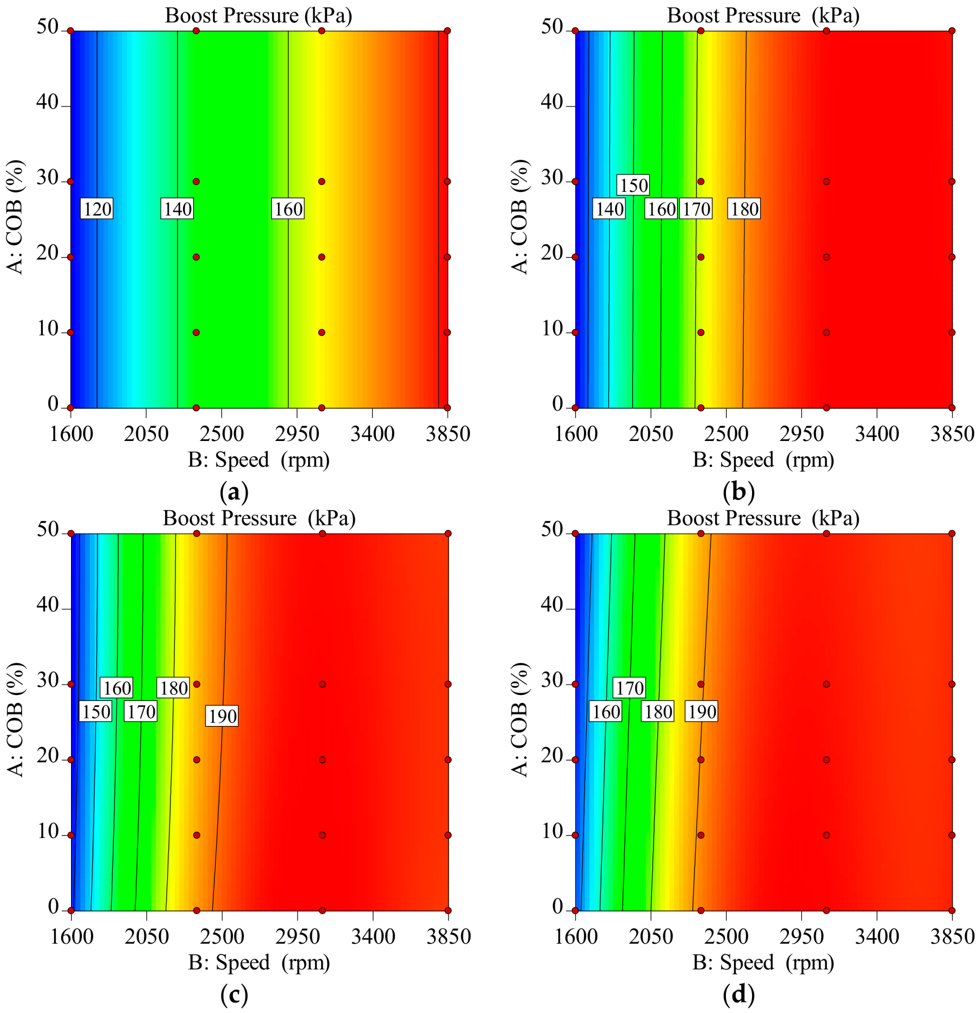
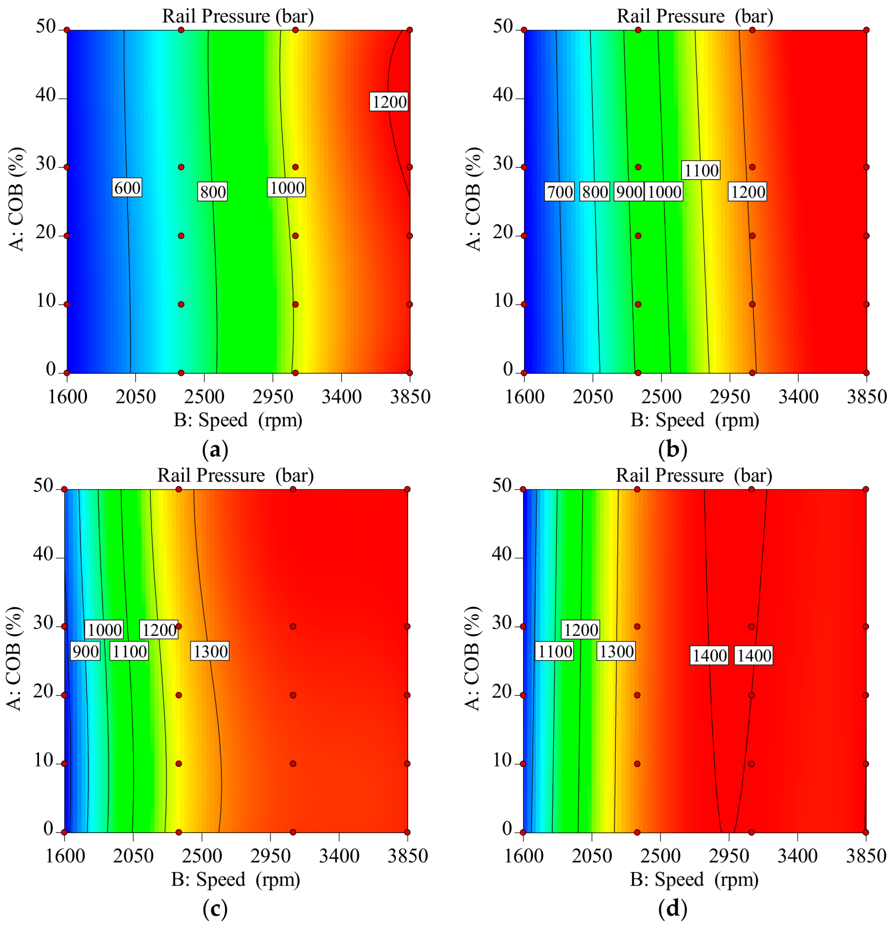


**Figure 5.** Interactive effect of speed and COB blends on boost pressure at various engine loads; (**a**) 25%, (**b**) 50%, (**c**) 75% and (**d**) 100%.

### 3.1.4. Common-Rail Fuel Line Pressure

Common-rail fuel line pressure is noted to increase marginally with increasing COB blends at higher loads and is shown in Figure 6. At 75% load and speed of 3850, 3100, 2350 and 1600 rpm, common-rail pressure raised by a significant change in the value of 1.43%, 2.66%, 3.84% and 4.34% which is 1382, 1376, 1273 and 813 bar for COB50 compared to diesel operation at 1362, 1340, 1226 and 779 bar, respectively. Breda Kegl [43] explains that in MFI system, the rise in injection pressure for increasing biodiesel blends is due to higher viscosity in fuel content leading to a rapid evolution of pressure and lower fuel losses during the injection. Even in a CRDI system, a similar trend is observed since the pressure is evenly distributed among all volumes between the common-rail and the electronic injector. Compared to MFI, CRDI works on a greater system pressure which results in lower vapor content leading to a decrease in injection delay and subsequently advances injection timing.



(**a**) (**b**) (**c**) (**d**)

**Figure 6.** Interactive effect of speed and COB blends on rail pressure at various engine loads; (**a**) 25%, (**b**) 50%, (**c**) 75% and (**d**) 100%.

### *3.2. Particulate Matter (PM)*

#### 3.2.1. PM Mass

The results demonstrated in Figure 7 indicated that diesel had a greater mass (5.37 mg) of particulate matter found on the Tissuquartz filter sample than COB-diesel blends. This finding is in good agreement with studies by Wang et al. [48], Chang et al. [49], McCormick et al. [50] that reported reduced particulate matter emission by biodiesel or its blends. The figure also depicts a decline in PM mass with rising COB content in the COB-diesel blends. The PM mass recorded for COB10 was significantly higher than that for COB50, there was a 1.63 mg reduction in mass when 40% more COB was present in the blends. A study by Lapuerta et al. [51] on diesel particulate emissions revealed that increasing biodiesel concentration in fuels used resulted in sharp drops in both smoke and particulate matter emissions. At a high load where diffusion combustion is dominant, more oxygenated ester fuel promotes combustion and soot radiation even in fuel-rich regions. Therefore, higher oxygen content in fuels provides an effective reduction of PM emission [52]. Hence, COB and its more oxygenated blends have a higher ability to burn cleaner with more complete combustion. This promotes the oxidation of carbon to form carbon dioxide and prevents soot formation. Since anthropogenic carbonaceous elements whether organic or elemental made up of a large fraction of particulate matter released from diesel engines, reduction of carbon in the exhaust will reduce PM mass [53]. COB has lower carbon content and less carbon residue; therefore, its blends were compared with diesel. Consequently, there will be less carbon for soot formation in the exhaust gas and thus less mass accumulated on the samples.

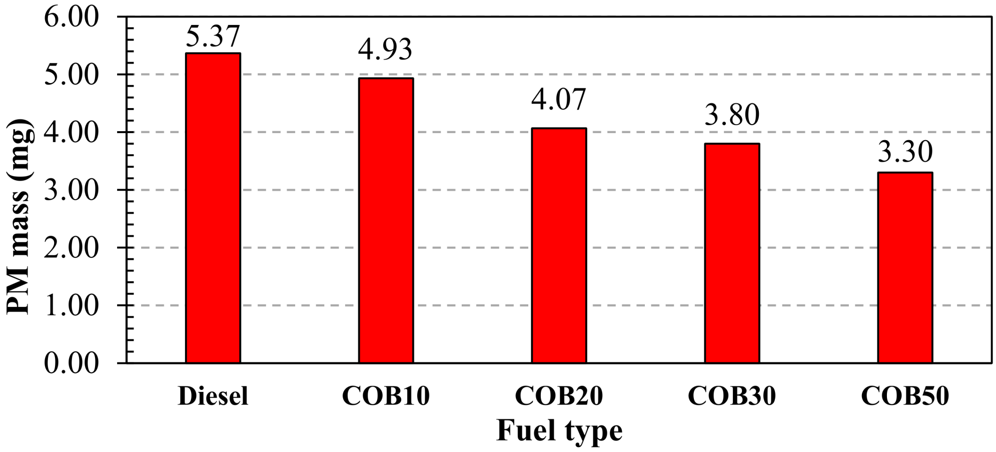


**Figure 7.** PM mass for all fuels under 16 modes speed-load test.

### 3.2.2. SEM Scans on Filter Samples

From Figure 8, it is evident that all the quartz filter samples were darkened after 16 min of collection and filtering of exhaust gases each. From the SEM micrograph for the blank unused quartz filter sample, there was only very fine and thin quartz fibers on the filter sample. After being employed to filter exhaust emission from the diesel engine, it was obvious that the visibility of the quartz fiber was lower for all the filter samples. Moreover, it can be observed that there were solid particulate particles accumulated on the quartz fibers after they were used to filter exhaust emission. Nonetheless, another noteworthy result was the reducing visibility of quartz fiber with increasing diesel content in the fuels. There was only a handful of quartz fiber that can be clearly observed in the SEM image for diesel, while the SEM image of B50 showed a significantly greater amount of visible quartz fibers. Furthermore, the size of the particles accumulated on the filter sample was revealed to be larger with higher diesel content in fuel. These results are very well aligned with the results in PM mass. A larger granular size of PM particles accumulated reflects greater PM mass accumulated due to the combustion of petroleum diesel.

### 3.2.3. Element Composition in PM

Figure 9 illustrates the element composition of PM collected for different fuel types. All the fuels were found to contain three main elements, which were carbon (C), Oxygen (O) and Silicon (Si). The results showed lower carbon content and overall higher oxygen content for all COB-diesel blends than diesel, which may be attributed to essentially lower carbon content and higher oxygen content in COB than diesel. In addition, the carbon content in PM was observed to decline with an increasing percentage of COB in blends. There was 68.9% carbon content in PM for COB50 in comparison with 79.5% for COB10 or a 10.6% decline in carbon content in PM with 40% increase in COB percentage in the blend. This phenomenon may have been caused by less soot production due to higher oxygen content with more COB content in blends that promote oxidation of carbon. Meanwhile, COB-diesel blends also had higher silicon contents than petroleum diesel. For instance, 7.3%, 9.9%, 8.6% and 8.4% of PM by COB10, COB20, COB30 and COB50, respectively, were found to be silicon. These figures were significantly larger than that of diesel (3.2% Si). The presence of silicon in PM for the fuels may be originated by the mixing of impurities during the biodiesel production processes [54]. This finding is compatible with an investigation by Gangwar et al. [55] where silicon was found to present in considerable amount among other metals in a CRDI engine exhaust.

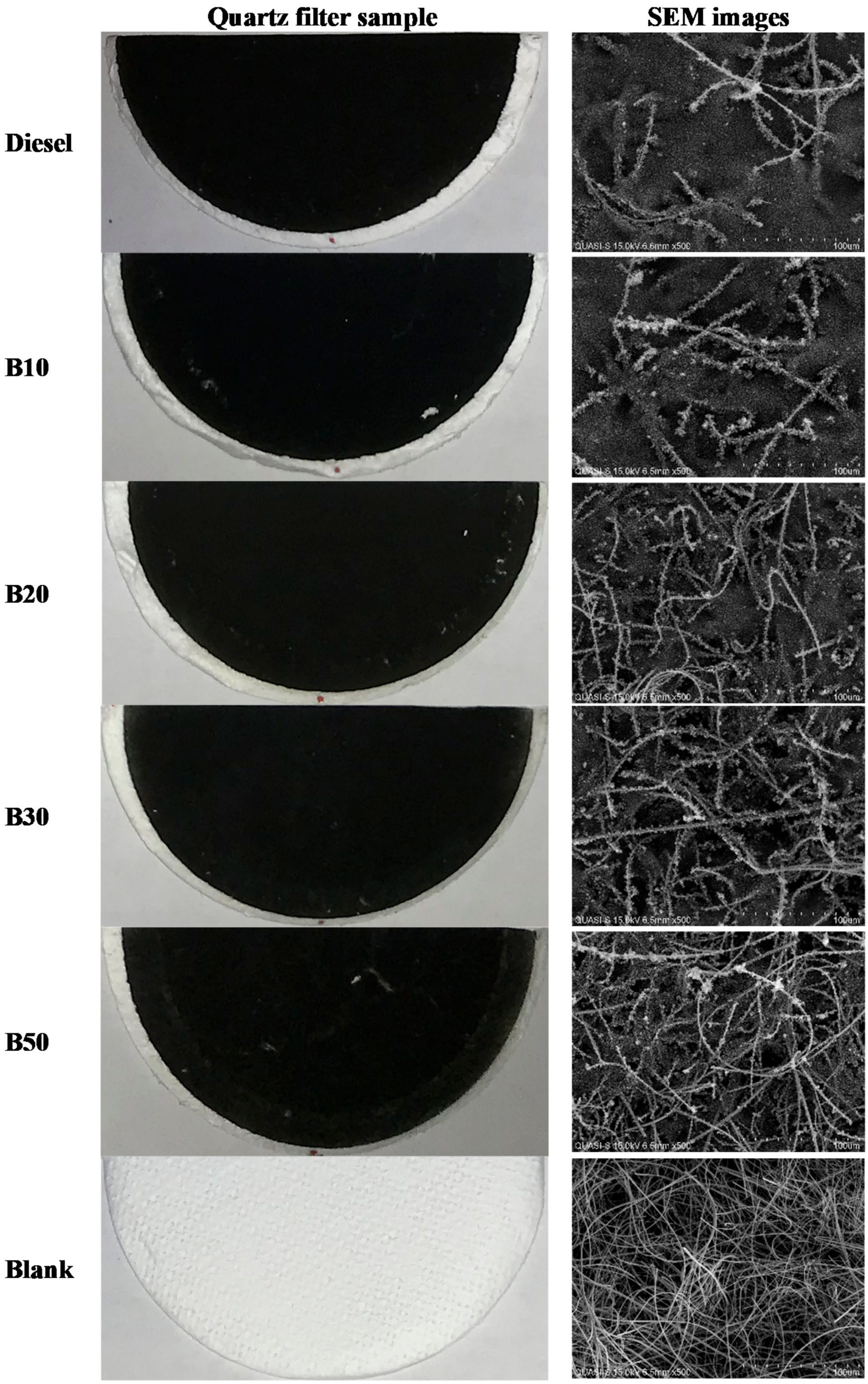


**Figure 8.** Scanning Electron Micrographs (at 500×) and PM samples on the quartz filter of all particulate samples for all fuels under 16 modes speed-load test.

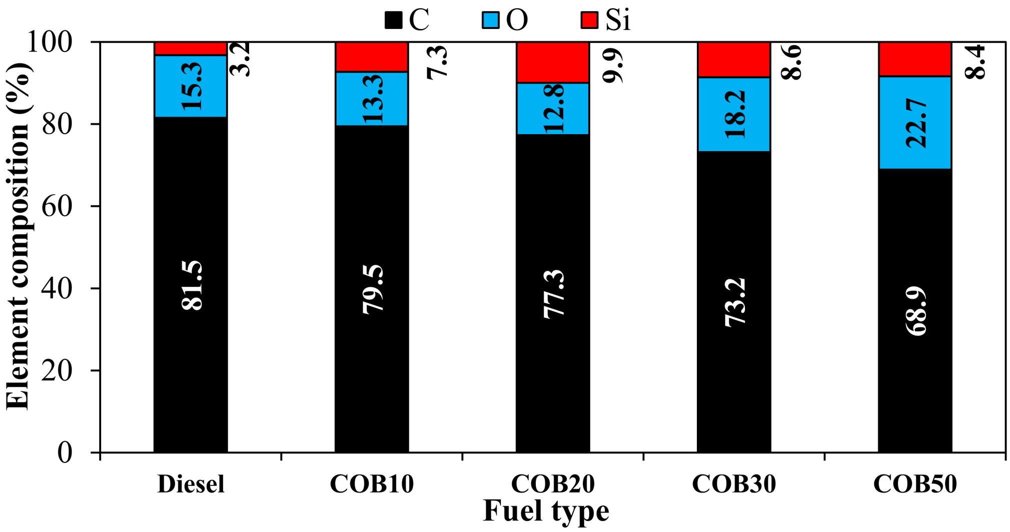


**Figure 9.** Element composition of PM for all tested fuels under 16 modes speed-load test.

## 4. Conclusions

The engine exhaust PM and fuel injection parameter responses of baseline diesel, COB10, COB20, COB30 and COB50 biodiesel blended fuels have been experimentally tested in a medium-duty common-rail diesel engine under different speed and load conditions. The key physicochemical properties of neat biodiesel, biodiesel-diesel blends and diesel were characterized and analyzed. The following main conclusion is drawn from the investigations.

- All key properties of the produced COB biodiesel were able to meet the ASTM biodiesel standard and its blends have physicochemical properties relatively close to those of petroleum diesel.
- In terms of common-rail fuel injection system responses, the results showed a marginally advanced SOI timing and longer injection duration with increasing COB blends at higher load as compared to diesel fuel. Additionally, the lower calorific value (CV) and higher viscosity of the COB fuel blends have resulted in reduced turbo boost pressure and increased common-rail fuel injection pressure, respectively, across all engine speeds and loads.
- On the aspects of PM emissions characterization, results indicated that the blending of COB with conventional diesel had benefits over diesel in PM reduction. In fact, the largest achievable PM mass reduction of 38.55% was attained with COB50. In addition, it was noticed that the size of PM particles accumulated such that the granular size increased with higher diesel content in the blend. Furthermore, the composition analysis on the PM collected by EDX spectroscopy has revealed that the C, O and Si as three main elements that made up the PM particles in descending order.

Overall, the experimental outcomes revealed that COB biodiesel is a clean-burning alternative fuel and could be used satisfactorily in the multi-cylinder high-pressure common-rail diesel engine without modification (i.e., ECU remapping) due to its excellent performance in the particulate matter emissions, while still maintaining a comparable engine's performance as with baseline diesel.

**Author Contributions:** Conceptualization, Y.H.T. and H.G.H.; Methodology, Y.H.T., H.G.H. and T.D.L.; Formal analysis, Project administration, Y.H.T., F.S.; Validation, Writing—Original draft preparation, Resources, F.S., Y.H.T.; Data curation, Y.H.T., H.G.H. and H.T.N., Writing—Original draft preparation, Y.H.T., H.G.H. and H.Y.; Writing—Review and editing, Funding Acquisition, Y.H.T., H.G.H. and F.S.; Visualization, T.D.L. and H.T.N.; Supervision, Y.H.T. and H.G.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors would like to acknowledge the Ministry of Higher Education of Malaysia and Universiti Sains Malaysia for the support through Fundamental Research Grant Scheme (FRGS)—203.PMEKANIK.6071444 (Title: Mechanism Study of Combustion and Formulation of Surrogate Biomass Producer Gas Using a CVCC System) and Universiti Sains Malaysia Research University (RUI) Grant Scheme—1001.PMEKANIK.8014136 (Title: Effect of Fuel Injection Strategies and Intake Air Supply Control on Performance, Emissions, and Combustion Characteristics of Diesel Engine Fueled with Biodiesel Blended Fuels).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to acknowledge the Universiti Sains Malaysia for financial support toward this study.

**Conflicts of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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