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Experimental Investigation of Performance, Emission and Combustion Characteristics of a Common-Rail Diesel Engine Fuelled with Bioethanol as a Fuel Additive in Coconut Oil Biodiesel Blends

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Abstract: In the present study, the effects of adding of bioethanol as a fuel additive to a coconut biodiesel-diesel fuel blend on engine performance, exhaust emissions, and combustion characteristics were studied in a medium-duty, high-pressure common-rail turbocharged four-cylinder diesel engine under different torque conditions. The test fuels used were fossil diesel fuels, B20 (20% biodiesel blend), B20E5 (20% biodiesel + 5% bioethanol blend), and B20E10 (20% biodiesel + 10% bioethanol blend). The experimental results demonstrated that there was an improvement in the brake specific energy consumption (BSEC) and brake thermal efficiency (BTE) of the blends at the expense of brake specific fuel consumption (BSFC) for each bioethanol blend. An increment in nitrogen oxide (NOx) across the entire load range, except at low load conditions, was found with a higher percentage of the bioethanol blend. Also, it was found that simultaneous smoke and carbon monoxide (CO) emission reduction from the baseline levels of petroleum diesel fuel is attainable by utilizing all types of fuel blends. In terms of combustion characteristics, the utilization of bioethanol blended fuels presented a rise in the peak in-cylinder pressure and peak heat release rate (HRR) at a low engine load, especially for the B20E10 blend. Furthermore, the B20E10 showed shorter combustion duration, which reduced by an average of 1.375 °CA compared to the corresponding baseline diesel. This study therefore showed that the B20E10 blend exhibited great improvements in the diesel engine, thus demonstrating that bioethanol is a feasible fuel additive for coconut biodiesel-diesel blends.

Keywords: Combustion; bioethanol; biodiesel; common-rail; emissions

1. Introduction

Increased modernisation, industrialisation and development have led to a huge demand for energy, and the major energy resources are from non-renewable fossil fuels such as petroleum, natural gas and coal. According to the British Petroleum (BP) Energy Output Report, the world's primary energy demand is predicted to increase by 41% between 2012 and 2030, with growth averaging 1.5% per annum [1]. In reality, the remaining liquid fuel stock can only sustain the need for standard daily work practices until the year 2023 [2]. Furthermore, growing concern about the plunge of the petroleum price as well as severe environmental issues, such as global warming, climate change, ozone depletion, desertification, etc., have also encouraged more research into clean alternative fuels [3]. Biodiesel is claimed to be one of the most promising and notable renewable alternative fuels. Researchers have studied the potential of biodiesel to be used in the conventional diesel engine for years [4–6]. Biodiesel consists of alkyl monoesters of fatty acids and can be derived from natural resources such as vegetable oils and animal fats [7]. Most importantly, biodiesel works well in the engine with minor or even no modifications, meanwhile it is harmless and can be decomposed naturally [8].

Nevertheless, there are other concerns associated with the physicochemical properties of biodiesel that might lead to potential damage to the diesel engine in long term operation. For instance, the high viscosity of biodiesel fuel can lead to poor atomisation and consequently result in inferior in-cylinder air-fuel mixing [9]. Several studies conducted by researchers showed that the higher viscosity of biodiesel negatively affects its combustion characteristics. Dhar and Agarwal [10] investigated on the use of Karanja biodiesel and its blends in a multi-cylinder diesel engine. The authors observed that the cylinder pressure dropped with an increase in the biodiesel blend ratio because of the increased fuel viscosity. Moreover, a recent review study by Balamurugan et al. [11] on the use of corn oil biodiesel in diesel engines also deduced that the high viscosity and density of biodiesel decreased the spray characteristics and thereby resulted in a lower peak cylinder pressure. Another concerning issue is that the tendency to increase carbon deposits on the fuel injector when biodiesel blends are employed is also a hindrance to the use of biodiesel as a fuel in compression-ignition (CI) engines [12].

In consideration of the above-mentioned issues, some researchers have proposed the use of fuel additives to improve biodiesel-diesel properties like viscosity, flash point and pour point etc. [13,14]. It has been reported that the addition of an alcohol-based fuel as the additive in the biodiesel-diesel fuel blends indicated a remarkable improvement in the combustion characteristics, as well as the engine-out emissions [15–18]. Besides, alcohol-based fuel also provides many benefits to the environment and can stimulate economic growth in rural areas, as well as reducing the demand for the fossil fuel utilization [19]. Furthermore, alcohol fuel is considered as a potential alternative fuel for CI engines due to their favourable characteristics such as lower viscosity, higher heat of vaporisation and laminar flame propagation speed properties, which make it suitable for use as a blended fuel with conventional diesel [20,21].

From an environmental point of view, oxygenated alcohol fuel, such as bioethanol, is a biodegradable resource and plays a role in reducing net greenhouse gas emissions [22]. Bioethanol is renewable and can be produced from the grown energy crops, e.g., vegetable biomass (first generation bioethanol) such as corn, sugarcane molasses, barley, wheat, sweet sorghum, cassava, beet etc. [23,24]. The second generation of bioethanol is derived primarily from non-edible feedstocks derived from lignocellulosic biomass such as waste woods, agricultural and forest residues etc. [23,25,26]. It has received much interest because the adopted feedstock is abundant, low-cost and does not compete with food crops [27,28]. In addition, more than one-third of the ethanol is made up of oxygen molecules that aid the enhancement of the combustion process, thereby reducing the emissions of particulate matter in CI engines [29,30]. However, ethanol has the limitation of its solubility in conventional diesel fuel [31]. It was claimed that this factor depends on the amount of hydrocarbon (HC) content in the diesel fuel, the wax content as well as the room temperature [30].

Several experimental studies have been conducted to examine the potential of various types of oxygenated fuels as a partial replacement for diesel fuel in CI engines. Yilmaz et al. [32] studied the engine characteristics fuelled with the blend of diesel, waste oil biodiesel, soybean oil and alcohol. They observed an improved outcome in reduced nitrogen oxide (NOx) emissions by 11.9% but brake specific fuel consumption (BSFC) was found to be increased for the propanol blended fuel. Yilmaz [33] also conducted another study to compare the difference between the biodiesel-diesel blends of methanol and ethanol. The results showed that the methanol blended fuel emitted less carbon monoxide (CO) and HC compared to the baseline diesel with the expense of nitrogen monoxide (NO) emission. On the other hand, ethanol blended fuel exhibited opposite trends in emissions. Moreover, Mat Yasin et al. [34] investigated the engine performance for the blend of methanol, diesel and palm oil biodiesel. They deduced that the addition of methanol resulted in the rises in BSFC and the slight increments in the emission of CO, but with the improvements in the NOx emission. Furthermore, Tan et al. [35] evaluated the effects of the addition of bioethanol in a biodiesel -diesel fuel blend. It was found that the emissions of CO, carbon dioxide (CO_2) and NOx can be reduced at certain engine conditions with the bioethanol fuel blend, but with an increase of BSFC as compared to the baseline diesel.

In another study [36], the influence of different percentages of butanol from 5% to 20% in the diesel blends on particulate emissions of a single cylinder, direct injection (DI) and stationary diesel engine was investigated. The results indicated that butanol blended fuels can reduce $PM_{2.5}$ (particles less than 2.5 micrometers in diameter) mass and element carbon emissions with a greater butanol fraction in the blends. The total number of concentrations of volatile and non-volatile particles was effectively reduced for fuel blends. However, the number of particles with diameter less than 15 nm increased for the 15% and 20% butanol blends at low engine loads. The increased in total polycyclic aromatic hydrocarbons emission was also observed with the higher proportion of blend fuels. Karabektas and Hosoz [37] also examined the effect of isobutanol–diesel blends in a naturally aspirated, DI diesel engine at full-load conditions with engine speed ranging from 1200 to 2800 rpm. As expected, the results showed that the isobutanol blend fuels produced lower brake power but higher BSFC. The 10% isobutanol blended fuel resulted in the minimal rise in brake thermal efficiency (BTE) at high engine speeds. In addition, the alcohol also reduced the CO and NOx emissions with the considerable expense in higher HC emission.

In previous studies, most researchers have focused on the potential of biodiesels as the alternative fuels to replace conventional diesel fuel. Although there are some researches on the use of an alcohol additive in the biodiesel-diesel blends, most of the outcomes are based on the engine performance and the exhaust emissions only. The literature reviews show that there is lack of research regarding combustion characteristics, especially for the coconut biodiesel blends with an oxygenated bioethanol additive in a common-rail diesel engine. Therefore, this study was conducted with blends of bioethanol, coconut biodiesel and diesel in a common-rail, DI diesel engine as an attempt to fill the research gap.

In this research, the coconut biodiesel also acts as a co-solvent in the bioethanol–diesel fuels for stabilising and preventing phase separation. Also, the 20% biodiesel blend was chosen due to its optimum performance in terms of its engine compatibility and improved emissions compared to other blend ratios, as reported by other authors [38,39]. The bioethanol used was also derived from the natural product of sugarcane, which is biodegradable and friendly to the environment [40]. Notably, the feasibility of the bioethanol as the fuel additive was ascertained via this study.

2. Methodology

2.1. Biodiesel Production

The experiments were conducted in Engines Laboratory, School of Mechanical Engineering, Universiti Sains Malaysia (USM). The coconut oil biodiesel employed in the present study was obtained through a two-step transesterification process. Firstly, esterification process of the coconut oil with an acid catalyst, followed by a base-catalysed transesterification. Sulfuric acid (H_2SO_4) is used in conversion to reduce the free fatty acid (FFA) percentage in the coconut oil to maximum 2% by weight. Then, the resultant oil was poured into a reactor, which was heated to 60 °C. Concurrently, a mixture of methanol (40% by volume) and H_2SO_4 catalyst (1% by volume) was premixed and made ready before adding it to the coconut oil. An overhead electrical powered stirrer with 800 rpm rotational speed was constantly applied throughout the two hour stirring process. Likewise, during the stirring process, the temperature of the reactor was kept the same at 60 °C. After that, water and methanol residues in the mixture were separated from the product in a separation funnel for 4 h. Distillation process was also employed on the esterified oil by using a rotary evaporator. This step was carried out under vacuum distillation with evaporator temperature maintained at 60 °C to eliminate the presence of methanol and water in the oil.

Upon the completion of esterification process, the FFA content was measured and it was observed that the value is lower than 2% by weight. Then, the volume and density of esterified oil was carefully measured with a measuring cylinder and density meter, respectively. The oil was then transferred and processed in a jacket reactor at 60 °C using heating circulator water bath. Then 1% by weight of alkali catalyst (potassium hydroxide, KOH) and methanol (30% vol.) were thoroughly mixed until all the catalyst had been fully dissolved. After that, the prepared mixtures of methanol and catalyst were added into the preheated esterified oil. Similar to the aforementioned stirring process, the resultant mixture was stirred with a stirring speed of 800 rpm. The reactor temperature was maintained at the preheated temperature throughout the two hour process.

The end products which consisted of coconut methyl ester and glycerol were then separated using a separation funnel (Manufacturer: FAVORIT, Malaysia). The separated coconut biodiesel was rinsed with distilled water at 50 °C; the impurities which settled at the bottom of the separation funnel were discharged and removed. Anhydrous sodium sulphate was used to dry the coconut methyl ester. The final product was then filtered using a filter paper and further purified in a rotary evaporator at 60 °C.

2.2. Fuel Properties Test and Analysis

The diesel fuel employed in this study was acquired from local automotive fuel supplier in Malaysia. The biodiesel was derived from coconut oil and produced through alkaline-catalysed transesterification as discussed above. Besides, the bioethanol fuel with high purity (≥99.8%) which produced by the fermentation of sugarcane was procured from Chemical Industries (Malaya) Sdn. Bhd., Malaysia. The main properties of each of the blend feedstocks were listed in Table 1.

Table 1. Main properties of blending feedstock.

Properties	Unit	Diesel	Coconut Biodiesel	Bioethanol	Test Method
Kinematic viscosity @ 40 °C	mm^2s^{-1}	3.51	4.1	1.08	D445
Density @ 15 °C	kgm^{-3}	851.9	886.2	794.0	D127
Calorific value	$MJkg^{-1}$	45.31	38.1	29.0	D240
Flash point	°C	71.5	115.5	14	D93
Cetane number	-	52	55.9	5–8	D6890
Carbon	wt.%	88	78	52	D5291
Hydrogen	wt.%	13	12	13	D5292
Oxygen	wt.%	0	11	35	D5293

The fuel test results indicated lower calorific values for neat coconut biodiesel (B100) and bioethanol, which were approximately 16% and 36% lower than baseline diesel fuel, respectively. Besides, the oxygen content of bioethanol was the highest among the neat fuels. As can be seen, approximately 35 wt.% of bioethanol was made up of oxygen molecules compared to 11 wt.% of that for coconut biodiesel, while negligible oxygen can be found in diesel. Furthermore, the viscosity of the coconut biodiesel was around 3.8-fold higher than that of the bioethanol. In this research, three different fuel blends were prepared, and their primary physicochemical properties are listed in Table 2. As can be seen, all the fuel property tests were carried out according to American Society for Testing and Materials (ASTM) standards.

Table 2. The composition and fuel properties of tested fuels.

Fuels	Unit	B20	B20E5	B20E10	Test Method
Diesel	%(v/v)	80	75	70	-
Methyl ester	%(v/v)	20	20	20	-
Bioethanol	%(v/v)	0	5	10	-
Kinematic viscosity @ 40 °C	mm^2s^{-1}	3.74	3.33	2.98	D445
Density @ 15 °C	kgm^{-3}	859.6	856	852.1	D127
Calorific value	$MJkg^{-1}$	43.89	43.12	42.25	D240

2.3. Engine Setup and Instrumentation

Experiments in this study were conducted with a four-cylinder, common-rail, high-pressure turbocharged diesel engine. The specifications of the test engine are depicted in Table 3, while Figure 1 shows the illustration of the experimental set-up. To analyse the fuel combustion process, a Kistler 6058A piezoelectric sensor was employed in the engine to monitor the in-cylinder pressure. The pressure sensor signal was sent to a data acquisition unit (DAQ) after amplification using a DAQ-Charge-B charge amplifier. For each test point, data from 100 successive engine cycles were recorded and analysed. On the other hand, exhaust emission measurements were carried out using an AVL gas analyser and a portable smoke opacity meter. The engine was programmed to operate at a constant speed of 2000 rpm with engine torque varying between 20 and 120 Nm in 20 Nm increments.

Table 3. Specifications of the test engine.

Engine Type	Diesel, Direct Injection, Turbocharged
Number of cylinders	4
Number of valves per cylinder	2
Bore	76.0 mm
Stroke	80.5 mm
Maximum power	48 kW @ 4000 rpm
Maximum torque	160 Nm @ 2000 rpm

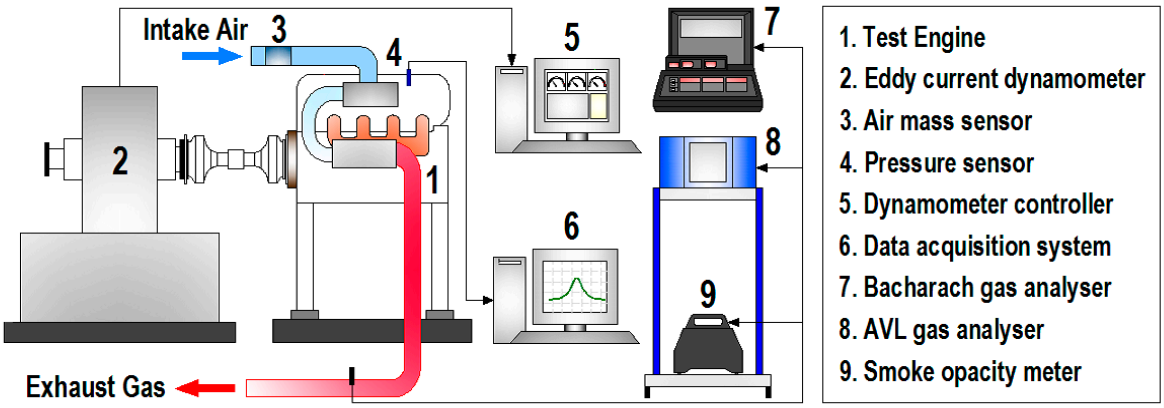

Figure 1. Schematic diagram of the experiment setup.

3. Calculations

3.1. Engine Performance

The engine performance in this experiment was compared based on BSFC, brake specific energy consumption (BSEC) and BTE achieved. These parameters can be determined using the equations below: [41,42].

$$\text{BSFC}\ (\text{gkW}^{-1}\text{h}^{-1}) = \frac{\text{Fuel Consumption}}{\text{Brake Power}} \quad (1)$$

$$\text{BSEC}\ (\text{MJkW}^{-1}\text{h}^{-1}) = \frac{\text{Calorific Value x Fuel Consumption}}{\text{Brake Power}} \quad (2)$$

$$\text{BTE}\ (\%) = \frac{\text{Brake Power} \times 100}{\text{Calorific Value} \times \text{Fuel Consumption}} \quad (3)$$

3.2. Heat Release Rate Analysis

In this study, the heat release rate (HRR) was essentially determined from the in-cylinder pressure data and volume measurements. Assumptions such as negligible leakage and heat transfer to the wall were made for the sake of simplicity [43]. In fact, this simplification has an insignificant effect on the HRR results. This is because the HRR results are relatively insensitive to the wall temperature [44]. According to the first law of thermodynamics, the below equation as derived by Heywood [45] was used to determine the HRR:

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (4)$$

where $\frac{dQ}{d\theta}$ is the HRR per crank angle, θ is the crank angle, P is the pressure, V is the cylinder volume, and γ is the specific ratio.

4. Results and Discussions

4.1. Engine Performance

As shown in Figure 2a is the BSFC of fuel blends under constant speed of 2000 rpm and at various engine loads. With the substitution of biofuel in the blend, the general trend indicates that the BSFC is consistently higher than that of baseline diesel regardless of engine load. For instance, the average increments in BSFC compared to baseline diesel are 1.5%, 1.9%, and 3.1% for B20, B20E5, and B20E10, respectively. This can be explained with the relatively lower calorific value of coconut biodiesel and bioethanol blends when compared with the baseline diesel, as shown in Tables 1 and 2. Consequently, more fuel is required to produce the similar power output as for the baseline diesel fuel [46,47]. Besides, it was discovered that the BSFC increased with an increase in the bioethanol blending ratio in the coconut biodiesel blend across all engine loads. This phenomenon can be associated with decreases in the energy content of ternary blends of bioethanol-biodiesel-diesel fuel blend, as indicated in Table 2. As a result, with increases in the portion of bioethanol in the blends, the BSFC also increases. Another observation is that the BSFC decrease with the increase in engine torque for all test fuels. This signifies that the conversion of the fuel at a higher load is more effective. At higher engine loads, the high in-cylinder temperature and turbulence flow led to the atomization and proper mixing of fuel which resulted in higher combustion efficiency.

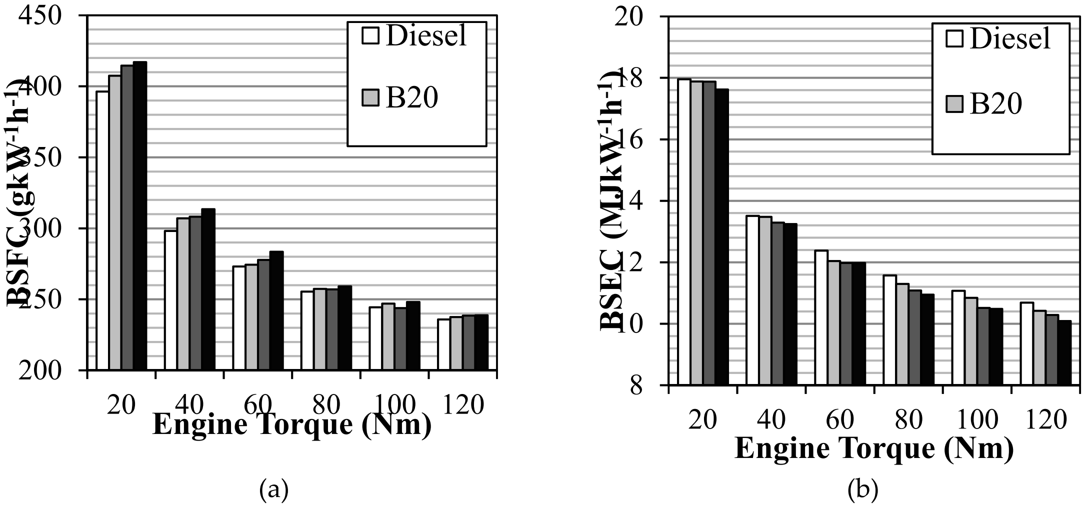

Figure 2. (**a**) BSFC and (**b**) BSEC for the tested fuels at different engine loads.

As shown in Figure 2b is the BSEC for all the tested fuels under various engine load conditions. BSEC is a more practical parameter than BSFC because it is independent of the fuel type and therefore more suitable for analysing the engine performance of fuels with different calorific values [48]. BSEC measures the energy input required to develop a unit power. The lower the value of BSEC, the better the efficiency of energy consumption is. On average, the results indicated that B20, B20E5 and B20E10 produce 1.7%, 3.1% and 3.9%, lower BSEC compared to baseline diesel fuel, respectively. This may be credited to the increased availability of fuel-bound oxygen in biodiesel and bioethanol fuel as shown in Table 1, which promoted better combustion efficiency [49]. Furthermore, the B20E10 marked the minimum BSEC among all the tested fuels across all engine torques. This is due to the less viscous property of the bioethanol, which strongly enhanced the fuel atomization process, thereby promoting complete combustion [50]. As illustrated in Table 2, it is apparent that the viscosity decreases as the percentage of bioethanol increases. Therefore, it aids a more complete combustion of the fuel and therefore lowering the energy consumption.

As shown in Figure 3 is the BTE for all the tested fuels under various engine load conditions. Generally, the results showed that the BTE increased with the increment in engine load. Also, the results indicated that the BTE of all blended fuels was consistently improved over the baseline diesel across all engine loads. For instance, the addition of 5% and 10% of bioethanol in the biodiesel-diesel fuel blend have each given a rise to the BTE by 0.4–5.3% and 1.9–5.9% respectively, with respect to baseline diesel. This trend can be attributed to the relatively lower viscosity of the bioethanol as explained in the aforementioned observation of BSEC result, thereby allowing a more complete mixing of air and fuel [51]. Similar observations were also recorded by other researchers. Imdadul et al. [52] and Anand et al. [53] observed that the ternary fuel blends (biodiesel, diesel, and alcohol) showed improved BTE over the binary blends of biodiesel-diesel and this phenomenon can be associated with the improvement in fuel properties. Another explanation is due to the improvements which related to the presence of rich oxygen molecules in the fuel blends of B20, B20E5 and B20E10 [54]. This characteristic will promote more complete combustion in the engine, thereby increasing the BTE. In addition, the results also reveal that the variations in BTE are very similar with the variation in BSEC, where the B20E10 fuel blend recorded the lowest energy consumption, thereby it had the greatest thermal efficiency.

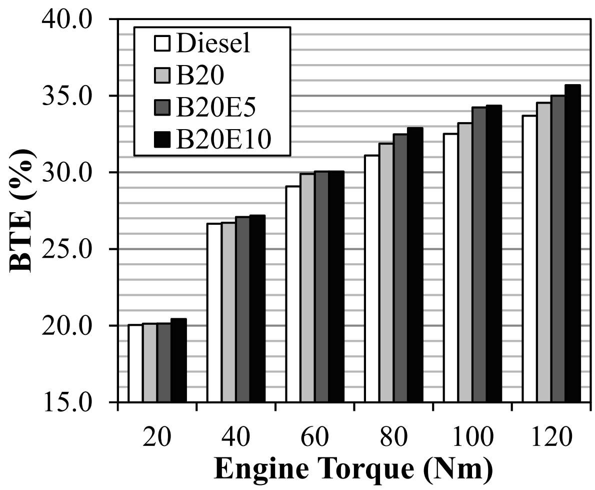

Figure 3. BTE for the tested fuels at different engine loads.

4.2. Exhaust Emissions

Potential human health effects and severe environmental issues are some of the greatest concerns that have arisen due to NOx emission from engines [55]. There are several factors contributing to NOx emission, such as the cylinder combustion temperature, oxygen content, residence time, fuel characteristics as well as the engine operating conditions [20]. The variation in NOx for all test fuels under various engine loads is depicted in Figure 4. In general, it can be observed that the B20 emitted higher NOx than the baseline diesel fuel across all engine load conditions. As indicated in Table 1, coconut biodiesel takes a greater weightage of oxygen content as compared to the diesel fuel, therefore resulting in an increased combustion temperature, and thereby promoting the formation of NOx [55]. This result is in good agreement with the findings obtained by Liaquat et al. [56].

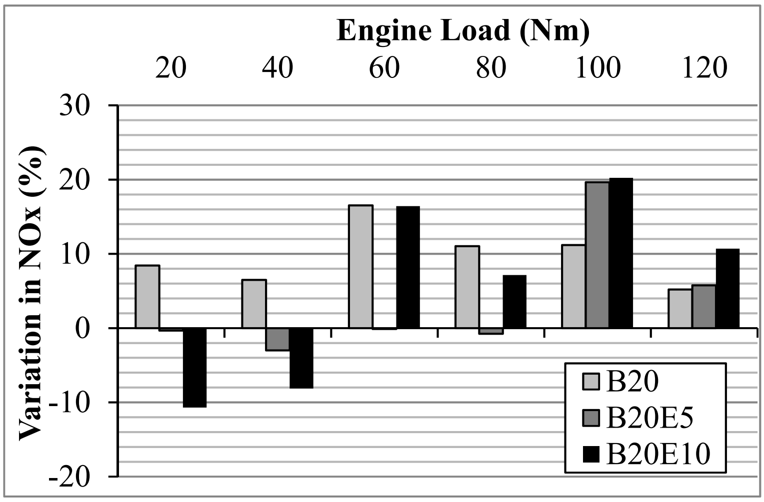

Figure 4. Variation in NOx emissions with the blends compared to diesel fuel as baseline.

At low engine load conditions, the addition of 5% and 10% of bioethanol in the blends indicated a drop in NOx emission by 0.3–3.0% and 8.1–10.7%, respectively. This phenomenon is mostly related to the evaporative cooling effect of the bioethanol, whereby the relatively lower calorific value and higher latent heat of vaporization [57] contributed to the drop of combustion temperature, hence reducing the NOx formation [58]. At medium engine load, there is no significant difference of NOx variation for B20E5 blend. Meanwhile, higher NOx emissions are produced by B20E5 and B20E10 at high engine load operations. This phenomenon can be associated to the higher oxygen content in bioethanol fuel, which therefore enhanced the NOx formation [59,60].

A similar trend in the variation of NOx emission was reported by Yilmaz et al. [61]. They used ternary blends of diesel-waste cooking oil biodiesel-ethanol and found that the NOx emission dropped with the increase of ethanol ratio at low engine load. They claimed that the evaporative cooling effect of the alcohol favoured the lower in-cylinder temperature, resulting in less formation of NOx. On the other hand, Atmanli [62] and Yilmaz [46] conducted a study on the engine characteristics for the effect of addition of alcohol in the fuel blends. They concluded that higher NOx emission was observed for the alcohol blended fuels. This is because of the oxygen enrichment in the alcohol blended fuels that led to an increase in combustion chamber temperature, thus resulting in more NOx emitted.

The exhaust emission of CO comes from the incomplete oxidation of the carbon particles in the fuel as a result of inadequate amount of oxygen for the complete oxidation [63]. The variation in CO emission with the oxygenated fuel blends compared to baseline diesel fuel is shown in Figure 5. Generally, the baseline diesel indicated the greatest emission of CO among all the tested fuel blends across all engine load conditions. The results showed that there were average reductions in CO emissions for B20, B20E5, and B20E10 of 3.2%, 7.5%, and 9.3%, respectively. The oxygenated fuel property of the coconut biodiesel and bioethanol-biodiesel blends was claimed to be the main reason for this situation, due to the more complete combustion process that occurred [64,65].

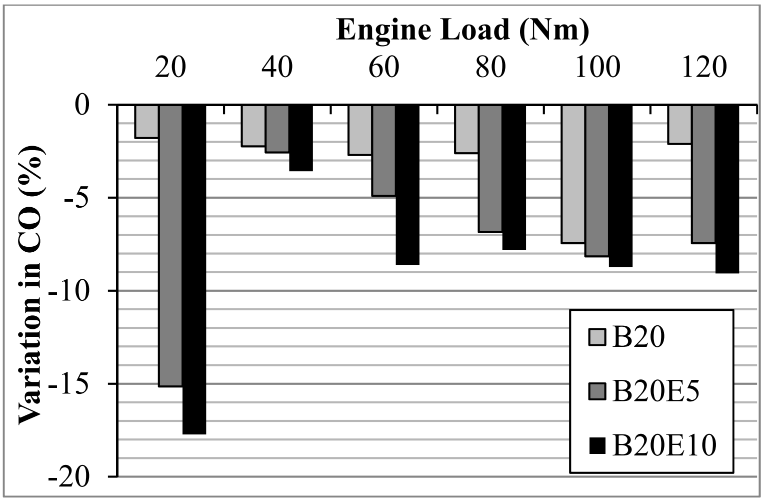

Figure 5. Variation in CO emissions with the blends compared to diesel fuel as a baseline.

Also, the lower kinematic viscosity of the bioethanol favoured the depletion of CO emission. This is due to the ethanol is ease of breaking down from its liquid form, especially for the fuel blend with 10% bioethanol and thus resulting in enhanced combustion process as compared to other tested fuels, which releasing less amount of CO. In fact, the most significant variation was noticed especially at the low engine load of 20 Nm. Generally, the emission of CO at low engine load is comparatively high due to combustion inefficiencies and relatively low in-cylinder combustion temperature. With bioethanol fuel in the blend, the oxygen content of ethanol may lead to a higher combustion efficiency, which results in a cleaner combustion process even at relatively low temperatures, therefore reducing the formation of CO.

Smoke is generated from the incomplete combustion process in the CI engine, and it is definitely undesirable exhaust emission [66]. Figure 6 represents the variation in smoke emission in the form of percentage difference as compared with the baseline diesel at various engine loads. Based on the results obtained, all fuel blends tested showed a significant reduction in smoke emission across all engine loads. This is mainly due to the fact that bioethanol has less carbon and more oxygen than baseline diesel, promoting an increase of the oxygen/fuel ratio and, consequently, improving the combustion process and resulting in lower CO emissions [67]. Also, the rich fuel-borne oxygen content in biodiesel and bioethanol blends promoted the oxidation of carbon atoms during the combustion process as reported in the literature [68–70]. Besides, the result also reveals that the variation of percentage difference in smoke is more prominent and higher with the increases in bioethanol concentration in the blend under all loading conditions. For instance, the percentage reductions of smoke for B20, B20E5, and B20E10 are 11%, 42%, and 52%, respectively as compared to baseline diesel at high engine load of 120 Nm. In general, the blending of bioethanol with the biodiesel-diesel mixture favoured noticeably improved smoke emissions.

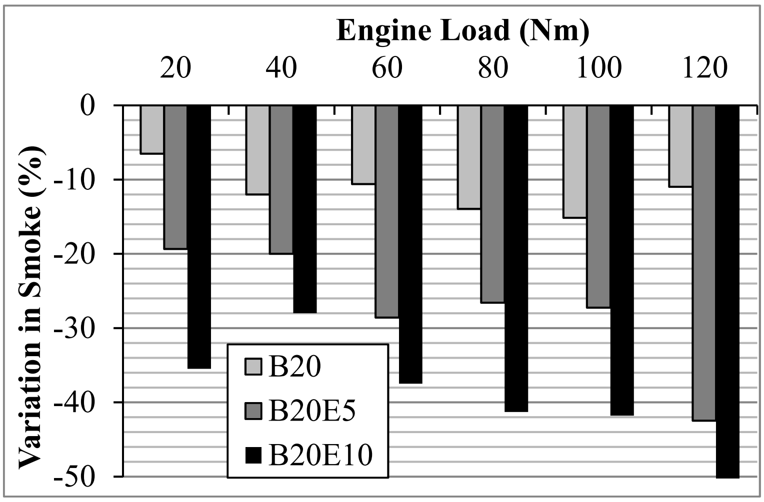

Figure 6. Variation in smoke emissions with the blends compared to diesel fuel as baseline.

4.3. Combustion Characteristics

Figure 7 illustrates the plot of in-cylinder combustion pressure versus crank angle for all the tested fuels under different engine load conditions. Generally, it can be seen that the first peak pressure for all the fuel blends are comparable to that of baseline diesel at all engine loads, except for 20 Nm. Specifically, at the top dead center (TDC), the B20E10 achieved the greatest first peak pressure of 53.82 bar, while the lowest first peak pressure was recorded with 51.59 bar by the B20 at the crank angle of −1 °ATDC (degree after top dead center). Noticeably, the trend indicated a rise in the first peak pressure with the addition of bioethanol in the blends, but it dropped without bioethanol as compared to the baseline diesel.

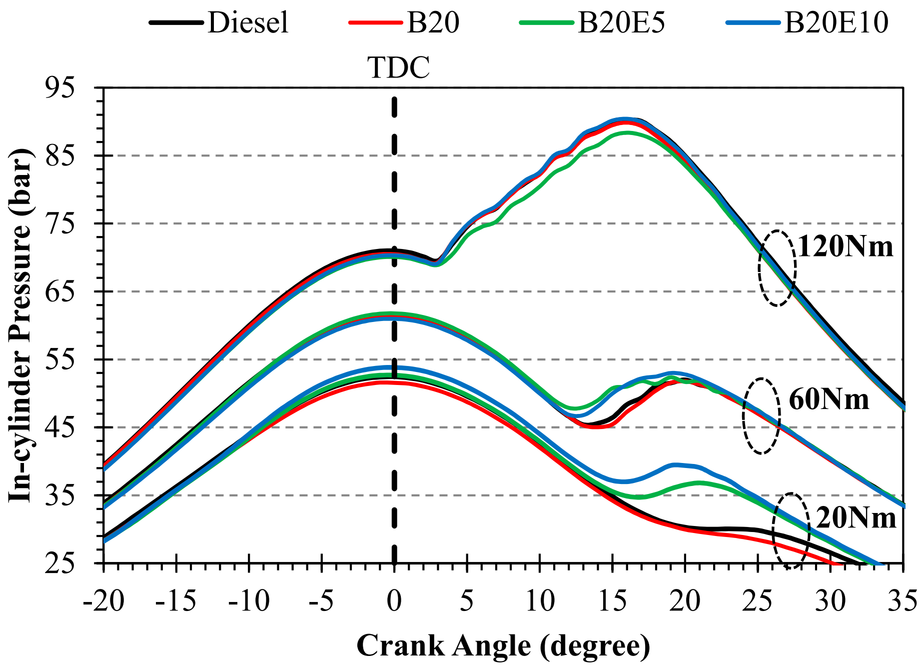

Figure 7. The variation in combustion pressure for diesel, B20 and B20E5 at an engine load of 20 Nm, 60 Nm, and 120 Nm.

At medium engine load of 60 Nm, it was observed that there was no significant variation in the first peak pressure for all types of tested fuel. On the other hand, the second peak pressure of the B20E10 blend was slightly on top of others, recording a value of 52.99 bar at 19 °ATDC. In general, the B20E10 blend achieved greater peak in-cylinder pressure as compared to other tested fuel. This is mostly due to the less viscous property of the bioethanol, which further lowered the kinematic viscosity of the fuel blends, hence enhancing the fuel atomization process [69,71]. Also, bioethanol has much higher oxygen content, resulting in a shorter ignition delay. The relationship of the oxygen content and the ignition delay was also found by other researcher [72].

Besides, it can be seen that the second peaks cylinder pressure for both of the B20E5 and B20E10 fuel blends tend to shift nearer to the TDC at low and medium engine loads. This phenomenon demonstrated that the combustion process started earlier, consequently leading to a more complete combustion and greater in-cylinder pressure [73]. A similar observation was also found at the high engine load of 120 Nm, but the B20E5 blend marked a slight deterioration in the second peak pressure as compared to that of baseline diesel fuel, from 90.26 bar to 88.36 bar, while others showed a comparable magnitude. This situation was mostly due to the dominant effect of calorific value over the oxygen content at the high engine load.

Another worthy observation that can be observed is that the first peaks cylinder pressure at the engine load of 20 Nm and 60 Nm were lower than the second peaks cylinder pressure, except at higher load of 120 Nm. This can be attributed to the pilot combustion phase occurred due to the pilot fuel injection, resulting higher in-cylinder temperature during the compression stroke, thereby raising the peak in-cylinder pressure. At a high engine load of 120 Nm, the main injection takes over the dominant effect, causing greater heat released and higher in-cylinder pressure. Also, the greater amount of heat released at high engine load also favoured the utilization of fuel energy, hence producing more power at the main combustion phase.

In the analysis of HRR curve, for engine load of 20 Nm, the B20E10 fuel blend marked the maximum peak HRR of 22.62 J/°CA at 19 °ATDC, while the B20 blend showed the lowest peak HRR of 13.96 J/°CA at 23 °ATDC, as shown in Figure 8. In fact, the general trend indicates that the variations in peak HRR are very similar with the variation in the second peak in-cylinder pressure. Also, the excess oxygen atoms contained in the hydroxyl group of the ethanol promoted an efficient combustion, resulting in more heat being released. In addition, the decrease in the peak HRR of the B20 blend was mostly attributed to the lower calorific value, and thus leads to the lower amount of heat released during combustion [47].

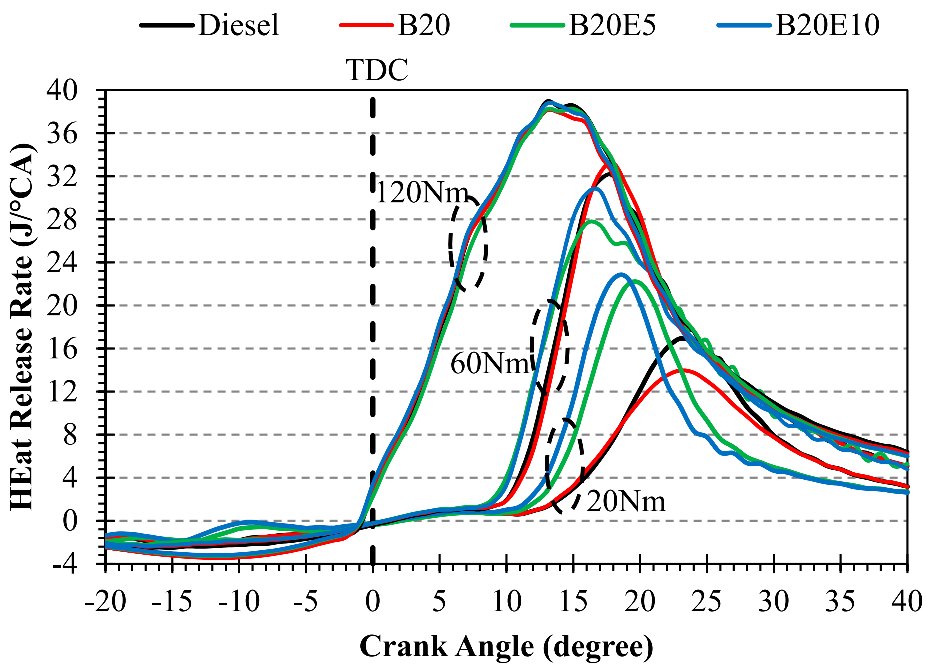

Figure 8. The variation in heat release rate for diesel, B20 and B20E5 at an engine load of 20 Nm, 60 Nm, and 120 Nm.

Furthermore, the minimal rise in the HRR before the TDC recorded by both the B20E5 and B20E10 blends was mostly due to their physicochemical property, especially their relatively lower flash points. Based on Table 1, it can be seen that the flash point of bioethanol is much smaller compared to baseline diesel and coconut biodiesel. Therefore, the fuel reached the auto-ignition temperature before the TDC due to the compression of the fuel. To this end, the combustion of the pilot injection fuel started earlier and marked an insignificant rise before the TDC. With engine load increased to 60 Nm, the highest peak HRR recorded was 33.20 J/°CA by the B20 blend at the crank angle of 18 °ATDC. On the other hand, the B20E5 blend achieved the minimum peak HRR of 27.63 J/°CA at the crank angle of 16 °ATDC. The lower calorific value of the bioethanol contributed lower total heat released, thereby reducing the peak HRR. At a higher engine load of 120 Nm, the HRR curve for all tested fuels are comparable, where the peaks HRR recorded were occurred at the crank angle of 15 °ATDC for B20E5 and 13 °ATDC for other blends and diesel fuel. This situation is credited to the balance achieved by the physicochemical properties of the fuel at the high engine load, resulting in a similar rate of the fuel burned and consequently comparable HRR curves.

The results for the peak in-cylinder pressure and peak HRR are in good agreement with the published researches by other authors. In a research conducted by Yang et al. [49] on the application of pentanol-biodiesel blends in diesel engine, they confirmed that the alcohol influenced in the rise of the maximum in-cylinder pressure and the peak HRR, due to earlier timing of start of combustion. Also, Qi et al. [74] evaluated the combustion behaviour by using ethanol-tung oil-diesel blends as their fuels. Based on the results obtained, the peak combustion pressure and the peak HRR for bioethanol blended fuels were above those obtained for the baseline diesel.

Another worthy observation from the combustion analysis is the mass fraction burned of the fuels. Figure 9 indicates the mass fraction burned of the tested fuel at various crank angles, whereby the dotted lines are the different mass fraction burned, such as 10% (CA10), 50% (CA50) and 90% (CA90). Based on the figure, it was found that all the tested fuels have similar mass fraction burned at all engine loads, except for 20 Nm. For instance, the B20E10 blend achieved the steeper curve of the mass fraction burned with the shorter combustion duration.

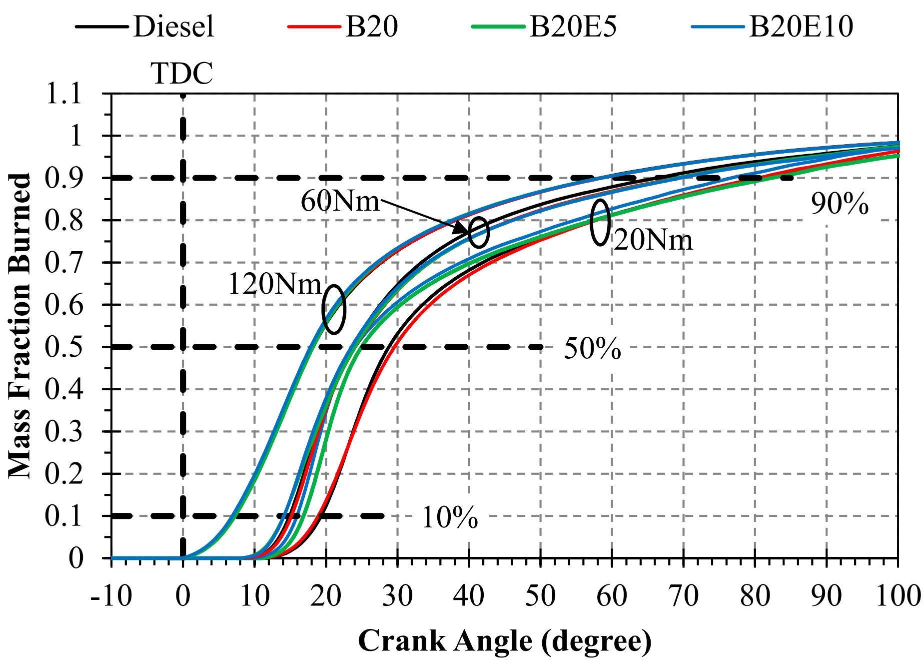

Figure 9. Variation in mass fraction burned for all tested fuels at an engine load of 20 Nm, 60 Nm, and 120 Nm.

Furthermore, it can be seen that the B20E10 reached the 90% mass fraction burned earlier than other fuels. This observation is in agreement with another author, Alptekin [71] who claimed that the alcohol-based fuels tend to shift the CA10 and CA90 values earlier. This is ascribed to the shorter ignition delay as discussed earlier, enabling the combustion to start slightly earlier than other tested fuels. Although the start of combustion timing was occurred at about the same crank angle of 9° ATDC, there was still some variation in the earlier occurrence of combustion for both of the B20E5 and B20E10 fuels. This could be explained by the lower kinematic viscosity and density of the bioethanol and, consequently caused the blended fuel vaporized faster and mixed well with the intake air [71]. Besides, it can be observed that the B20E10 showed shorter combustion duration, which reduced by an average of 1.375 °CA compared to the corresponding baseline diesel. As a result, energy was released at a faster rate, which reduced the heat loss from the engine as there is insufficient time for this heat to leave the cylinder via heat transfer to the coolant. Moreover, the slight gain in the BTE with increased bioethanol substitution as aforementioned can be attributed to the same reason that is responsible for the slightly faster rate of combustion.

5. Conclusions

In this study, the effect of bioethanol as a fuel additive in coconut biodiesel blends was studied in a four-cylinder, direct-injection and common-rail diesel engine. The addition of bioethanol into the 20% coconut biodiesel blends was found feasible and it minimized the issues originating from the biodiesel. Notably, 5% and 10% bioethanol on a volume basis were separately added into the B20 blend to compare their respective performance. The following main conclusion can be drawn from this investigation:

1. An improvement in the BSEC and BTE of the blends at the expense of brake specific fuel consumption (BSFC) can be observed for each bioethanol blend.
2. A higher percentage of bioethanol blends causes an increment in NOx across the entire load range, except at low load condition.
3. Simultaneous smoke and CO emission reduction from the baseline levels of petroleum diesel fuel can be attained by utilizing all types of fuel blends. Besides, the results showed that B20E10 achieved the highest average reduction of 9.3% and 52% in smoke and CO emissions, respectively, as compared to the baseline diesel.
4. An increment in both of the peak in-cylinder pressure and HRR can be observed with the utilization of bioethanol blended fuels at the low engine load, especially for the B20E10 blend. Besides, the combustion process is comparable at the medium and high load for all the tested fuels. In addition, the B20E10 showed shorter combustion duration, which reduced by an average of 1.375 °CA compared to the corresponding baseline diesel.

Overall, the experimental results proved that the B20E10 blend exhibited great improvements in the diesel engine, thus, bioethanol is a feasible fuel additive for the coconut biodiesel-diesel blends.

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