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An Experimental Investigation on the Characteristics of a Compression Ignition Engine Fuelled by Diesel-Palm Biodiesel–Ethanol/Propanol Based Ternary Blends

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Abstract: Issues such as rising fuel prices, fuel costs, and lowering reserves highlight the importance of research into sustainable fuels derived from biological sources. This study is focused on experiments on a CI engine using ethanol and propanol-based ternary blends. Palm biodiesel is kept constant at 40% volumetric concentration, while diesel and ethanol/propanol are varied in different batches. The results obtained with ternary blends were compared with reference fuel diesel, pure palm biodiesel, and a palm biodiesel–diesel binary blend. The ternary blends exhibit lower brake thermal efficiency and higher brake specific energy consumption than diesel and binary blends due to their lower calorific value. Despite in-fuel oxygen presence, lower brake specific oxides of nitrogen and smoke opacity were observed for engine operation with a ternary blend due to the predominant role of higher latent heat of vaporization and volatility of alcohols, but unburned hydrocarbon and carbon monoxide emissions increased due to the interactive effect of a lower cetane number, higher latent heat of vaporization, and lower kinematic viscosity of alcohols when compared to reference fuels. Among the tested fuels, in-cylinder pressure was observed to decrease with ternary blends due to their lower calorific value, but a raised heat release rate was attributed to lower viscosity and faster burning of alcohols.

Keywords: biodiesel; alcohol; ternary blends; sustainable fuel; CI engine

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1. Introduction

Since the advent of automobiles, fossil fuels have seen growing demands, and they are set to peak in the upcoming years due to the transition to cleaner energy sources [1]. According to a 2021 report by British Petroleum [2], the proven global petroleum reserves stand at 244,400 million tonnes. The fuel price surge [3] does not only correlate with a typical rise in consumer demand but also depends on geopolitical [4] and economic factors [5]. In addition, such rises in fuel costs are a huge problem for both businesses and individuals to overcome [6]. Fossil-fueled vehicles are well known to have a detrimental effect on air quality [7] and human health [8]. When compared to results obtained during approval tests, diesel-powered cars were found to emit 4–7 times more nitrogen oxide (NO_X) emissions.

In 2013 [9], the NO_X emissions from diesel-powered vehicles were attributed to the nearly 10,000 premature deaths from particulate matter ($PM_{2.5}$) and ozone in the adult population greater than 30 years of age. The combined issue of rising fuel demand, fuel costs, and air pollution motivates us to move ahead in search of better solutions for the long term. In this study, biofuels from numerous feedstocks [10] are promoted to replace existing fossil fuels such as gasoline and diesel [11]. However, not all feedstocks can be good candidates for commercial sale as transport fuel due to the limited availability of the feedstock itself [12]. This stems from the fact that if large quantities of biodiesel were produced from edible oils, then it could lead to an edible oil shortage, thus affecting human consumption [13] and cooking [14]. So, newer generation biodiesels derived from non-edible natural sources such as algae are being studied [15]. Malaysia [16] and Indonesia [17] are two of the largest palm oil producers in the world. Palm oil is an edible oil that can be used for both cooking and as a biodiesel feedstock [18]. In a study by Chen et al. [19], it was reported that elevated ischemic heart disease mortality rates could be attributed to higher palm oil consumption in developing countries. This effect can be a deviating factor in converting palm oil for biodiesel use only and relying on other edible oils for human consumption. According to a market research analyst [20], the biofuel market is set to be worth $51.47 billion by the year 2029. The proceeds from biodiesel sales could be invested in such a way that will lead to overcoming socio-economic woes [21].

Recently, the experimental studies using ternary fuel blends on CI engines have been extensively investigated globally. In this regard, Prakash et al. [22] used castor oil–diesel–ethanol-based ternary fuel blends in their experiment to study the characteristics of the Kirloskar TV1 compression ignition (CI) engine. They report that at full engine loading with B40D30E30 and diesel fueling, the brake thermal efficiency (BTE) was at 31.25 and 32.94%, brake-specific nitrogen oxide ($BSNO_X$) emission was at 6.11 and 8.17 g/kWh, smoke opacity (SM) was at 68% and 57%, brake-specific energy consumption (BSEC) was observed to be 11.87 and 10.38 MJ/kWh, and ignition delay (ID) was at 13 and 9 CAD, respectively. Waste cooking oil biodiesel–diesel–ethanol fuel blends were used by El-Sheekh et al. [23] in their study on the characteristics of a Deutz FL511/W CI engine. Further, with B40D40E20 blend fueling, BTE increased and was observed to be 33% at full engine load when compared to operation with B50D50 blend at 27% BTE. The NO_X formation is significantly reduced with 10% ethanol enrichment, while 20% ethanol blending reduces hydrocarbon (HC) and carbon monoxide (CO) emissions.

Mukhtar et al. [24] used palm oil–diesel–ethanol-based fuel blends in their experiment to study the characteristics of the Yanmar TF120 CI engine. The results show that at full engine loading conditions, the B5D90E5 blend exhibits an average indicated mean effective pressure (IMEP) of 6.14 bars, followed by diesel at 5.96 bar, and the B15D70E15 blend at 4.56 bar. The B5D90E5 attains the highest in-cylinder pressure (CP), followed by the B15D70E15 and diesel fuel. The ID is observed to be higher for ternary blends when compared to diesel fuel operations. The biodiesel-diesel-ethanol fuel blends were used by Bhurat et al. [25] in their research on the characteristics of a CI engine. In addition, with ethanol blending, NO_X emissions are higher when compared to diesel fueling. Further, the HC and CO emissions were also reportedly higher for all engine loads with ternary blends. The brake specific fuel consumption (BSFC) increased for ethanol-blended operation but was comparable to diesel at medium-to-high engine load.

Kulanthaivel et al. [26] used algae biodiesel-diesel-anhydrous ethanol-based ternary blends in their study on the characteristics of a Kirloskar CI engine and reported higher BSFC and lower BTE with ternary blend fueling when compared to pure diesel. Azadirachta indica biodiesel-diesel-ethanol fuel blends were used by Satish et al. [27] in their study on the characteristics of a CI engine. The D60B20E20 fuel blend resulted in 4.25% and 4.43% higher BTE and NO_X emissions and 18% and 8.54% lower CO and HC emissions when compared to pure diesel fuel operation.

Zuo et al. [28] used cotton seed oil-diesel–ethanol-based ternary fuel blends in their experiment to study the characteristics of the 4B28V16 CI engine. They report that ternary blends exhibit larger CO and HC emissions and lower SM than other tested fuels. Moringa seed oil Diesel–ethanol fuel blends were used by Jegadheesan et al. [29] in their study on the characteristics of a CI engine. They report that when compared to diesel, higher BTE, CP, Heat Release Rate (HRR), and NO_X with ternary fuel engine operation. Kandasamy et al. [30] used cotton seed oil–diesel–ethanol-based ternary fuel blends in their experiment to study the durability characteristics of the CI engine. In addition, after 500 h of durability testing, the cylinder pressure and lubricating oil consumption were higher for the B5D75E20 blend when compared to the B5D95 fuel. Further, within the entire engine speed range, both SM and CO were seen to be lower while HC and NO_X were reduced at lower and medium engine speeds, respectively.

Ghadikolaei et al. [31] used waste cooking oil-diesel–propanol-based fuel blends in their experiment to study the characteristics of the Isuzu 4HF1 CI engine. They report that the highest CP for all tested fuels increased slightly. However, decreases in BSCO and $BSCO_2$ were observed with ternary blend base engine operation. Bencheikh et al. [32] also used waste cooking oil–diesel–propanol-based fuel blends in their experiment to study the performance and emission characteristics of the Katana KM178FE CI engine. The results show that when compared to pure diesel fueling, using B5D80E15, B10D80E10, and B15D80E5 reduced SM by 2.85%, 2.56%, and 1.59%, reduced NO_X emissions by 3.56, 3.08, and 2.85 ppm, and CO emissions by 16.98%, 1.42%, and 15.09%, but increased BSFC by 8.33%, 8.07%, and 4.95%, respectively. Jatropha biodiesel-diesel-propanol fuel blends were used by Ahmed et al. [33] in their research on the characteristics of a CI engine. The results showed that BSFC increased and power dropped when the engine was run on propanol-blend fuel. Similar findings were reported by Gad et al. [34] in their study of a Deutz F1L511 CI engine fueled by a Mandarin essential oil–diesel–propanol fuel blend.

Motive of Work

The discussion in the former section reports numerous experiments on ternary fuel blends utilising a variety of biodiesel feedstocks. However, for better mass adoption, there is a need for further research on ternary fuel blends involving commercially marketed biodiesel. In this respect, palm biodiesel was seen as a prime candidate due to high feedstock availability, well established biodiesel production facilities, distribution infrastructure, and a readily available market for mass adoption. These scenarios hold true in countries such as Malaysia and Indonesia, where palm biodiesel blends are commercially available for the transportation sector [35]. Almost a decade earlier, in 2011, Malaysia introduced diesel–palm biodiesel B5D95 blends. This was followed by the subsequent release of increased palm biodiesel blending in the year 2014 with a B7D93 blend and a B10D90 blend in the year 2018 [36]. By the end of the year 2022, it also plans to make a B20D80 blend for consumers [37]. Malaysia was planning to upgrade its refineries in order to turn out B30D30 blends and also had consultations with numerous associates [38]. Indonesia, the neighbouring equatorial country, is a step ahead of Malaysia in terms of biodiesel implementation and currently markets palm-based B30D70 blends for its inland consumers. This was mandated in order to reduce its reliance on imported petro-diesel fuel [39], and it also plans to raise it to B35D65 blending standards [40]. As of the year 2022, the country is also testing B40D60 blends in six Toyota Innova cars. The vehicles will traverse the country, and test data will be studied for the feasibility of using high-concentrated biodiesel fuel in CI engines [41].

In addition, with respect to the second fuel in the ternary blend, alcohols possessing a higher latent heat of vaporisation were the primary criteria for selection. This physiochemical property helps in lowering combustion temperatures and thus hindering NO_X formation. In this study, lower-order alcohols such as ethanol and propanol exhibit elevated standards of latent heat of evaporation compared to alcohols in the higher order. However, this preferred physiochemical property comes with a trade-off of a lowered cetane number (CN) in the respective alcohol [42]. The higher-order alcohols possess CN values closer to those of diesel, but their lower latent heat of vaporization negates the purpose of their use in blended form, as the intended motive is to reduce NO_X formation. Another added advantage of alcohols such as ethanol [43] and propanol [44] is that they can be derived from biomass. The third fuel in the blend is petro-diesel, and here the common notion is to increase the volume concentration of biodiesel and alcohol in the ternary blend, thus lowering the need for fossil-based diesel.

Further, when reviewing prior literature, a study by Mukhtar et al. [24] using palm biodiesel-diesel–ethanol blends B5D90E5 and B15D70E15 is identified as falling in line with the purpose of this work of using commercially available biodiesel feedstock in ternary blends. As earlier indicated, countries are planning to implement biodiesel blending rates as high as 40% to supplement diesel. In addition, no studies were found using palm biodiesel-diesel–propanol blends. So, this work will explore using palm biodiesel-diesel–ethanol blends and palm biodiesel–diesel–propanol blends, where palm biodiesel blends are kept at a constant 40% of the overall ternary blend volume. While volumetric concentrations of diesel-ethanol in the first batch and diesel-propanol in the second batch are varied in the ternary blend.

The task ahead is to identify the optimum blend concentration that exhibits elevated combustion, performance, and lower exhaust emission values when used in a CI engine. Standard diesel, pure palm biodiesel (B100), and palm biodiesel-diesel (B40D60)-based binary blends are also tested in order to serve as reference fuels, so the scope of operating a CI engine with ternary blends can be effectively judged. The structure of this article is defined in the following: Section 1 emphasises the need for biofuels, summarises prior studies on ternary blends, and highlights the importance and novelty of this study. The description of fuel preparation and experimental setup is provided in Section 2. Section 3 describes the outcome of the test results in terms of various performance, emission, and combustion parameters, with illustrations. Finally, the study is concluded with key takeaways and a heat map for graphical comparison.

2. Materials and Methods

2.1. Fuel Preparation

In order to prepare ternary blends, palm oil was procured in the required quantities from the local market and sent to the Biofuels Lab at the Center for Waste Management at the Sathyabama Institute of Science and Technology, India. In this study, raw palm oil is converted into biodiesel using the transesterification process. The process parameters for raw palm oil to biodiesel conversion are reported in Table 1. Before studying the physiochemical properties, the biodiesel composition analysis was performed using a Gas Chromatography-Flame Ionization Detection (GC-FID) instrument available at the same facility. The assessment results are illustrated in Figure 1, with their respective identified compound names reported in Table 2. Once the processed palm biodiesel was received from the biofuel lab, other fuels such as ethanol, propanol, and diesel required for the test were procured from local suppliers. Then the blends were prepared in various volumetric concentrations and later tested for their physiochemical properties. Furthermore, the values of kinematic viscosity (KV) and CN for binary and ternary blends were calculated using the Kay mixing rule [45] and are indicated using the * symbol. The data is tabulated in Tables 3 and 4, respectively.

Table 1. Transesterification process parameters for palm oil.

Parameters	Results
Free fatty acid	0.21%
Catalyst (NaOH) quantity	0.5 wt.%
Oil to Methanol molar ratio	1:6
Temperature	60 °C
Reaction time	90 min
Yield	96.5%

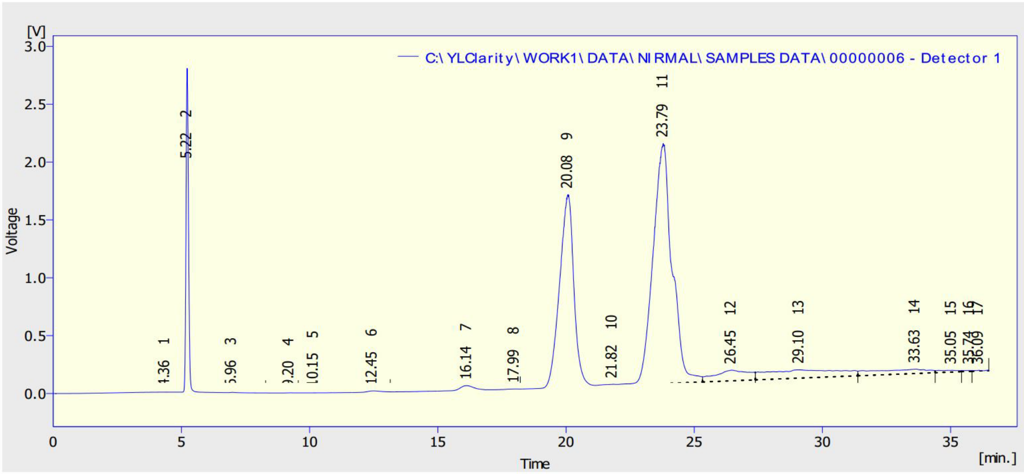

Figure 1. Results from GC-FID instrument with palm biodiesel sample. Dotted line shows overall trend.

Table 2. Compounds identified in palm biodiesel sample using GC-FID.

S. No	Retention Time (min)	Area (mV.S)	Compound Name
1	4.363	1180.947	Methanol
2	5.223	19,755.900	Methyl hexonate
3	6.960	210.017	Methyl caproate
4	9.203	19.848	Methyl dodecanoate
5	10.153	3.070	Methyl Palmitate
6	12.453	362.277	Methyl Oleate
7	16.137	1557.738	Methyl caproate
8	17.990	73.597	Methyl heptadecanoate
9	20.077	64,529.002	Methyl stearate
10	21.817	487.417	Methyl oleate
11	23.793	107,362.941	Methyl decanoate
12	26.453	8465.260	Methyl undecanoate
13	29.103	14,233.112	Methyl dodecanoate
14	33.627	6192.297	Methyl tridecanoate
15	35.047	912.875	Methyl myristate
16	35.743	197.500	Methyl myristrate
17	36.093	133.365	Methyl myristoleate

Table 3. Volumetric (%) concentration of tested fuels.

Nomenclature	Diesel	Palm Biodiesel	Ethanol	Propanol
Diesel	100	0	0	0
B100	0	100	0	0
B40D60	60	40	0	0
B40D50E10	50	40	10	0
B40D40E20	40	40	20	0
B40D30E30	30	40	30	0
B40D50P10	50	40	0	10
B40D40P20	40	40	0	20
B40D30P30	30	40	0	30

2.2. Experimental Procedure and Setup

Once the required reference fuels and ternary fuel blends were prepared, the experiments on a constant-speed CI engine were carried out at a for-hire test facility located in Chennai, India. First, the engine was cranked with diesel fuel and allowed to run until it reached a steady operating temperature. Then the dynamometer load was incrementally increased until the 100% engine loading capacity was reached. Once the engine attained steady state conditions, the test readings were documented for various performance, combustion, and emission characteristics, such as engine load, engine speed, airflow rate, fuel flow rate, in-cylinder pressure, NO_X, HC, CO, and SM. The average in-cylinder pressure crank angle data was processed from a dataset of 100 consecutive cycles retrieved using a data acquisition system. The same procedure was repeated for other test fuels. The technical specifications of the test engine are provided in Table 5, and a schematic of the test setup is presented in Figure 2. The experimental conditions, calibration, and environment can all lead to errors. In order to confirm the dependability of experiments, defining uncertainty is essential. The uncertainty calculation presented in Equation (1) is based on methodology developed by Kline [48].

$$\begin{aligned}\text{Uncertainty} &= \text{Square root of }[(\text{uncertainty of BTE})^2 + (\text{uncertainty of BSEC})^2 \\ &\quad + (\text{uncertainty of NO}_x)^2 + (\text{uncertainty of CO})^2 + (\text{uncertainty of HC})^2 \\ &\quad + (\text{Uncertainty of SM})^2] \\ &= \sqrt{1^2 + 1^2 + 1.76^2 + 0.2^2 + 1.54^2 + 1.21^2} \\ &= \pm 2.996\%\end{aligned} \tag{1}$$

Table 4. Physiochemical properties of various fuels.

Property	**Density @ 15 °C**	**KV@ 40 °C**	**CV**	**CN**
Units	**kg/m^3**	**cSt**	**MJ/kg**	
Standards	**ASTMD4052M**	**ASTMD445**	**ASTMD240**	**ASTMD4737**
Diesel [42]	835	2.72	42.50	52
Ethanol [42]	789	1.13	26.83	8
Propanol [37]	803	1.74	30.63	12
Palm Oil	920	12.3	31.19	84 [46]
B100	875	4.5	38.49	61 [47]
B40D60	864	3.43 *	40.89	55.60 *
B40D50E10	860	3.27 *	39.33	49.04 *
B40D40E20	853	3.11 *	37.76	44.64 *
B40D30E30	847	2.95 *	36.19	40.24 *
B40D50P10	860	3.33 *	39.71	49.44 *
B40D40P20	850	3.23 *	38.52	45.44 *
B40D30P30	845	3.13 *	37.33	41.44 *

* Calculated.

Table 5. Technical details of the test rig.

Parameter	**Specification**
Engine	Make Kirloskar, Model TV1, Type 1 cylinder, 4 stroke diesel, water cooled, power 5.2 kW @ 1500 rpm, stroke 110 mm, bore 87.5 mm. 661 cc, CR 17.5, injection pressure 200 bar, injection timing 23 CAD BTDC.
Dynamometer	SAJ ED1, Eddy Current Type, Rated Power 7.5 kW @ 3000 rpm
Piezo sensor	Range 5000 PSI, with low noise cable
Crank angle sensor	Resolution 1 Deg, Speed 5500 RPM with TDC pulse
Data acquisition device	National Instruments, USB-6210, 16-bit, 250 kS/s
Piezo powering unit	Model AX-409
Load sensor	Load cell, type strain gauge, range 0–50 kg
Software	"Enginesoft" Engine performance analysis software
Gas analyzer	AVL Di-Gas 444, HC 0–20,000 ppm volume, CO 0–10% by volume, NO 0–5000 ppm volume
Smoke meter	AVL 437, 0–100% SM

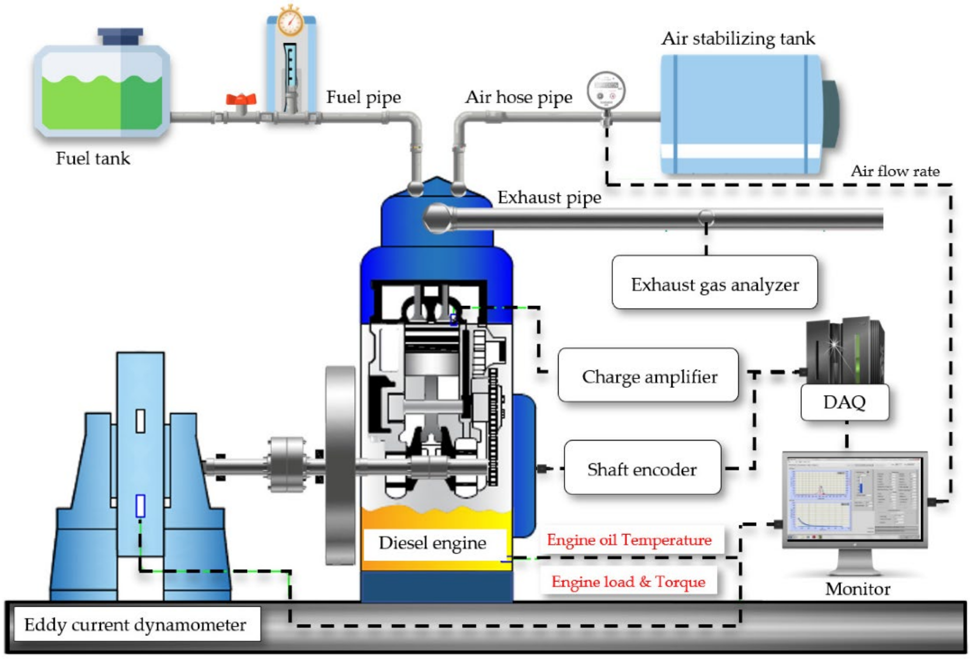

Figure 2. Schematic illustration of the experimental setup [49].

3. Results and Discussion

In this section, the experimental results are comparatively evaluated under the performance, emission, and combustion characteristic verticals to identify the optimum ternary blend for use in CI engine. The inference with respect to each parameter is described below:

3.1. Performance

The BTE obtained for all tested fuels at 100% engine loading is illustrated in Figure 3. It can be inferred that BTE for reference fuels such as diesel, B100, and B40D60 is 29.9%, 26.7%, and 28.5%, respectively. The ethanol-based ternary blends such as B40D50E10, B40D40E20, and B40D30E30 attained 27.3%, 26.4%, and 26%, respectively, whereas propanol-based ternary blends such as B40D50P10, B40D40P20, and B40D30P30 attained 27.8%, 27%, and 26.2%, respectively. Compared to diesel, all other fuels score lower in terms of BTE. The presence of diesel in the B40D50 binary blend raises its BTE by 1.8%. In addition, with ternary blends, the increasing volumetric presence of alcohols such as ethanol and propanol in their respective blends results in decreasing BTE values. These characteristics can be attributed to the CV of tested fuels [50,51]. Overall, B40D30E30 and B40D30P30 blends saw the highest decline among the tested fuels in BTE, and in comparison to diesel, the drop was estimated at 3.9% and 3.7%, respectively. Other ternary blends, such as B40D50P10, B40D40P20, B40D50E10, and B40D40E20, saw similar drops in BTE values of 2.1%, 2.9%, 2.6%, and 3.5%, respectively, when compared to diesel. Similar observations were also seen by Satish et al. [27] and Kulanthaivel et al. [26] in their experiments using ternary blends.

Figure 4 depicts BSEC data for all tested fuels at 100% engine loading condition. The BSEC is a better indicator than BSFC [52], as it accounts for the CV of the respective fuel along with fuel consumed, as the tested engine is designed for governor-controlled constant speed operation. Typically, as the engine load increases, the engine speed decreases equally. Here, the governor releases more fuel to maintain the desired engine speed. As diesel has the highest CV, it releases more heat energy per volumetric unit of fuel when compared to other tested fuels. Thus, the engine consumes less diesel fuel. The BSEC values are 12.1 MJ/kWh, 13.3 MJ/kWh, and 12.6 MJ/kWh for diesel, B100, and B40D60, respectively. The obtained values for propanol-based ternary blends B40D50P10, B40D40P20, and B40D30P30 are 12.9 MJ/kWh, 13.3 MJ/kWh, and 13.7 MJ/kWh, respectively. Meanwhile, 13.1 MJ/kWh, 13.5 MJ/kWh, and 13.8 MJ/kWh were noted for the ethanol-based ternary blends B40D50E10, B40D40E20, and B40D30E30, respectively. In a comparative perspective among the tested fuels, engine operation with the fuel blend containing the highest alcohol concentration consumed more energy. In relation to the B40D60 binary blend, it is calculated to be about an increase of 1.2 MJ/kWh and 1.1 MJ/kWh for B40D30E30 and B40D30P30, respectively. On the other hand, a similar increase of 0.5 MJ/kWh, 0.9 MJ/kWh, 0.3 MJ/kWh, and 0.7 MJ/kWh was seen for blends B40D50E10, B40D40E20, B40D50P10, and B40D40P20 individually when compared to the B40D60 blend.

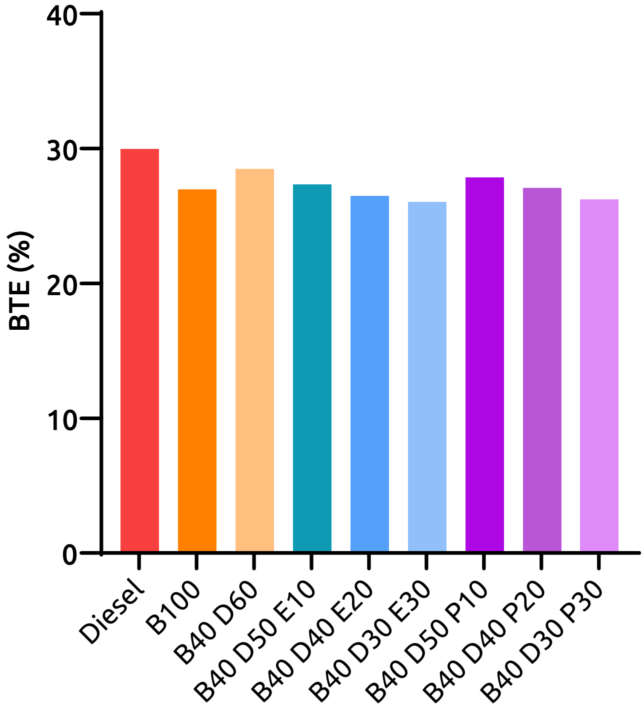

Figure 3. Brake thermal efficiency for tested fuels at full engine load.

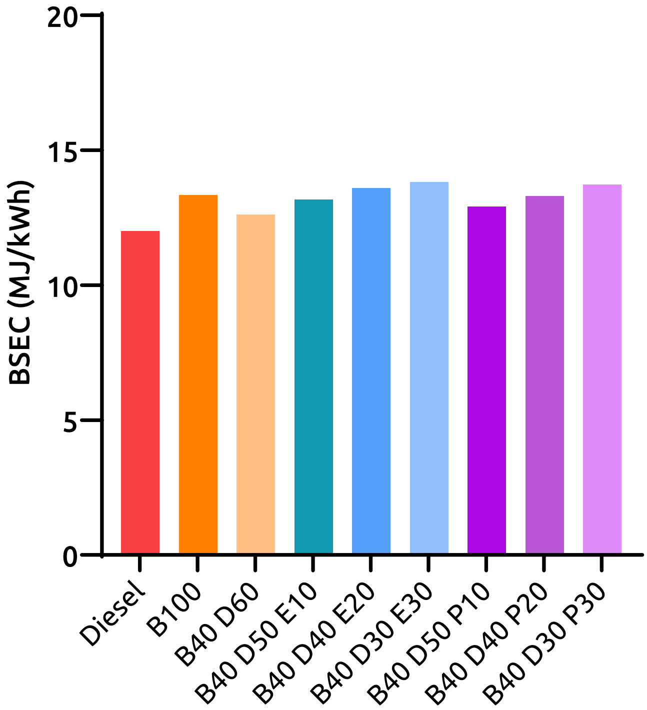

Figure 4. Brake specific energy consumption for tested fuels at full engine load.

3.2. Combustion

The CP recorded for all tested fuels at 100% engine loading is shown in Figure 5. The maximum CP for reference fuels diesel, B100, and B40D60 are 71.91 bars, 68.62 bars, and 70.1 bars, respectively. The ternary blends B40D50E10, B40D40E20, and B40D30E30 containing ethanol reported 69.29 bar, 68.42 bar, and 67.85 bar, respectively, while the propanol-based blends B40D50P10, B40D40P20, and B40D30P30 reported 69.80 bar, 68.88 bar, and 68.08 bar, respectively. In a comparative analysis among the tested fuels, the highest in-cylinder pressure was denoted for diesel-fueled engine operation. A drop in pressure of 3.29 bar and 1.81 bar was observed for B100 and B40D60, respectively. As earlier emphasized, the concentration of diesel raises the CV [53] of the binary blend, thus releasing more heat and subsequently raising the in-cylinder pressure slightly when compared to engine operation with B100. The results show that a 10% volumetric concentration of alcohol in both ethanol and propanol-based ternary blends gave rise to better in-cylinder pressure when compared to the other ternary blends. However, the values for B40D50E10 and B40D50P10 are slightly lower by 0.81 bar and 0.30 bar when compared to B40D60.

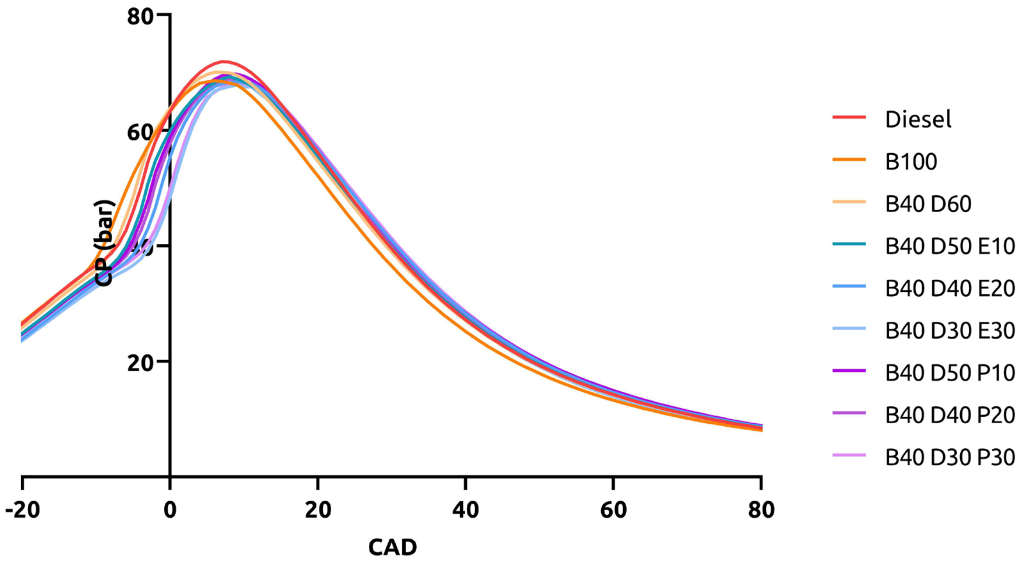

Figure 5. In-cylinder pressure for tested fuels at full engine load.

Figure 6 represents HRR results for all tested fuels at 100% engine loading condition. The maximum HRR values are 76.55 J/CAD, 68.21 J/CAD, and 71.3 J/CAD for diesel, B100, and B40D60, respectively. The 74.14 J/CAD, 76.94 J/CAD, and 77.93 J/CAD HRR values were observed for B40D50P10, B40D40P20, and B40D30P30 propanol-based ternary blends, respectively. Meanwhile, engine operation with the ethanol-containing blends B40D50E10, B40D40E20, and B40D30E30 gave 75.06 J/CAD, 77.25 J/CAD, and 78.46 J/CAD, respectively. Compared to reference fuels, a higher heat release rate was seen proportional to the alcohol concentration in the ternary fuel blends. Similar results were observed by Paul et al. [54]. This can be attributed to the higher oxygen content present in alcohols [55]. The delayed ignition in ternary blends allows for a better fuel-air mixture, which equips them for rapid combustion [56]. In contrast to the B40D60 binary blend, B40D50E10, B40D40E20, and B40D30E30 blends showed a raise of 3.76 J/CAD, 5.95 J/CAD, and 7.16 J/CAD, respectively, while an increase of 2.84 J/CAD, 5.64 J/CAD, and 6.63 J/CAD was observed for B40D50P10, B40D40P20, and B40D30P30 blends, respectively. Both B100 and B40D60 showed lower HRR values by 8.34 J/CAD and 5.25 J/CAD, respectively, when compared to diesel.

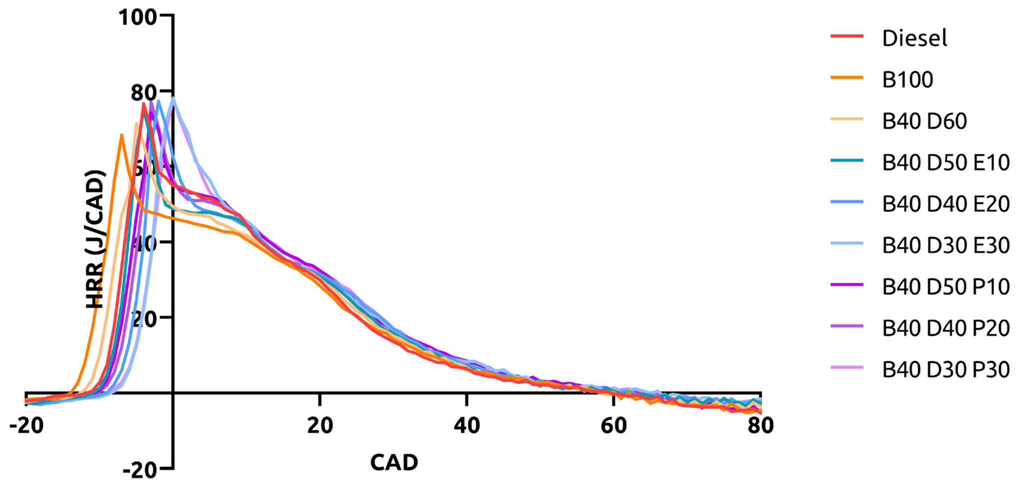

Figure 6. Heat release rate for tested fuels at full engine load.

3.3. Emission

Generally, gaseous emissions containing various compounds are a by-product of fuel combustion [57]. The quantity of emissions is directly related to the fuel's physiochemical properties and heat of combustion [58]. The BSCO gains for all tested fuels at 100% engine loading are shown in Figure 7. The BSCO for reference fuel diesel, B100, and B40D60 are 0.132 g/kWh, 0.102 g/kWh, and 0.112 g/kWh, respectively. The ternary blends B40D50E10, B40D40E20, and B40D30E30 containing ethanol reported 0.131 g/kWh, 0.158 g/kWh, and 0.188 g/kWh, while the B40D50P10, B40D40P20, and B40D30P30 propanol-based blends reported 0.119 g/kWh, 0.144 g/kWh, and 0.171 g/kWh, respectively. An increase of 0.007 g/kWh, 0.032 g/kWh, and 0.059 g/kWh were noted for B40D50P10, B40D40P20, and B40D30P30, along with B40D50E10, B40D40E20, and B40D30E30, which saw a raise of 0.019 g/kWh, 0.046 g/kWh, and 0.076 g/kWh, respectively, when compared to the B40D60 binary blend B40D60. The B100 was observed to give the lowest BSCO value, followed by the B40D60 and diesel with an increment of 0.010 g/kWh and 0.030 g/kWh, respectively. The in-cylinder temperature, chemical reaction rate, and fuel mixture's oxygen concentration are three key factors that affect CO release. This pollutant is a by-product of burning carbon-containing substances. BSCO and BSHC almost share similar characteristics in trend for all the tested fuels [28].

Figure 8 represents the BSHC results for all tested fuels at 100% engine loading condition. The BSHC values are 0.113 g/kWh, 0.069 g/kWh, and 0.092 g/kWh for diesel, B100, and B40D60, respectively. 0.100 g/kWh, 0.121 g/kWh, and 0.143 g/kWh of BSHC emissions were observed for B40D50P10, B40D40P20, and B40D30P30 propanol-based ternary blends, respectively. On the other hand, engine operation with the ethanol-containing blends B40D50E10, B40D40E20, and B40D30E30 gave 0.110 g/kWh, 0.131 g/kWh, and 0.152 g/kWh, respectively. When compared to B40D60 binary blend engine operation, B40D50E10, B40D40E20, and B40D30E30 blends showed a growth of 0.018 g/kWh, 0.039 g/kWh, and 0.060 g/kWh, while a rise of 0.008 g/kWh, 0.029 g/kWh, and 0.051 g/kWh was observed for B40D50P10, B40D40P20, and B40D30P30 blends. When compared to diesel, both B100 and B40D60 revealed lower BSHC values by 0.044 g/kWh and 0.021 g/kWh, respectively. The combined physiochemical properties of alcohols in ternary blends played a predominant role in HC emissions, which are observed to be higher than those of other tested fuels. Both ethanol and propanol possess an inferior CN, thus increasing the self-ignition period for ternary blends [23]. The higher latent heat of vaporisation in alcohol results in a lower cylinder temperature, while lower kinematic viscosity increases fuel-air mixture formation time. Zuo et al. [28] have indicated that these factors contribute to a leaner mixture, thus resulting in higher HC emissions with ternary blended engine operation.

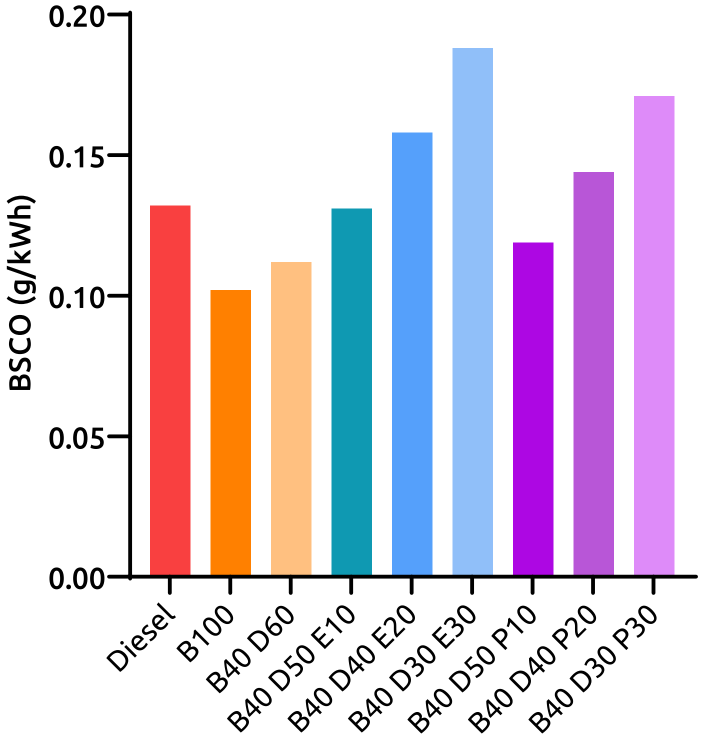

Figure 7. Brake specific carbon monoxide emissions for tested fuels at full engine load.

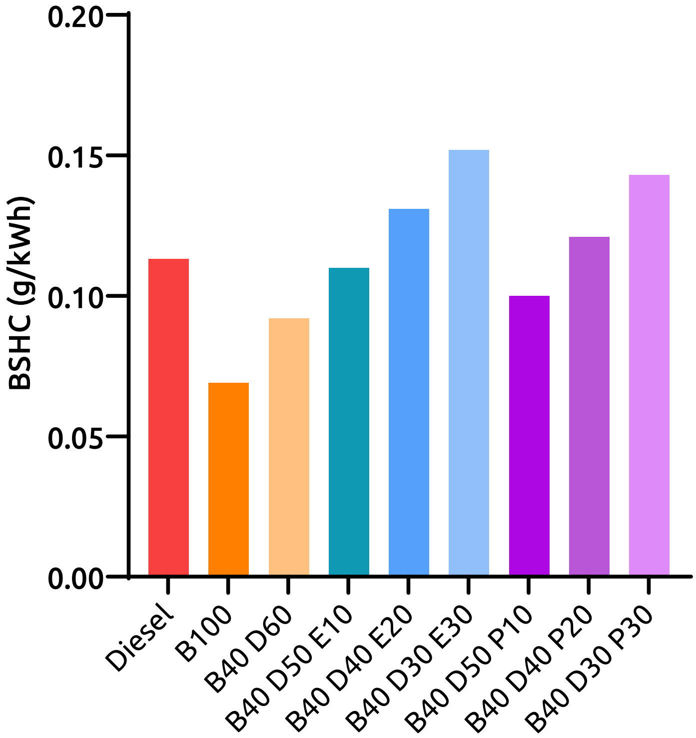

Figure 8. Brake specific hydrocarbon emissions for tested fuels at full engine load.

The $BSNO_X$ values obtained for all tested fuels at 100% engine loading conditions are illustrated in Figure 9. It can be inferred that the BSNO for reference fuels such as diesel, B100, and B40D60 are 5.368 g/kWh, 5.990 g/kWh, and 5.575 g/kWh, respectively. The ethanol-based ternary blends such as B40D50E10, B40D40E20, and B40D30E30 showed 5.210 g/kWh, 5.026 g/kWh, and 4.504 g/kWh, while propanol-based ternary blends such as B40D50P10, B40D40P20, and B40D30P30 showed 5.266 g/kWh, 5.128 g/kWh, and 4.672 g/kWh, the increasing volumetric presence of alcohols in ternary blends lowers $BSNO_X$ emissions correspondingly due to the high latent heat of vaporization. A decrease of 0.0309 g/kWh, 0.447 g/kWh, and 0.903 g/kWh was noted for B40D50P10, B40D40P20, and B40D30P30, along with B40D50E10, B40D40E20, and B40D30E30, which also saw a decrease of 0.365 g/kWh, 0.549 g/kWh, and 1.071 g/kWh, respectively, when compared to the B40D60 binary blend. The B100 was seen to give the highest $BSNO_X$ value, followed by the B40D60 and diesel with a decrement of 0.415 g/kWh and 0.622 g/kWh, respectively. Zeldovich's mechanism [59] states that an O_2 rich mixture, elevated combustion temperature, and long combustion duration are the conditions that contribute to a surge in NO formation. Compared to diesel, both B100 and B4D60 blend exhibit higher $BSNO_X$ emissions due to the in-fuel O_2 available in Palm biodiesel. In ternary blends, the higher latent heat of vaporisation of propanol and ethanol is observed to be more predominant than the increased O_2 concentration in the fuel mixture brought by the addition of alcohols [60]. This lowered the combustion temperature and caused a decrease in $BSNO_X$ emissions when compared to other tested fuels.

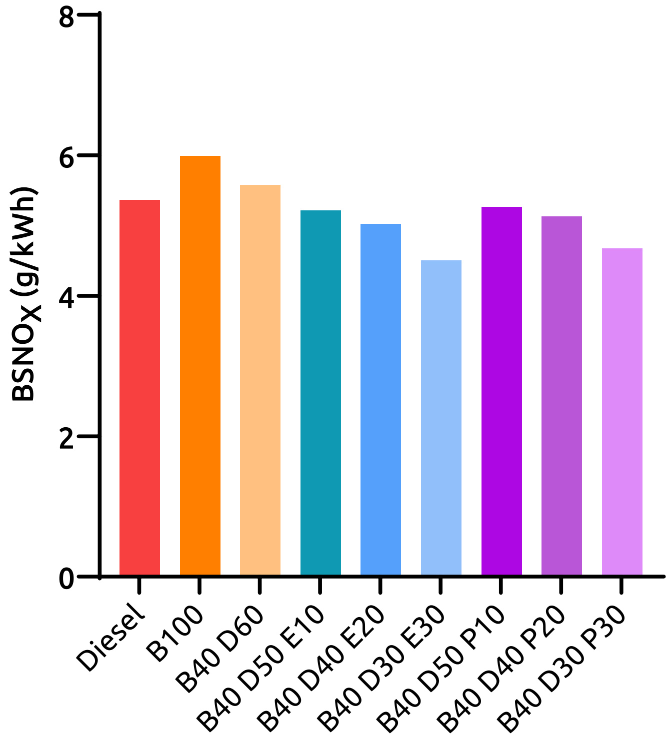

Figure 9. Brake Specific oxides of nitrogen emissions for tested fuels at full engine load.

Figure 10 depicts SM data for all tested fuels at 100% engine loading. The SM values are 54.7%, 80.4%, and 75.9% for diesel, B100, and B40D60, respectively. The acquired values for propanol-based ternary blends B40D50P10, B40D40P20, and B40D30P30 are 70.6%, 64.9%, and 60.1%, respectively. Meanwhile, 73.6%, 67.3%, and 63.6% were stated for ethanol-based ternary blends B40D50E10, B40D40E20, and B40D30E30, respectively. When compared with B40D60 binary blend engine operation, B40D50E10, B40D40E20, and B40D30E30 blends presented a decrement of 2.3%, 8.6%, and 12.3%, respectively, while a lower value of 5.3%, 11%, and 15.8% was observed for B40D50P10, B40D40P20, and B40D30P30, respectively. When compared to diesel, both B100 and B40D60 revealed higher SM values by 25.7% and 21.2%, respectively. Prakash et al. [22] also observed similar results in their experiments and reported that lower SM values for ternary blends can be attributed to improved combustion brought about by the decreased viscosity and density of alcohol-containing fuel blends.

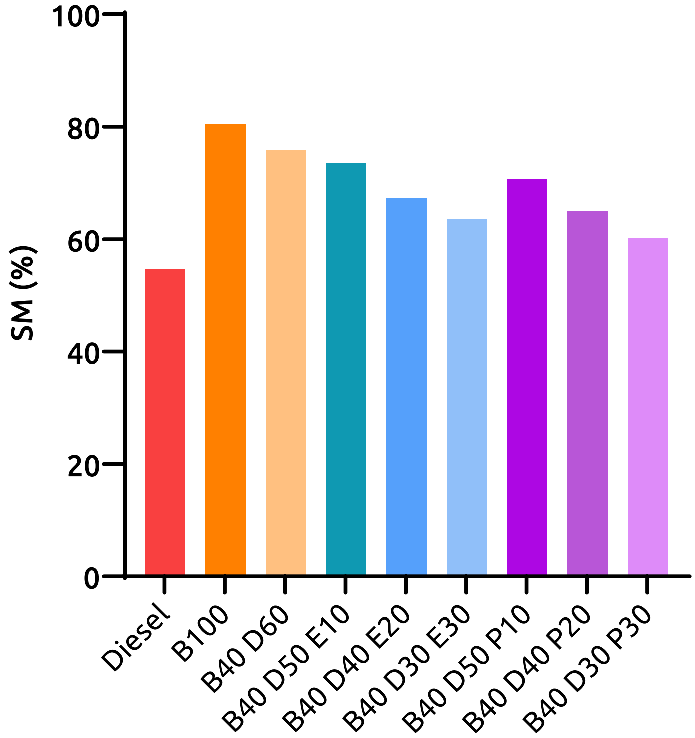

Figure 10. Smoke opacity for tested fuels at full engine load.

4. Conclusions

In this study, tests were carried out on a Kirloskar TV1 661 cc CI engine with reference fuels, namely diesel, B100, and B40D60. Then the experiments were continued with ethanol-based ternary blends, namely B40D50E10, B40D40E20, and B40D30E30, and propanol-based ternary blends, namely B40D50P10, B40D40P20, and B40D30P30. The test results were studied in terms of various performance, combustion, and emission parameters.

A heat map comparing the observed results is illustrated in Figure 11. To select an optimum blend, ternary fuel blends exhibiting the highest BTE are considered the primary selection criteria. The engine operation using B40D50E10 and B40D50P10 exhibits superior BTE in terms of performance among other ternary blends tested. However, even though higher alcohol blending rates in ternary fuel blends showed a proportional increase in HRR, values of CP were seen to decrease. In this study, both the values of CP and HRR for B40D50E10 and B40D50P10 fuels are closer to the values obtained with diesel fuel. When comparing emission characteristics, both SM and $BSNO_X$ are seen to lower with higher alcohol blending rates in ternary fuel blends, but BSHC and BSCO are observed to raise proportionally. Similarly, the ternary fuels B40D50E10 and B40D50P10 provide the best trade-off, with values for BSHC, BSCO, and $BSNO_X$ lower than the results seen with diesel fuel engine operation. However, although the SM values obtained with B40D50E10 and B40D50P10 fuels are higher than diesel, they are lower when compared to the values obtained with B100 and B40D60. In this regard, ethanol and propanol-based ternary blends having alcohol at a 10% volumetric concentration are found to be most suitable for engine application.

The key takeaways from the study are as follows:

1. In terms of BTE, engine operation with diesel fuel, which had the highest CV among tested fuels, was observed to give the highest estimate at 29.9%, while the lowest BTE values were observed with ternary blends containing 30% volumetric concentration of alcohol.
2. The BSEC trend for tested fuels was observed to be the opposite of the trend seen with BTE. In this study, BSEC values were 13.7 MJ/kWh for B40D30P30 and 13.8 MJ/kWh for B40D30E30 due to lower CV in the fuel blends.

3. In terms of combustion parameters, the trend for CP observed was similar to that of BTE where the highest value was observed by 71.91 bars with diesel fuelling and was followed by other tested fuels. Meanwhile, for HRR, ternary blends showed faster combustion characteristics, which can be attributed to better mixture preparation timing that caused a longer ignition delay. Both B40D30E30 and B40D30P30 showed the highest HRR values at 78.46 J/CAD and 77.93 J/CAD, respectively while B100 reported the lowest value at 68.21 J/CAD.
4. BSHC and BSCO show similar trends among the tested fuels. For ternary blends, there is a visible increase in the respective emissions with increasing alcohol concentration. Both palm biodiesel-based fuels, B100 and B40D60, were observed to give lower BSHC at 0.069 g/kWh and 0.092 g/kWh, while BSCO were at 0.132 g/kWh and 0.102 g/kWh, respectively.
5. Physicochemical properties such as lower viscosity, lower density, and a higher latent heat of vaporization in alcohols are noticed to have a tremendous effect on both SM and $BSNO_X$ emissions. The respective emission values for ternary blends were observed to be lower than reference fuels. The SM values were observed to be lowest at 63.6% and 60.1%, while $BSNO_X$ was observed to be lowest at 4.504 g/kWh and 4.672 g/kWh for B40D30E30 and B40D30P30, respectively.
6. Further studies using B40D50E10 and B40D50P10 blends could be tested on CI–powered vehicles to study on-road vehicular emissions. The strategies such as water injection and exhaust gas recirculation could be utilised to lower emissions even further.

Parameters	Diesel	B100	B40 D60	B40 D50 E10	B40 D40 E20	B40 D30 E30	B40 D50 P10	B40 D40 P20	B40 D30 P30
BTE, %	29.9	26.7	28.5	27.3	26.4	26.0	27.8	27.0	26.2
BSEC, MJ/kWh	12.1	13.3	12.6	13.1	13.5	13.8	12.9	13.3	13.7
CP, bar	71.91	68.62	70.10	69.29	68.42	67.85	69.80	68.88	68.08
HRR, J/CAD	76.55	68.21	71.30	75.06	77.25	78.46	74.14	76.94	77.93
BSHC, g/kWh	0.113	0.069	0.092	0.110	0.131	0.152	0.100	0.121	0.143
BSCO, g/kWh	0.132	0.102	0.112	0.131	0.158	0.188	0.119	0.144	0.171
BSNOx, g/kWh	5.368	5.990	5.575	5.210	5.026	4.504	5.266	5.128	4.672
SM, %	54.7	80.4	75.9	73.6	67.3	63.6	70.6	64.9	60.1

Figure 11. Comparative outlook for tested fuels at full engine load.

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Nomenclature

ASTM	American Society for Testing and Materials
BSCO	Brake Specific Carbon Monoxide
$BSCO_2$	Brake Specific Carbon Di Oxide
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BSHC	Brake Specific Hydrocarbon
$BSNO_X$	Brake Specific Oxides of Nitrogen
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CP	In-Cylinder Pressure
CV	Calorific Value
GC-FID	Gas Chromatography-Flame Ionization Detection
HC	Hydrocarbon
HRR	Heat Release Rate
ID	Ignition Delay
IMEP	Indicated Mean Effective Pressure
KV	Kinematic Viscosity
NO_X	Oxides Of Nitrogen
PM	Particulate Matter
SM	Smoke Opacity
cSt	Centistokes
Cc	Cubic Centimeter
°C	Degree Celsius
CAD	Crank Angle Degree
Cyl.	Cylinder
g/kWh	Gram per Kilo Watt Hour
J/CAD	Joules per Crank Angle Degree
Kg	Kilogram
Kg/m^3	Kilogram per cubic meter
kW	Kilo Watt
MJ/kg	Mega Joules per Kilogram
MJ/kWh	Mega Joules per Kilo Watt Hour
Ppm	Parts per Million
Rpm	Revolutions per Minute
BXX	(Volume %)
BXXDXX	Biodiesel XX + Diesel XX (Volume %)
BXXDXXEXX	Biodiesel XX + Diesel XX + Ethanol XX (Volume %)
BXXDXXPXX	Biodiesel XX + Diesel XX + Propanol XX (Volume %)

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