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Effect of primary and secondary alcohols as oxygenated additives on the performance and emission characteristics of diesel engine

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ABSTRACT

The demand for renewable energy sources is gradually escalating due to the spontaneously growing population and global economic development. The access to fossil fuels is gradually declining due to the limited available reserves. Hence, renewable energy resources, technology choice, and energy policy are always being revised due to the modernization of society. Meanwhile, the liquid energy sources such as methyl ester from locally produced vegetable oils are readily accepted by many countries globally, although it is currently being blended (up to 20%) with diesel. Oxides of nitrogen are the most substantial emissions from diesel engines produced due to high combustion temperature. The addition of alcohol in the fuel reduces the NO_x formation since alcohols have high latent heat of evaporation. The present study's primary purpose is to investigate the effect of different alcohol types on engine performance and emission characteristics. For this purpose, seven test fuels and neat diesel were used. The test fuels P20 (20% palm biodiesel with 70% neat diesel and 10% alcohol on a volume basis), $D_{70}P_{20}E_{10}$, $D_{70}P_{20}Pr_{10}$, $D_{70}P_{20}B_{10}$, $D_{70}P_{20}Pe_{10}$, $D_{70}P_{20}H_{10}$ were prepared and tested on a single-cylinder, 4-stroke, DI-diesel engine at different speeds at 100 % load. The P20E10 ternary fuel blend illustrated the most practical combination of all the bioethanol-based blends, which considerably improves the BTE, BSFC and reduces NO_xformation at high speed compared to other types of alcoholic fuel blends. Also, the P20E10 fuel blend improved the cloud point of neat diesel.

1. Introduction

Rapid growth in the population and demand for energy in each sector, such as transport, domestic, agriculture, etc., is increasing gradually worldwide. Currently, the global annual energy usage of 12.2 x 10^9 tons is fulfilled by crude oil. This energy utilization will rise to 1.75 x 10^9 tons of crude oil by 2035 (Cecrle et al., 2012; Marikatti et al., 2020). In the future, the world will face fuel shortages due to the depletion of fuel reserves (Ahmed et al., 2020). The transport sector consumed 50% of the total fossil fuels to meet energy demand (Mujtaba et al., 2020b; Soudagar et al., 2020a). The transport sector is the backbone of oil consumption. 50% of greenhouse gas emissions will be contributed to by the transport sector until 2030 (REN21 RN, 2019; Mujtaba et al., 2020a). Environmental issues like climate change, global warming, and human health concerns have been jeopardized by the harmful gases from petroleum fuel combustion. The increased usage of fossil fuels and the negative impact of exhaust gases on

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List of abbreviations

Nomenclature

CI	Compression ignition
E	Bioethanol
Pr	Propanol
H	Hexanol
CR	Compression ratio
BTE	Brake thermal efficiency
BP	Brake power
CD	Combustion duration
CO_2	Carbon dioxide
ID	Ignition delay
UHC	Unburnt hydrocarbon
IP	Injection pressure
$D_{70}P_{20}Pe_{10}$	70% diesel+20% palm biodiesel+10% pentanol
$D_{70}P_{20}Pr_{10}$	70% diesel+20% palm biodiesel+10% propanol
$D_{70}P_{20}E_{10}$	70% diesel+20% palm biodiesel+10% bioethanol
CP	Cloud Point
ASTM	American Standard for Testing Materials
P	Palm
B	Butanol
Pe	Pentanol
DI	Direct Injection
BSFC	Break specific fuel consumption
PM	Particulate Matter
CO	Carbon monoxide
NO_X	Oxides of nitrogen
P20	20% palm biodiesel
HC	Hydrocarbon
ppm	Parts per million
$D_{70}P_{20}B_{10}$	70% diesel+20% palm biodiesel+10% butanol
$D_{70}P_{20}H_{10}$	70% diesel+20% palm biodiesel+10% hexanol
D100	100% crude diesel
PP	Pour Point

human health and climate change has led researchers to find renewable fuels to eradicate combustion emissions (Aransiola et al., 2014). Air is polluted by exhaust gases released from the burning of fossil fuels in diesel engines like nitrogen oxide (NOx), carbon monoxide (CO), minute particulate matter (PM), and unburned hydrocarbons (UHC) (Gavhane et al., 2020; Hussain et al., 2020). Severe medical health issues like cancer, respiratory diseases (allergies, asthma, etc.) can occur due to the large quantity of particulate matter in the air (Vardoulakis et al., 2015). Biodiesel fuels capture a prominent place amongst all the other alternative fuels. Biodiesel is used directly or as a blend with diesel in CI engines without any fuel or engine modification. It is observed from the previous literature that there is a significant reduction in unburned hydrocarbons (HC), carbon monoxide (CO), and particulate emissions during the combustion of biodiesel (Mujtaba et al., 2020d; Khan et al., 2020; Soudagar et al., 2021). It has also been found that, in diesel/biodiesel blend, particle emissions reduce consistently with fuel oxygen content (Hedayat et al., 2016; Rahman et al., 2015). This significant decrease is due to a lack of aromatic content and a high quantity of oxygen in biodiesel (Lapuerta et al., 2008). The biodiesel utilization in the unmodified engine has many demerits like brake specific fuel consumption (BSFC), oxidation stability, higher viscosity, smoke emissions, and nitrogen oxides (NOx) (Yang et al., 2016; Soudagar et al., 2020b). NOx emissions directly affect human health (Yang et al., 2017). Various researches have reported that biodiesel utilization in a diesel engine results in less HC and CO exhaust emissions but higher NOx emissions than diesel fuel (Balan et al., 2019; Razzaq et al., 2020). The significance of biodiesel is questionable due to high NOx emissions and lesser brake thermal efficiency. Various researchers worldwide put their commendable efforts to eradicate this problem by reducing the compression ratio, delaying the fuel injection, and installing the supercharger during engine modifications (Rao and Reddi, 2017; Devarajan, 2019). Many researchers worked on fuel modification to minimize the NOx emissions by adding water, additives in liquid or metal form in biodiesel blends (Hazar, 2017; Dhinesh et al., 2017; Pandian et al., 2017; Wei et al., 2017; Mujtaba et al., 2020c).

Various diesel engine experts reported that the mixing of alcohol (as fuel additives) with diesel or biodiesel decreases the NOx and PM because alcohol provides more oxygen and high latent heat of vaporization in high carbon emissions lack of oxygen during the burning of fuel. An incomplete combustion issue can be resolved with the addition of oxygenated alcohols as a fuel additive because alcohols will enhance the air–fuel ratio by providing extra oxygen, which resulted in better fuel spray characteristics and resulting incomplete combustion (Khalife et al., 2017).

In fuel modification, various researchers used oxygenated additives like n-butanol, ethanol, and methanol in diesel, biodiesel, and diesel–biodiesel blends to significantly reduce the NOx, smoke, CO emissions and get valuable increment in brake thermal efficiency (Zhu et al., 2010; Bhale et al., 2009; Doğan, 2011; Soudagar et al., 2018). Atmanli (2016) reported a significant reduction in NOx emissions with the addition of oxygenated alcohols (propanol, n-butanol, and 1-pentanol) with diesel–biodiesel blends. Goga et al. (2019) investigated the use of butanol alcohol as a fuel additive with diesel–biodiesel blends in the diesel engine. He reported a significant reduction in NOx and CO emissions compared to clean diesel–biodiesel blends. Hence, it is also needed to observe other oxygenated additives' performance and emission characteristics like bioethanol, propanol, pentanol, butanol, and hexanol in diesel–biodiesel fuel blends on the same engine under similar operating conditions. Various physicochemical properties (flash point, oxygen content, calorific value, self-ignition temperature, density, kinematic viscosity, and cetane number) should be given more preference in selecting the best suitable oxygenated ternary fuel blend for the diesel engine. Various researchers overlook another important property (alcohol toxicity), which should be considered to enhance the diesel engine's durability (Patil and Taji, 2013).

The purpose of this research is to evaluate the effect of different oxygenated additives (like bioethanol, propanol, butanol, pentanol, hexanol) on the performance and emissions characteristics of a diesel engine at various loads. Different researchers worked on various oxygenated alcohols to analyze the effect on engine performance and emission characteristics. In this research work, five different oxygenated alcohols were selected with the same concentration and engine operating conditions to analyze these additives' effects on diesel engine performance and emission characteristics. The various alcohols (10% quantity) are added in 70% diesel-20% biodiesel blends. The obtained results are compared with pure diesel, and 20% biodiesel blends (B20) tested on the same engine with similar working conditions.

The main objectives of this research are: (1) to determine the most suitable oxygenated alcohol among primary and secondary

Table 1
Composition of all fuel blends.

Fuel blend	Diesel	Palm biodiesel	Alcohol
D100	100%	0	0
P20	80%	20%	0
P20E10	70%	20%	10% Bioethanol
P20Pr10	70%	20%	10% Propanol
P20B10	70%	20%	10% Butanol
P20Pe10	70%	20%	10% Pentanol
P20H10	70%	20%	10% Hexanol

alcohols as a fuel additive for diesel engine, (2) to evaluate the physicochemical properties of ternary fuel blends for selection of the best oxygenated ternary blend for diesel engine application and (3) to determine the most ecofriendly oxygenated alcohol to eradicate the emissions for diesel engine application.

2. Materials and methods

Neat diesel was obtained from Petronas, Malaysia, and used as the base fuel. The palm oil was purchased from the local market of Malaysia. The bioethanol, propanol, butanol, pentanol, and hexanol were obtained from QREC Chemical Company, Thailand.

2.1. Biodiesel production

The transesterification process produced palm biodiesel. Palm oil was mixed with methanol with a molar ratio of 6:1 (Methanol to oil) and 1% (w/w) potassium hydroxide (KOH) in the reactor for 2 h at 60 °C at 900 rpm steering speed. The prepared mixture was poured into the separation funnel to remove glycerol. Finally, after washing the biodiesel was produced, it was dried in a rotary evaporator for removing water and excess methanol.

2.2. Formation of ternary blends

Homogeneous blends of diesel–biodiesel and alcohols were prepared by a motor stirrer clamped at the vertical stand and rotated at 4000 rpm. Table 1describes the exact V/V % composition of all the fuels for making ternary blends used in diesel engines for performance and emission analysis. Diesel–biodiesel blends with 10% oxygenated alcohols were selected to investigate the engine performance and emission characteristics. This selection was based on the development proposed by European directives 2009/28/EC (Off J EU, 0000a) and 2015/1513/EC (Off J EU, 0000b) on the use of biofuels. Various researchers recommended not to exceed 10% addition of oxygenated alcohols with diesel–biodiesel blends. Higher alcoholic concentrations minimize the density and viscosity but as well as calorific value and cetane number. Lower calorific value and cetane number of higher oxygenated ternary blend negatively affect engine performance (BTE, BSFC, and BP). A higher concentration will also decrease the lubricity of diesel–biodiesel blends (Lapuerta et al., 2017, 2010).

2.3. Characterization of physicochemical properties of fuels

The first step to analyze the feasibility of any fuel for use in internal combustion engines included assessing its physicochemical properties, which directly affects the engine's performance and emission. These properties include density, viscosity, acidic value, flash point, oxidation stability, cloud point (CP), calorific value, pour point (PP), etc. Table 2 presents the details of equipment (model no, name, accuracy level, and manufacturer detail) used to measure tested fuels' physicochemical properties following the ASTM standard.

2.4. Experimental setup of engine

A single-cylinder, 4-stroke, naturally aspirated DI diesel engine was used as a test engine, illustrated in Fig. 1. Every single reading presented in the manuscript is averaged from three repetitions. Initially, the diesel engine was operated at no load to warm up for 10–15 min to reach the steady state condition. Subsequently, the engine was loaded slowly to the required speed and load according to the engine testing's operating parameters. The diesel engine was kept steady on these operating conditions for 5–10 min, and then readings and observations were recorded at normal condition.

A graduated measuring cylinder is attached to the fuel tank. During a single test run, three readings took every 10 ml by clicking stopwatch for the respective engine speed. Mass flowrate, BSFC, BP, and BTE were calculated by using these equations, respectively:

$$m_{\dot{f}} = \frac{V\ \ (\mathrm{mL}) \times \rho\ (\mathrm{kg/m^3})}{t(h)}$$

$$BSFC = \frac{m_{\dot{f}}}{BP}$$

$$BP = \frac{2\pi N \times T}{60 \times 1000}$$

$$BTE = \frac{3600}{BSFC \times CV}$$

Every single reading presented in the manuscript is averaged from three recording or repetitions. The relative deviations concerning each parameter were generally in a range of a maximum ±5%.

Table 2
Equipment used for characterization of physicochemical properties of fuels.

Property	Equipment	Manufacturer	Standard method	ASTM D6751 limit	Accuracy
Density at 40 °C	SVM 3000	Anton Paar, UK	ASTM D7042	–	0.0005 g/c m3
Kinematic viscosity at 40 °C	SVM 3000	Anton Paar, UK	ASTM D7042	1.9–6.0	±0.35%
Acid value	Mettler Toledo G20 compact titrator	Mettler Toledo, Switzerland	ASTM D664	0.5 max	±0.001 mg KOH/g
Oxidation stability	873 Rancimat	Metrohm, Switzerland	EN 14112	3 h	±0.01 h
Calorific value	C2000 basic calorimeter	IKA, UK	ASTM D4809	–	±0.1% of reading
Cloud point	NORMA LAB NTE 450	Normalab, France	ASTM D2500	–	±0.1 °C
Pour point	NORMA LAB NTE 450	Normalab, France	ASTM D97	–	±0.1 °C

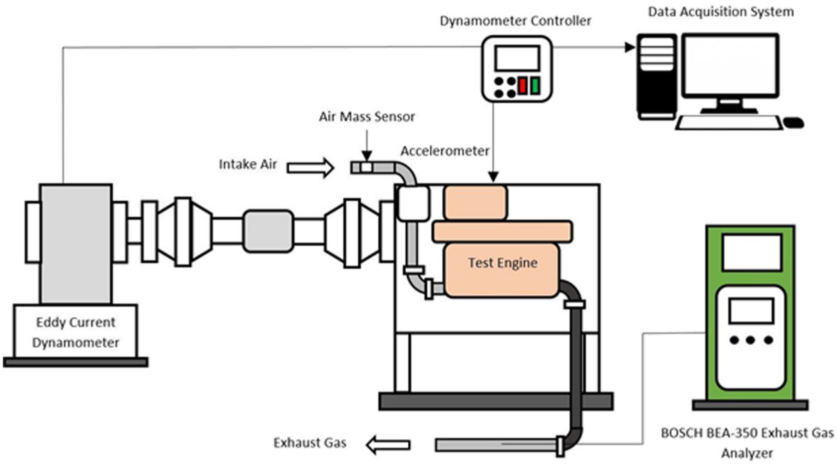

Fig. 1. Schematic diagram of the engine test setup.

Table 3
Engine specifications used for experimental work.

Engine specification	Description
No. of cylinders	1
Aspiration	Radiator cooling
Cylinder bore × stroke (mm)	92 × 96
Displacement (L)	0.638
Compression ratio	17.7
Maximum engine speed (rpm)	2400
Maximum power (kW)	7.7
Injection timing (deg.)	17° BTDC
Injection pressure (kg/cm^2)	200
Power take-off position	Flywheel side
Cooling system	Radiator cooling
Connecting rod length (mm)	149.5

A BOSCH BEA-350 emission tester measured the engine's emission (NOX, CO, and HC). Smoke emissions were measured using BOSCH RTM 430 emission analyzer. Engine and different measuring instrument specifications are presented in Tables 3 and 4, respectively.

The Yanmar diesel engine was run with eight (8) different speeds (1000–2400 rpm) with a step of 200 rpm under full load (100%) conditions. Percentage relative uncertainty for engine parameters (BSFC, BP, BTE, CO, HC, NO$_x$) was determined through different equipment uncertainties. The overall uncertainty of experiments was predicted by given below equation:

$$\mathit{Overall\ uncertainty} = \sqrt{\mathit{Uncertainty}\ \%\ \mathit{of}\ \left(BP^2 + BSFC^2 + BTE^2 + CO^2 + HC^2 + NOx^2\right)}$$

$$\sqrt{\left((0.73)^2 + (1.63)^2 + (1.47)^2 + (1)^2 + (1)^2 + (1.3)^2\right)} = \pm 3.01\%$$

3. Results and discussion

3.1. Characterization of fuel properties

The most important physicochemical characteristics of neat fuel and their ternary fuel blends are presented in Table 5. The physicochemical properties of all blends are acceptable with the ASTM standard's limits. Therefore, all these blends are suitable for diesel engines, requiring no engine hardware modifications.

3.2. Performance analysis

Performance parameters like BSFC and BTE were measured for all tested fuels and their ternary blends at full load by varying the speed, as discussed below.

3.2.1. Brake Specific Fuel Consumption (BSFC)

The variation of engine BSFC with respect to engine speed is shown in Fig. 2. BSFC of an engine is the ratio of the fuel consumed and the brake power output. There is a significant reduction in the BSFC value for all test fuels with an increment in speed from 1000 rpm to 2000 rpm. This reduction in BSFC is due to the higher atomization ratio, whereas, at higher speed, volumetric efficiency decreases due to which BSFC value increases after 2000 rpm. P20 exhibited the highest BSFC value among the blends, which is 7.65% higher than D100 on average. This increase in the case of P20 is due to high density and viscosity value as compared to neat diesel. Owing to high density, more fuel is injected during combustion, which increases the BSFC. The high value of BSFC was recoded for all ternary blends compared to crude diesel but lower than P20, P20E10, P20Pr10, P20B10, P20Pe10, and P20H10 ternary blends exhibited 4.63%, 4.45%, 5.99%, 4.27%, and 7.53% higher BSFC compare to D100. This increment in BSFC value of ternary blends is due to the low calorific value, which consumes more fuel for producing the same amount of power as neat diesel produced at the same operating condition. The same behavior is also reported by other researchers (Barabás and Todoruţ, 2011; Ghobadian et al., 2009; Subbaiah et al., 2010). Attributes of ternary blends influence the BSFC of the CI engine, including volumetric fuel injection, lower heating value, fuel density, and viscosity. Among these factors, lower heating value is the most important factor influencing the BSFCs of diesel engines for ternary blends. As mentioned in the description, the injector injects the same amount of fuel irrespective of any blend in a given amount of instantaneous time. Hence the volume of denser fluid injected will have more quantity causing more fuel consumption. Among all other ternary blends, the P20Pe10 blend shows the lowest BSFC, which is 4.27% higher than D100 but 3.13% lower than P20. At 2400 rpm, the P20E10 blend exhibits minimum BSFC, among other fuels, including D100. The decrement in P20E10 BSFC value among other ternary blends is due to viscosity and cetane index, which is very close to D100. Oxygenated alcohols contain oxygen content in their molecular structure. The calorific value and energy content of fuel decrease with an increase in the oxygen content resulting

Table 4
Different measuring instrument specifications.

Equipment	Method	Measurement	Measurement range	Resolution
BOSCH BEA 350	Non-dispersive infrared	CO	0%–10% vol.	±0.001% vol.
		HC	0–9999 ppm	±1 ppm
		NO_X	0–5000 ppm	±1 ppm
BOSCH RTM 430	Photodiode receiver	Smoke	100%	±0.1%
SAJ SE20 Dynamometer	Strain gauge load cell	Torque	0–80 Nm	±0.25 Nm
Thermocouple	K-Type	Temperature	−200 °C to +1000 °C	±1 °C

Table 5
Physicochemical properties of engine test fuels.

Research fuel blends	Density at 40 °C (kg/m^3)	Kinematic viscosity at 40 °C (mm^2/s)	Oxygen stability (h)	Pour point (°C)	Calorific value (MJ/kg)	Cetane index CI
D100	835.2	3.6765	59.1	7	45.46	48
Biodiesel	858.1	4.49	3.92	15	39.91	61
Bioethanol	775.9	1.11	1.5	−114	28.85	8
2-Propanol	768.9	1.67	1	−126	29.7	12
Iso-Butanol	786.4	2.69	2	−89	32.8	17
Pentanol	793.7	2.99	1.85	−75	34.5	20
1-Hexanol	804.3	3.65	1.3	−70	35.8	42
P20	837.3	4.0256	30.2	8	44.35	50.6
P20E10	830.0	3.1802	11.1	−3	42.69	46.6
P20Pr10	829.2	3.3049	10.2	−5	42.77	47
P20B10	831.3	3.5160	12.0	−1	43.08	47.5
P20Pe10	832.6	3.5803	11.58	1	43.25	47.8
P20H10	833.8	3.9119	10.73	1	43.38	50

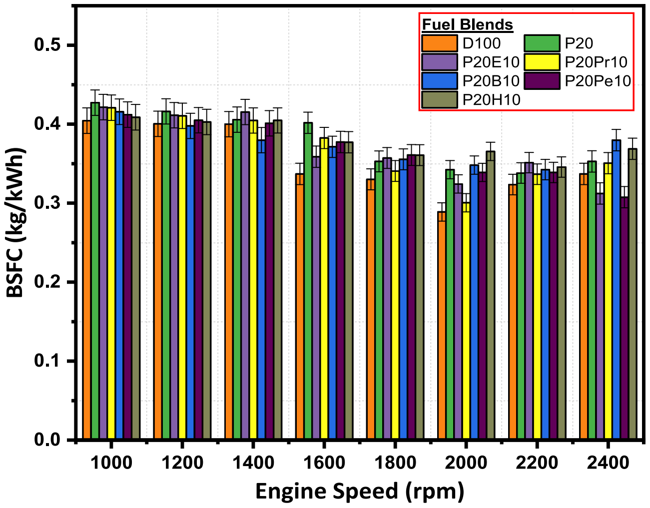

Fig. 2. Trend of brake specific fuel consumption for ternary blends with speed at full load.

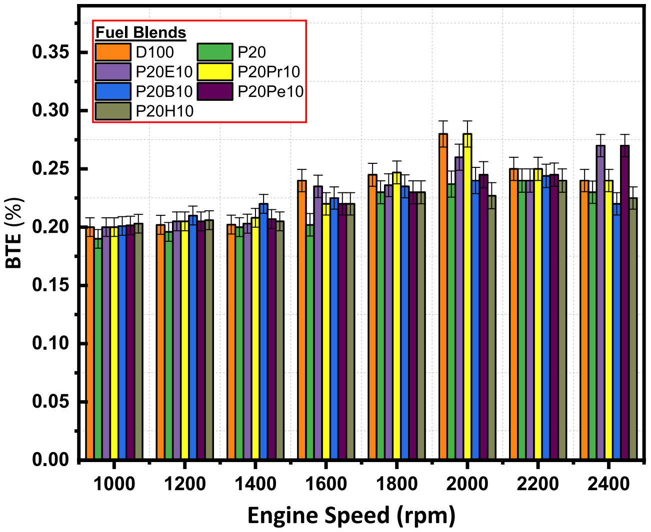

Fig. 3. Trend of brake thermal efficiency for ternary blends with speed at full load.

in higher BSFC leading to the burning of more fuel to obtain the same engine output (Atmanli, 2016). P20Pe10 showed lowest BSFC among all ternary oxygenated blends due to presence of less oxygen content (18.15%) compared to P20B10 (21.59%), P20Pr10 (26.7%) and P20E10 (34.8%) (Khalife et al., 2017).

3.2.2. Brake Thermal Efficiency (BTE)

BTE is an important parameter to measure engine performance. BTE of an engine indicates its efficiency of converting the chemical energy of the fuel into useful work. BTE is inversely proportional to BSFC for a given fuel. It can be observed that the engine exhibited the lowest BTE while running on P20 binary blend among all the engine test fuels. On average, the engine produced power 21.56% efficiently while running on the P20 blend of diesel and palm biodiesel. On the contrary, the engine produced power more efficiently while running on the ternary blends of diesel, biodiesel, and alcohol. BTE of the engine running on P20E10, P20Pr10, P20B10, P20Pe10, and P20H10 ternary blends are found to be 23.11%, 23.13%, 22.43%, 22.80%, and 21.95% on average respectively and 23.24% while running on neat diesel. Thus, it is seen that only the ternary blends containing bioethanol and pentanol can produce usable power more efficiently than neat diesel.

At 2400 rpm, the BTE of the engine is increased when diesel–palm biodiesel–bioethanol and diesel–palm biodiesel–pentanol ternary blends are used as fuel respectively rather than neat diesel. Atmanli (2016) reported a similar increment in BTE values for diesel–biodiesel–alcohol blends (propanol, butanol, and pentanol). The higher oxygen content of oxygenated alcohol in ternary fuel blends improved the combustion and reduction in heat losses because of the lower boiling point of alcohols compared to petroleum diesel. This better BTE is associated with the calorific value and low BSFC of the blends. Indeed, diesel has outpaced all the blends at different speeds. An increased amount of temperature in the engine at higher speeds causes proper combustion and engine output enhancement. Hence BSFC at lower speeds is more, and the corresponding value of BTE is lower. The BTE at higher speeds is more due to lower BSFC. As blends have lower calorific value, it causes under BTE performance. In the case of ternary blends containing bioethanol, this better BTE might be due to the lower value of viscosity, density, and flashpoint, which favor leaner combustion and extended ignition delay (Subbaiah et al., 2010).

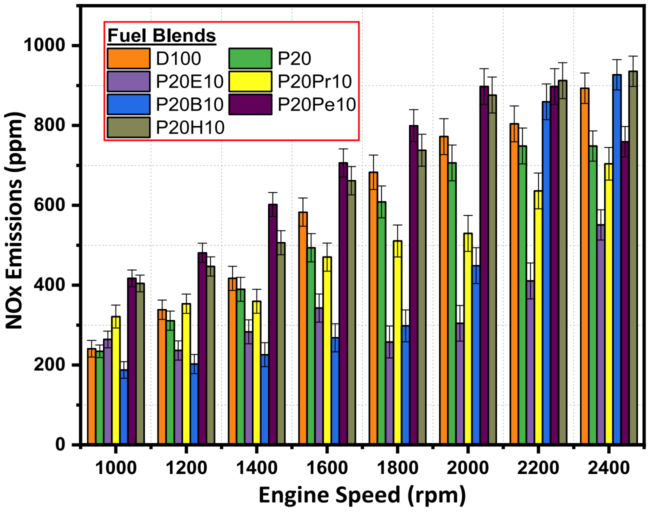

Fig. 4. Trend of NOx emission for ternary blends with speed at full load.

3.3. Emission analysis

3.3.1. NOx emission

The change in engine NOx emission with respect to engine rpm is shown in Fig. 3. The formation of NOx mainly depends on in-cylinder combustion temperature, the residence time of reaction, and oxygen concentration (Sharon et al., 2013; Challen and Baranescu, 1999). In-cylinder temperature increases as engine rpm increases, which results in an increment of NOx emissions at higher rpm, as indicated in Fig. 4. It can be observed that P20, P20E10, P20Pr10, and P20B10 produced 10.29%, 44.03%, 17.85%, and 28.03% lower NO$_X$ than diesel fuel, respectively. The reduction of NOx is due to the lower cetane index and heating value of fuel blends, which results in lower combustion temperature. The addition of alcohol, in general, increases the oxygen content and reduces the cetane index of fuel blends. This behavior of alcohol leads to the cooling effect and longer ignition delay (Atmanli, 2016). At higher speeds, the P20E10 ternary blend, among other fuels, emits significantly fewer NOx emissions. One of ethanol's properties is that the oxygen present in it is sensitive to pressure and temperature. Hence as the engine increases, higher cylinder temperature, and pressure cause ethanol to release the oxygen more rapidly. This phenomenon may contribute to the fact of lower NOx emission with increasing speeds. As reported by Yilmaz et al. (2014), the addition of alcohol produces the cooling effect, which decreases the combustion temperature to reduce NOx emissions. The same phenomena were reported by other researchers (Atmanli, 2016; Yang et al., 2015; Park et al., 2012). Whereas P20Pe10 and P20H10 produced 17.50% and 15.88% higher NO$_X$ than diesel fuel, respectively. The higher oxygen content results in higher combustion temperature, which leads to higher NO$_X$ emission, which might be the reason behind higher NO$_X$ emission from blends containing pentanol and hexanol (Kwanchareon et al., 2007; Shi et al., 2005). Higher oxygen content and latent heat of vaporization of oxygenated ternary fuel blends have a more significant effect on combustion in reducing NOx compared to lower cetane number of fuel (Atmanli, 2016).

3.3.2. Carbon monoxide (CO) emissions

The variation in engine CO emission with respect to engine rpm is shown in Fig. 5. Carbon monoxide (CO) results from partial combustion, which lacks sufficient oxygen to produce CO$_2$ (Atmanli, 2016). There are few important factors such as fuel type, air–fuel ratio, injection timing, fuel pressure, and engine speed, which result in incomplete combustion of hydrocarbon fuels (Palash et al., 2013). From Fig. 5. it is understood that CO emission decreases with an increase in the engine rpm. This reduction in CO emissions is due to the use of oxygenated alcoholic fuels because oxygen improves the combustion quality by converting CO to CO$_2$ (Habibullah et al., 2014; Noorollahi et al., 2018). At 1000 rpm, the higher value of CO emissions is recorded for diesel, P20, P20E10, P20Pr10, P20B10, P20Pe10 and P20H10 are 3.76, 3.46, 4.41, 1.76, 3.17, 2.41 and 4.09 vol %, respectively. Same increment in CO emissions at lower rpm reported by Li et al. (2015a) and Wei et al. (2014). The diesel engine emitting high CO values has arisen due to the operating conditions, which are lower speeds, improper mixing at a lower temperature, and combustion characters at lower speeds. The rise in engine RPM overcomes this issue. Thus, on average the CO emissions for P20, P20E10, P20Pr10, P20B10, P20Pe10 and P20H10 reduced by 18.63%, 14.19%, 63.78%, 47.80%, 59.49% and 13.26%, respectively compared to D100.

All the fuel blends emit less CO emissions due to higher oxygen content, which ensured complete combustion compared to diesel fuel. P20B10 exhibited the lowest CO emission among the tested fuels. At high rpm, the P20E10 blend shows very less CO emissions as compared to other fuels. The higher cetane number of the ternary blend, including pure biodiesel compared to neat diesel, leads to complete combustion resulting in less CO emissions. When there is high amount of oxygen content in combustion process, CO is reduced due to high combustion rate. In-cylinder combustion temperature is also increased due to high oxygen content in ternary fuel blends which endorses the complete combustion of fuels within combustion chamber. Similar results of CO emission reduction due to higher oxygen content reported by other researchers (Li et al., 2015b; Yasin et al., 2015; Alptekin et al., 2015).

3.3.3. Hydrocarbon (HC) emission

An unburned hydrocarbon emission produced due to high viscosity and density of fuels that produce rich mixture zones within the cylinder is known as HC emissions (Atmanli, 2016). Due to an ignition delay period, a mixture of fuel is leaner than a lower combustion lean limit, leading to HC emissions in a diesel engine. Oxidation of unburned HC enhanced by a favorable condition like (high flame velocity, post flame oxidation, etc.) provided by biodiesel and alcohol's oxygen content in an air–fuel interaction (Ramos et al., 2009). Fig. 6 exhibits the trend of HC emissions for all fuel blends at various rpm. HC emissions

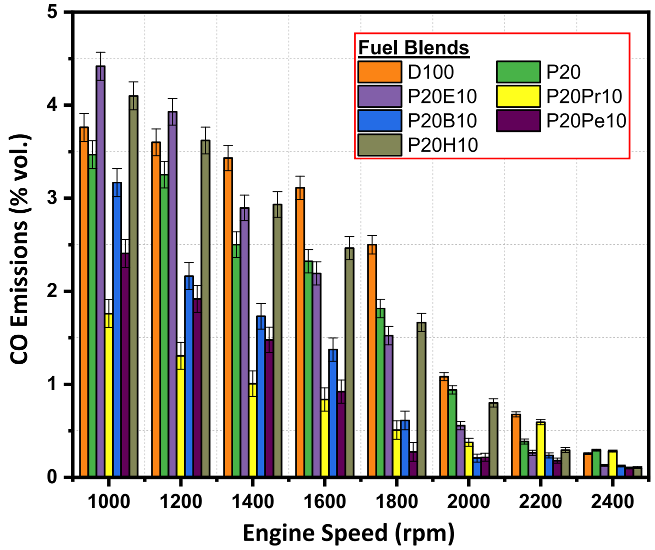

Fig. 5. Trend of CO emission for ternary blends with speed at full load.

decrease with an increase in engine rpm. High in-cylinder pressure increases the high in-cylinder temperature at high speed, which results in a decrement of HC emissions. At 1000 rpm, high value of hydrocarbon (HC) emission was noted like 154, 115.40, 192.60, 42.60, 129, 180.69 and 120.13 ppm for diesel, P20, P20E10, P20Pr10, P20B10, P20Pe10, and P20H10 respectively. The overall average HC emission for P20, P20Pr10, P20B10, and P20H10 ternary blends reduced by 55.57%, 36.04%, 64.17%, and 11.45%, respectively, whereas P20E10 and P20Pe10 ternary blends show an increased HC emission by 0.94% and 11.39% respectively, compare to that of neat diesel. This result matches the findings of other researchers also (Shi et al., 2005; Randazzo and Sodré, 2011). This increment in HC emission for P20E10 is due to incomplete combustion caused by longer ignition delay (Randazzo and Sodré, 2011). Another reason for high HC emissions is the formation of the leaner mixture within a localized portion of the combustion chamber due to the non-homogeneity blend of bioethanol with diesel fuel, which could be due to the effect of the slow evaporation rate of bioethanol (He et al., 2003).

3.3.4. Smoke emissions

Smoke emission results for all tested fuel samples are presented in Fig. 7. Air deficiency in diesel engine resulted in the formation of smoke emissions. Soot is formed by oxygen-deficient thermal cracking of long-chain molecules. Smoke emissions increases as air to fuel ratio decreases during engine operation (Hulwan and Joshi, 2011). Smoke emissions are mainly dependent on engine load. With an increase in engine load, the air–fuel ratio decreases as fuel injection increases, which resulted in higher smoke emissions. It is observed that smoke emissions increased at higher speed with full load condition for all tested fuel samples. All the ternary fuel blends showed a significant reduction in smoke emissions compared to petroleum diesel. P20Pr10 showed the least smoke emissions among all tested fuel samples, followed by P20H10 and P20B10. The presence of oxygen molecules in alcoholic blends have positive chemical control over soot formation.

Ternary alcoholic fuel blends improved the vaporization and atomization of fuel, which reduced soot formation due to a reduction in diffusion flame sheath. Leaner combustion occurred due to fuel-bound oxygen of alcohol, and biodiesel is locally rich zones. Proper mixing of air and fuel due to the addition of alcohol as a fuel additive in the premixed combustion phase resulted in lower smoke emissions in exhaust due to oxidation of soot particles because of inbuilt oxygen in ternary fuel blends (Xiao et al., 2000; Hulwan and Joshi, 2011).

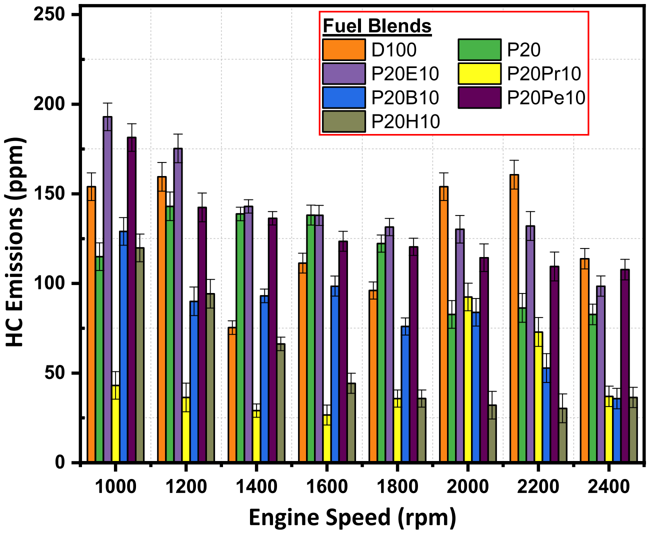

Fig. 6. Trend of HC emission for ternary blends with speed at full load.

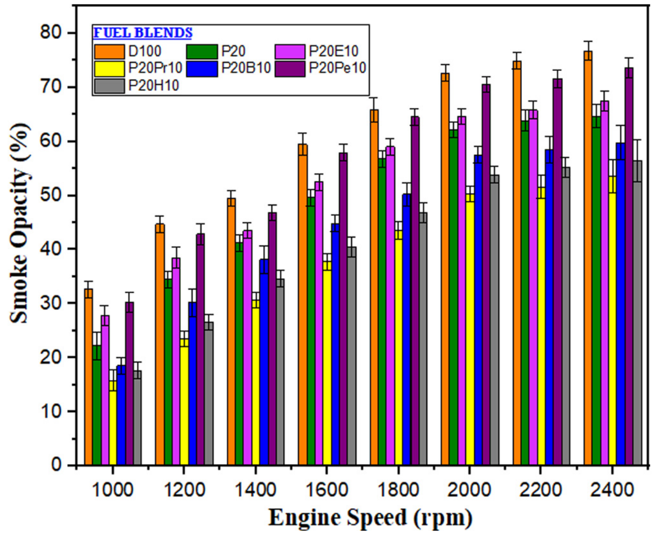

Fig. 7. Trend of smoke emissions for ternary blends with speed at full load.

3.3.5. Exhaust Gas Temperature (EGT)

The variation of exhaust gas temperature (EGT) and brake power of the engine is shown in Fig. 8 for various fuel blends. An increasing tread in EGT is observed with an increase in the speeds (Khan et al., 2020). The P20Pe10 illustrated the lowest EGT, and the P20 fuel blend without any additive has the highest EGT at all loads; P20E10, D100, and P20Pr10 have shown a very close range of values of EGT concerning P20Pe10 at all speeds. Palm biodiesel (P20) combined increases the EGT due to high viscosity, lower calorific value, and density. This indicates the EGT reduction with the presence of alcohol additives. The alcohol additives have higher thermal conductivity than the palm biodiesel, which facilitates faster heat transfer.

4. Conclusion

In Malaysia, palm oil has the highest production rate accounting for 424 million tonnes. The properties which hinder the use

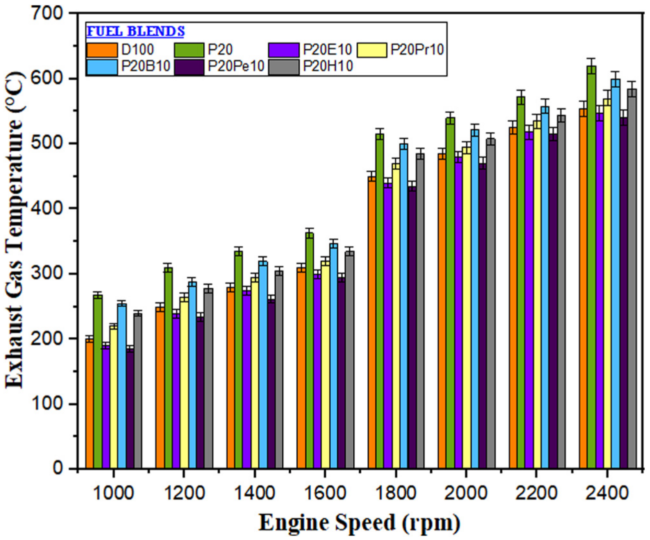

Fig. 8. Trend of exhaust gas temperature for ternary blends with speed at full load.

of a higher amount of palm biodiesel are its density, viscosity and cold flow properties. Alcohols can be used as a ternary blend with diesel and palm biodiesel to improve their physicochemical properties and performance and emission characteristics. In the current investigation, the diesel–palm biodiesel blend and diesel–palm biodiesel–alcohols (bioethanol, 2-propanol, isobutanol, pentanol, and 1-hexanol) blends were tested on the single-cylinder unmodified diesel engine to evaluate and compare the performance and exhaust emission characteristics. Thus, the following conclusions are drawn based on the results obtained:

1. Using the $D_{70}P_{20}$ Pe_{10} ternary blend, BSFC is reduced among other blends like 3.13% lower than P20 but 4.27% higher than D100.
2. At 2400 rpm, $D_{70}P_{20}$ E_{10} ternary fuel blend exhibits the minimum amount of BSFC value compared with other fuels including D100.
3. The BTE increased by 7.24% and 7.18% for $D_{70}P_{20}$ Pe_{10} and $D_{70}P_{20}E_{10}$ ternary fuel blends respectively in comparison with P20.
4. At 2400 rpm, $D_{70}P_{20}$ Pe_{10} and $D_{70}P_{20}H_{10}$ ternary blends produced higher NOx emissions.
5. For $D_{70}P_{20}$ E_{10}, NOx emissions reduced significantly with an increase in the engine rpm.
6. Higher values of CO emissions were generated by D100 with increasing speed and lower values of CO emissions were recorded for $D_{70}P_{20}$ B_{10}, $D_{70}P_{20}Pe_{10}$, and $D_{70}P_{20}E_{10}$ at higher rpm.
7. $D_{70}P_{20}$ E_{10} and $D_{70}P_{20}Pe_{10}$ ternary blends produced a high quantity of HC emissions 0.94% and 11.39% respectively when compared with neat diesel. $D_{70}P_{20}H_{10}$ fuel blend produced the lowest HC emissions at higher speeds and on an average $D_{70}P_{20}Pr_{10}$ ternary blend exhibited the lowest HC emissions compared with other fuels.
8. Alcoholic diesel–biodiesel ternary blends were prominent additives to improve the performance as well as emission characteristics. Ethanol was the most effective in terms of NOx reduction since it produces a cooling effect inside the combustion chamber and reduces combustion temperature. In the future, other oxygenated alcohols (dimethyl carbonate and diethyl ether) should be investigated to analyze their effect on engine performance and emission characteristics. The lubricity of primary and secondary ternary fuel lends should be investigated before addition to diesel–biodiesel blends in the transport sector. A tribological study should be conducted for these oxygenated alcohols.

CRediT authorship contribution statement

M.A. Mujtaba: Conceptualization, Investigation and Writing - Original Draft. **Haeng Muk Cho:** Funding acquisition. **H.H. Masjuki:** Supervision. **M.A. Kalam:** Supervision and Project administration. **M. Farooq:** Review & Editing. **Manzoore Elahi M. Soudagar:** Writing - Review & Editing and Visualization. **M. Gul:** Formal analysis and Review & Editing. **Asif Afzal:** Formal analysis and Review & Editing. **Waqar Ahmed:** Formal analysis and Review & Editing. **Asad Raza:** Formal analysis and Review & Editing. **T.M. Yunus Khan:** Resources. **Shahid Bashir:** Resources. **Zeeshan Ahmad:** Data Curation.

Declaration of competing 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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