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PERFORMANCE AND EMISSIONS OF DUAL ALCOHOL FUEL BLEND WITH B20 POME BIODIESEL IN DIESEL ENGINE

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Graphical abstract

Abstract

Biodiesel-diesel blends are known to result in increased NOx emissions compared to diesel alone, while ethanol as a ternary fuel in diesel-biodiesel shows that the blend successfully lowers diesel fuel NOx emissions but increases BSFC consumption. Hypothetically, pentanol, when added to blends as a second alcohol, may enhance engine performance and lower NOx emissions because pentanol exhibits superior characteristics including cetane number (CN) and viscosity, which is closer to diesel, as well as a higher calorific value. Therefore, this research aims to investigate engine performance and exhaust emission diesel engine operating with dual alcohol (ethanol and pentanol) +B20 POME biodiesel blend. The experiments involved evaluating different engine loads (25%, 50%, and 75%) at a constant speed of 1800 RPM. The findings indicate that the BSFC of dual alcohol blends are higher than diesel and B20 for all tested loads, with B20E10P10 showing least increment by 6.56% and 11.18% respectively. At 75% engine load, B20E10P30 exhibits a higher BTE by 2.11% compared to Diesel. The addition of dual alcohol in the blend significantly reduces NOx emissions, especially with B20E10P30. CO_2 emissions from B20E10P30 are closer to diesel fuel and B20, being only 1.54% lower than diesel and 0.79% higher than B20 at lower engine loads. For CO emissions, B20E10P10 shows the lowest CO emissions compared to B20E10P20 and B10E10P30. The findings suggest that combining higher alcohol with lower alcohol can effectively enhance the overall performance and emission characteristics of the fuel blend, supporting the hypothesis above.

Keywords: Dual alcohol, Pentanol, ethanol, B20 POME biodiesel, diesel engine

Abstrak

Campuran biodiesel-diesel menghasilkan pelepasan NOx yang lebih tinggi berbanding diesel, manakala ethanol sebagai bahan api ketiga dalam diesel-biodiesel menunjukkan bahawa campuran menurunkan pelepasan NOx bahan api diesel bagaimanapun meningkat dalam BSFC. Oleh itu, penambahan pentanol sebagai alkohol kedua dalam campuran berpotensi meningkatkan prestasi bahan api kerana pentanol mempunyai sifat yang sangat baik seperti calorific value dan cetane number (CN) lebih hampir kepada diesel daripada alkohol yang lebih rendah. Oleh itu, penyelidikan ini bertujuan untuk mengkaji prestasi enjin dan pelepasan ekzos enjin diesel yang beroperasi dengan campuran dwi alkohol (etanol dan pentanol) +B20 POME. Ujian telah dijalankan pada kelajuan tetap (1800 RPM) di bawah beban enjin yang berbeza (25%. 50%, 75%). Keputusan menunjukkan bahawa BSFC adalah lebih tinggi daripada diesel dan B20 untuk semua beban yang diuji, tetapi peningkatan adalah paling kecil dengan B20E10P10 masing-masing pada 6.56% dan 11.18%. Pada beban enjin 75%, BTE untuk B20E10P30 lebih tinggi sebanyak 2.11% berbanding Diesel. Penambahan dwi alkohol dalam adunan mengurangkan pelepasan NOx dengan ketara, terutamanya dengan B20E10P30. Pelepasan CO_2 daripada B20E10P30 lebih hampir kepada Diesel dan B20, iaitu hanya 1.54% lebih rendah daripada diesel dan 0.79% lebih tinggi daripada B20 pada beban enjin yang lebih rendah. Untuk pelepasan CO, B20E10P10 menunjukkan pelepasan CO yang paling rendah berbanding B20E10P20 dan B10E10P30. Penemuan menunjukkan bahawa menggabungkan alkohol yang lebih tinggi dengan alkohol yang lebih rendah secara berkesan boleh meningkatkan prestasi keseluruhan dan ciri-ciri pelepasan campuran bahan api.

Kata kunci: Dwi alkohol, Pentanol, ethanol, B20 POME biodiesel, enjin diesel

1.0 INTRODUCTION

In recent decades, the focus on energy demand has been gradually shifting from conventional fossil fuels towards sustainable and renewable energy sources. This transition is not merely driven by depleting fossil fuel reserves and surging oil prices, but also by the growing concerns over environmental degradation and climate change[1], [2]. Diesel engines, known for their high-power output and fuel efficiency, have been at the forefront of this transition, demanding cleaner and more efficient fuel alternatives [3].

The appeal of biofuels, particularly biodiesel and alcohols from renewable sources, has been steadily increasing as they present a viable option to not only meet the escalating energy demands but also to significantly reduce harmful exhaust emissions [4], [5] [6], [7]. Biodiesel is derived from either vegetable oils or animal fats, has emerged as a particularly viable substitute for diesel [8], [9], [10]. The blending of alcohols with biodiesel offers a promising avenue especially in reducing exhaust and particulate emisions[11].

Ethanol, a low carbon alcohol, has been widely studied for its potential benefits such as lower Nitrogen Oxide (NOx) emissions and higher brake thermal efficiency (BTE) however increased in brake specific fuel consumption (BSFC) when blended with biodiesel [12], [13], [14]. Several studies have explored the impact of alcohol-biodiesel blends on diesel engines. For example, the introduction of ethanol into biodiesel has been reported to enhance brake thermal efficiency (BTE) because there is more oxygen present and ethanol has a higher latent heat of vaporizationl [15], [16].

However, compared to lower alcohols, higher alcohols like pentanol have better properties such as cetane number (CN) and viscosity, which is closer to diesel, as well as a higher calorific value, which can improve combustion characteristics, although with mixed results on emissions [17], [18], [19], [20]. Hence, pentanol can potentially address some of the shortcomings associated with ethanol [21], [17], [22]. Combining these two alcohols into a dual blend could enhance the physicochemical properties of the fuel such as latent heat, calorific value and kinematic viscosity leading to reduced pollutants and improved engine performance.

Liang et al. [23] studied the impact of ethanol/diesel fuels and cosolvents such as biodiesel, n-pentanol, and tetrahydrofuran on combustion and exhaust properties of a diesel engine. The results show that n-pentanol/ethanol/diesel fuels can reduce NOx emissions at both low and high loads due to their high latent heat. This leads to lower in-cylinder gas temperature, affecting ignition performance and combustion temperature to decrease NOx emissions. While, *Liu et al.* [24] explored the effects of different alcohols on the solubility of diesel-hydrous ethanol blends, indicating that n-hexanol and n-octanol may be suitable co-solvent additives for hydrous ethanol/diesel systems based on their favorable characteristics.

However, the dual-alcohol approach, especially the integration of pentanol with ethanol in diesel-biodiesel blends, remains sparsely studied. Such dual-alcohol blends hold promise for achieving a harmonious balance between improved fuel properties and desirable engine performance. While individual studies have explored ethanol or pentanol as additives, a systematic investigation into the effects of an ethanol-pentanol blend with B20 POME biodiesel remains largely unfamiliar territory.

Given this above, the present research aims to bridge this gap. The objective is to analyze the effects of physicochemical properties of a dual alcohol fuel blend, encompassing ethanol and pentanol, when combined with B20 POME biodiesel, as well as their effects on engine performance and emissions in diesel engines. Comparisons will be drawn with traditional diesel fuel (D100) and B20 POME biodiesel fuel, offering insights into the potential viability of such blends for mainstream adoption. Through this endeavor, the study hopes to contribute significantly to the body of knowledge, potentially paving the way for more sustainable and efficient diesel engine operations in the future.

2.0 METHODOLOGY

2.1 Materials and Method of Blend Preparation

Diesel fuel and Palm oil biodiesel (POME) were obtained from a local industrial company in Selangor, Malaysia, while 1-pentanol (CAS No: 71-41-0) and ethanol (CAS No: 64-17-5) utilized in this research were procured from a chemical supplier. Test blends were prepared (by volume) using a magnetic stirrer. After continuous stirring for 20 minutes, the mixture was left to settle at ambient temperature for 30 minutes to attain equilibrium prior to any analysis and testing. It was observed that diesel and biodiesel had no issues of solubility or stability when blended with ethanol and pentanol. Throughout the tests, all fuel blends demonstrated miscibility and stability.

In this study, fuel samples B20 POME biodiesel were used as the base fuel except for Diesel fuel. B20 fuel was prepared by blending 80% diesel and 20% POME biodiesel (by volume). Subsequently, the B20 blended fuels will receive additions of 10% ethanol (by volume) and 10%, 20%, and 30% pentanol (by volume), which will be designated $B20_{80}E_{10}P_{10}$, $B20_{70}E_{10}P_{20}$, and $B20_{60}E_{10}P_{30}$, respectively as shown in Table 1. The fuel properties (kinematic viscosity, density, and calorific value) were tested using ASTM test standards while cetane numbers were calculated with the help of Kay's mixing rule which was based on Eqn. 1 [25], [26]. All the measured and computed values are presented in Table 1. According to Table 2, the density and kinematic viscosity of dual alcohol blends were found to be better than base fuel. However, it should be noted that these blended fuels have lower calorific values and cetane number values compared to diesel and B20 fuel. This is because ethanol and pentanol have inherently lower calorific values and cetane numbers than diesel fuel.

Table 1 Fuel sample by volume ratio (%) for every 1 liter

Sample	Content by volume (%)				
	Diesel	POME Biodiesel	B20	Ethanol	Pentanol
Diesel	100	0	0	0	0
B20	80	20	-	0	0
$B20_{80}E_{10}P_{10}$	-	-	80	10	10
$B20_{70}E_{10}P_{20}$	-	-	70	10	20
$B20_{60}E_{10}P_{30}$	-	-	60	10	30

Table 2 Properties of the tested fuels

	Kinematic viscosity (40 °C) (mm^2/s)	Density (at 15 °C) (Kg/m^3)	Calorific Value (MJ/kg)	Cetane Number
Diesel	3.08	836.9	45.08	49
B20	3.35	845.8	43.74	50.2
$B20_{80}E_{10}P_{10}$	2.69	837.5	41.66	43.26
$B20_{70}E_{10}P_{20}$	2.56	834.6	40.65	40.24
$B20_{60}E_{10}P_{30}$	2.51	832.6	40.07	37.22
ASTM Method	D7042	D7042	D240	Calculated

$$CN^b = \sum_{i}^{n} X_i \, CN_i \qquad \text{(Eqn. 1)}$$

Where:

X_i : fraction of the component

CN^b: the predicted cetana number of the blend

CN_i: known cetane number of each fuel component

2.2 Engine Test Procedure

The tests were conducted on a 4-stroke, air-cooled diesel engine with a single cylinder, depicted in Figure 1. The specific details of the engine used for testing are detailed in Table 3. Throughout the experiments, steady-state conditions were maintained without any alterations to the test engine. Engine performance and exhaust emission assessments took place under three distinct loads (25%, 50%, and 75%) while maintaining a constant engine speed of 1800 RPM. The measurements of engine load and speed were accomplished with the utilization of an eddy current dynamometer. To measure the flow rate of diesel, the data logging system and engine control unit were linked to the weighing balance. The measured data was recorded using a National Instruments system for data acquisition and LabVIEW software to facilitate subsequent analysis

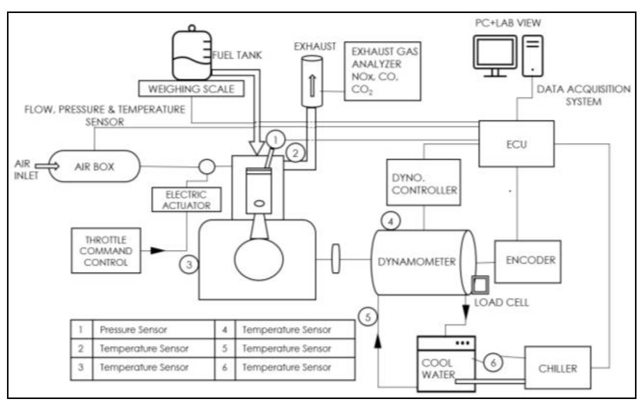

Figure 1 Schematic diagram of the experimental setup

Table 3 Specifications of test engine

Description	Specifications
Model	Yanmar L100N
Type	Single cylinder, 4-stroke, air-cooled engine
Bore	86 mm
Stroke	75 mm
Displacement	435 cm^3
Compression ratio	20.0 ± 0.3
Continuous Rate Output	6.2 kW
Maximum Rated Output	6.8 kW
Maximum Rated Speed	3600 rpm

The Nova 5640 Series Portable Exhaust Gas Analyzer was employed for the measurement of exhaust emissions. The CO, CO_2, and NOx measurement ranges that the analyzer offered were 0–10%, 0–20%, and 0–5000 ppm, respectively, with a resolution of 0.01%, 1%, and 1ppm, respectively. Data was recorded when all measuring apparatus was found to be in steady state. Before starting the experiment, the engine is run at idling condition until the engine reaches operating temperature by monitoring the engine temperature gauge. On this engine, it was found that it took about 10 minutes to reach the engine's operation. Additionally, the diesel engine was flushed with diesel fuel to accommodate potential mixtures of residual fuel before each test.

2.3 Error Analysis

Error analysis refers to the examination of uncertainties present in measured data and is crucial for ensuring the accuracy of measurements. The present study employed the root sum square method approach by Holman[27] to evaluate the uncertainties in the engine test [28]. Multiple data were collected for each test fuel, with a minimum of three measurements taken. The uncertainties of are calculated and presented in Table 4.

Table 4 Accuracy and uncertainty of instruments and calculated parameters

Measurement	Accuracy	% Uncertainty
Engine speed	±30 rpm	±0.5
Torque	±0.25 Nm	±0.83
NOx	±1 ppm	±0.79
CO	±0.01%	+0.16
CO2	±0.1%	±0.4
EGT		±1.7
BSFC		±1.88
BTE		±1.7
Overall uncertainty		±3.18

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Engine Performance

3.1.1 Brake Specific Fuel Consumption (BSFC)

Brake Specific Fuel Consumption (BSFC) described the quantity of fuel used in an hour to produce one kilowatt of power, making it essential for assessing and selecting fuels for different types of combustion engines [29]. Figure shows the differences in BSFC between various fuel samples at 1800 RPM engine speed. It can be seen that as the engine load increases from 25% to 75%, the BSFC values decrease significantly. Study by *Appavu et al*. [18] also found the similar trend due to the improved efficiency during fuel combustion, which occurs due to higher temperatures within the cylinders at increased loads.

At a 25% engine load there is a noticeable increase in BSFC values for blends $B20_{80}E_{10}P_{10}$ and $B20_{60}E_{10}P_{30}$, particularly when compared to Diesel with 17.40% and 28.63% increasing, respectively. However, at 50% engine load, the blend $B20_{80}E_{10}P_{10}$ shows BSFC increases the least when compared to diesel and B20 at percentages of only 6.56% and 11.18%, respectively. These observations are not isolated but align with previous study by *Atmanli et al*.[30] and *Yilmaz et al.* [31]. Atmanlı's shows that inclusion of pentanol in biodiesel-diesel blends led to a rise in BSFC due to lower heating values found in higher alcohol blends. This results in a greater need for fuel consumption to compensate for the reduced brake power.

Under all engine load conditions, there is a noticeable rise in BSFC for dual alcohol B20 blend when compared to both Diesel and B20 due to the decreased in calorific value and cetane numbers (Refer Table 2). Amongst all dual alcohol B20 blends, $B20_{80}E_{10}P_{10}$ demonstrates the smallest increase compared to pure diesel and B20. Diesel fuel, having a higher calorific value, requires less fuel consumption to achieve equivalent power outputs when compared to blends containing ethanol and pentanol [18].

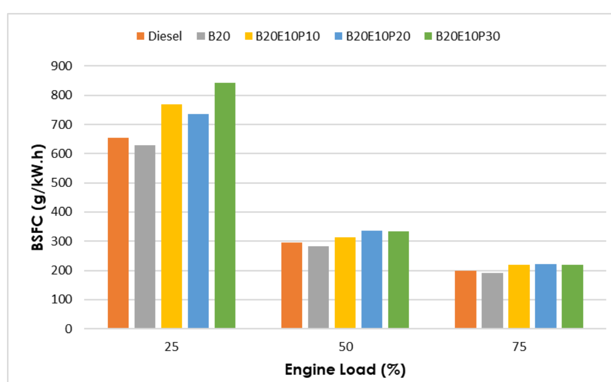

Figure 2 Brake Specific Fuel Consumption of fuel test at 1800RPM

3.1.2 Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) used to evaluate the effectiveness of converting the energy content of fuel into mechanical work [32]. As depicted in Figure 3, there is a notable correlation between BTE values and engine loads, with higher engine loads being associated with increased BTE.

Based on the result, B20 reveals a higher BTE value compared to pure Diesel by approximately 7.33% at a 25% engine load. This improvement can be attributed to biodiesel's unique physicochemical properties, particularly its increased oxygen content that promotes more complete combustion [3][33]. However, as the blend composition leans towards greater pentanol concentrations (from $B20_{80}E_{10}P_{10}$ to $B20_{60}E_{10}P_{30}$), the BTE values exhibit subtle variations, with $B20_{60}E_{10}P_{30}$ showcasing a higher decrease in BTE at 25% engine load with 12.06% compared to Diesel, while $B20_{70}E_{10}P_{20}$ shows a least decrease in BTE with approximately 0.33% at 75% engine load. This decline is likely influenced by differences in calorific values and altered fuel injection patterns associated with higher alcohol blends [34]. Interestingly, at 75% engine load, BTE for $B20_{60}E_{10}P_{30}$ higher 2.11% compared to Diesel. The increment in BTE can be credited to the increased number of oxygen molecules found in dual alcohol blend, the added oxygen and improved fuel atomization resulting from ethanol-pentanol's lower viscosity led to an enhanced combustion process [35]. Enhanced fuel vaporization can be achieved by operating under high load conditions, and/or by preheating the air before the intake process and can directly contribute to the efficient combustion fuel [36]. These experimental observations align with *Atmanli and Yilmaz et al.* [37] study which highlighted the influence pentanol on BTE performance, particularly under elevated engine operating conditions.

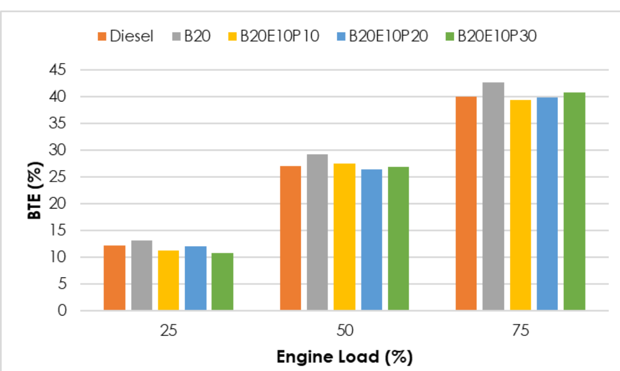

Figure 3 Brake Thermal Efficiency of fuel test at 1800RPM

3.1.3 Exhaust Gas Temperature (EGT)

Figure 4 illustrates the EGT of a fuel test conducted at 1800RPM, where it is observed that with an increase in engine load, there is also an increase in EGT. This occurrence can be attributed to the injection of more fuel into the combustion chamber as the engine load rises, consequently elevating in-cylinder temperature and leading to a corresponding rise in EGT [30].

As the concentration of pentanol in the blended fuels increases (from $B20_{80}E_{10}P_{10}$ to $B20_{70}E_{10}P_{20}$ to $B20_{60}E_{10}P_{30}$), there is a general increase in the EGT. More precisely, $B20_{60}E_{10}P_{30}$ displays the highest EGT across all engine load conditions. In comparison with Diesel, the increase of 21.96%, 26.9%, and 20.24% $B20_{60}E_{10}P_{30}$ were observed at 25%, 50%, and 75% loads, respectively. Alcohol, such as ethanol and pentanol, have a greater oxygen content compared to other fuel components. This increased oxygen presence creates an environment that promotes combustion zones rich in oxygen within the chamber. While such zones enhance complete combustion, they also tend to raise peak temperatures inside the cylinder. As a result, this phenomenon is reflected as a rise in EGT values [38].

This finding aligns with previous research that has investigated similar fuel blends [39]. However, other factors such as cetane number, ignition delay, and atomization quality of the blends should also be considered as they can potentially influence EGT profiles [31]. For instance, alcohol-dominant blends tend to have lower cetane numbers which may result in delayed combustion onset leading to varying EGT levels.

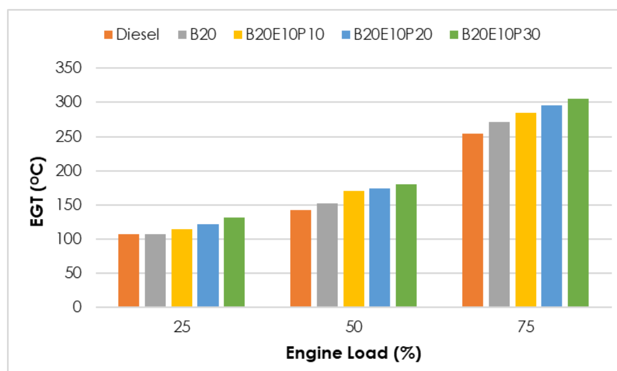

Figure 4 Exhaust Gas Temperature of fuel test at 1800RPM

3.2 Analysis of Exhaust Gas Emissions

3.2.1 Nitrogen Oxide (NOx)

The trend plot depicts NOx emissions as a function of engine load for various fuel blends as shown in Figure 5. Elevated in-cylinder temperatures predominantly lead to the formation of NOx emissions. An increase in engine load causes a rise in in-cylinder temperature, which leads to higher levels of NOx emissions.

At a significant engine load of 75%, the $B20_{80}E_{10}P_{10}$, $B20_{70}E_{10}P_{20}$, and $B20_{60}E_{10}P_{30}$ blends all exhibited lower NOx emissions compared to Diesel, with reductions of 12.14%, 26.21%, and 43.86% respectively. Those blended fuels exhibit a lower calorific value as well as a high latent heat of vaporization [40]. These properties contribute to combustion quenching and significant heat absorption from the combustion chamber. As a result, this leads to decreased flame temperature and subsequently reduces NOx emissions [41].

Ethanol and pentanol, as alcohols, possess chemical structures containing oxygen that inherently impact the combustion process. This influence can potentially result in a more even distribution of temperatures within the engine cylinder and prevent the formation of peak temperatures that contribute to NOx emissions [42]. These studies support the conclusion that dual alcohol blends have a positive impact on reducing NOx emissions. Furthermore, the results of this study align with prior research that examined the effects of alcohol blending on engine emissions [18], [36].

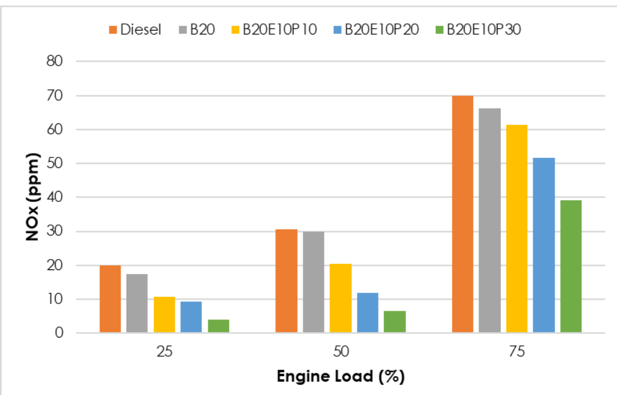

Figure 5 NOx fuel test at 1800RPM

3.2.2 *Carbon Monoxide (CO)*

In this study, CO emissions were examined across various fuel blends and at different engine loads as shown in Figure 6. Diesel and B20 fuels exhibited similar emission profiles under low load conditions. However, the blended fuels ($B20_{80}E_{10}P_{10}$, $B20_{70}E_{10}P_{20}$, $B20_{60}E_{10}P_{30}$) rise in emissions from 25% to 50% load was observed. At a 25% load, for instance, B20E10P10's emissions overtaken those of Diesel and B20 by approximately 77.73% and 89.50%, respectively. Dual alcohols have a higher latent heat of vaporization, they absorb more heat from the combustion chamber. This leads to a decrease in temperature, reduced efficiency of combustion, and increased emissions of CO [34]. This finding aligns with previous research [43], [25]. Additionally, as the engine load surged to 75%, dual alcohol fuel blends witnessed emission reductions likely due to increased combustion temperatures and pressures fostering more complete combustion. Additionally, consistent decline in emissions across at high load can be linked to its pentanol concentration, which, due to its oxygenated nature, might bolster combustion completeness [23], [44].

Overall, $B20_{80}E_{10}P_{10}$ emits less CO at all engine loads than $B20_{70}E_{10}P_{20}$ and $B20_{60}E_{10}P_{30}$ because the blended fuel's overall cetane number decreased as pentanol concentration increased. The longer premixed combustion stage duration is associated with lower cetane numbers, leading to timing issues during the combustion and expansion stages [38]. As a result, less carbon and oxygen are oxidized, resulting in increased CO emissions.

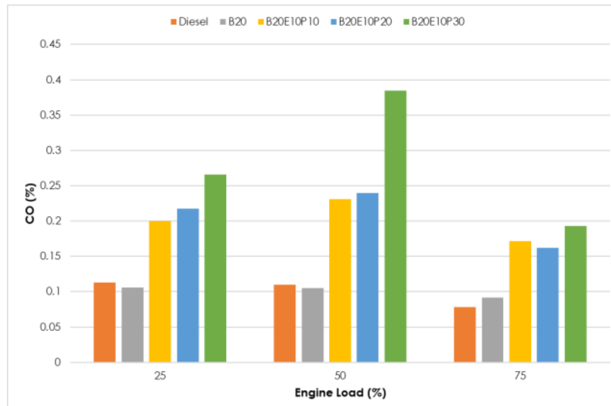

Figure 6 Carbon Monoxide of fuel test at 1800RPM

3.2.3 *Carbon Dioxide (CO_2)*

The results of CO_2 presented in Figure 7 show how different dual alcohol fuel concentrations perform under varying engine loads in comparison with Diesel and B20.

CO_2 emissions rise as engine load increases for all types of fuel tested. $B20_{60}E_{10}P_{30}$ has a CO_2 emission profile that's closer to Diesel and B20, especially at lower engine loads with 1.54% lower than Diesel, and 0.79% higher than B20. The presence of carbon dioxide varies based on the ratio of carbon/hydrogen in the fuel. Using dual alcohol blends in fuel reduces the carbon content per volume compared to diesel fuel due to the higher oxygen content of the alcohols. Therefore, it is anticipated that a higher pentanol concentration will result in lower CO_2 [45], [32]. While $B20_{80}E_{10}P_{10}$ consistently exhibited the highest levels of CO_2 emissions across all engine loads. Due to the existence of oxygen molecules in their chemical structure, alcohols have a smooth reaction with CO, which impacts the production of CO_2 emissions in exhaust gases [46]. These two conflicting factors are responsible for the overall CO_2 emissions. In the current scenario and based on the tested fuels, these opposing factors nearly offset each other, leading to minimal changes in CO_2 emission levels. Similar research indicates that introducing higher-alcohol components into blends consisting of diesel and biodiesel fuels can significantly affect CO_2 emission [32], [47].

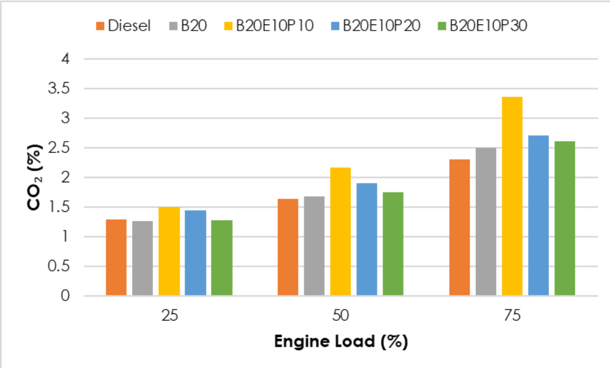

Figure 7 Carbon Dioxide of fuel test at 1800RPM

4.0 CONCLUSION

An experimental study was conducted to investigate the impact of dual alcohol (ethanol and pentanol) on B20 POME on both engine performance and exhaust emissions using a single-cylinder CI diesel engine.

All the dual alcohol B20 blends showed an increase in the BSFC compared to Diesel and B20 due to the reduced calorific value and cetane numbers in these blends. Amongst the dual alcohol B20 blends, B2080E10P10 demonstrates the smallest increase compared to pure diesel and B20, with increments of 6.56% and 11.18% respectively.

B20 demonstrated higher BTE value compared to the fuel blends. For the dual alcohol B20 blends, B2070E10P20 shows a least decrease in BTE with approximately 0.33% at 75% engine load. The introduction of higher alcohol in dual alcohol B20 blends led to a significant reduction in NOx emissions compared to Diesel and B20 fuel. This reduction becomes more significant as the proportion of higher alcohol in the blends rises.

Compared to another dual alcohol blend, B2060E10P30 produces the lowest NOx at all engine loads. B2060E10P30 has a CO2 emission profile that's closer to Diesel and B20, especially at lower engine loads with 1.54% lower than Diesel, and 0.79% higher than B20. CO emissions for dual alcohol B20 blended fuel are higher than diesel and B20 fuel at all engine loads. However, B2080E10P10 shows the lowest CO emissions compared to B2070E10P20 and B2060E10P30.

Hence, combining dual alcohol fuel (ethanol and pentanol) with B20 POME biodiesel resulted in comparable performance and emissions to Diesel and B20 POME biodiesel. Specifically, this blend showed significant enhancement in reducing NOx emissions. The findings suggest that combining higher carbon alcohol with lower carbon alcohol can effectively enhance the overall performance and emission characteristics of the fuel blend.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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