INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 21, ISSUE 4, 2024, 11893 – 11908
DOI: https://doi.org/10.15282/ijame.21.4.2024.12.0915

RESEARCH ARTICLE

Evaluation of Operability and Exhaust Emissions of Common Rail Direct Injection Engine using Biodiesel Blends in Moderate Cold Environment

J. Nursyairah[1]*, H. L. N. Lau[1] and R. I. A. Jalal[2]

[1]Energy and Environment Unit, Engineering and Processing Division, Malaysian Palm Oil Board (MPOB), No. 6, Persiaran Institusi, 43000 Kajang, Selangor, Malaysia

[2]Taylor's University, No. 1, Jalan Taylor's, 47500 Subang Jaya, Selangor, Malaysia

ABSTRACT – Malaysia has restricted the use of biodiesel blends to B7 in the highlands due to challenges related to cold flow operability, while B10 and B20 are used in the lowlands. This study evaluated the performance and emissions of a light-duty, 4-cylinder Euro III turbocharged common rail direct injection diesel vehicle using palm biodiesel blends (B10, B20, and B30) at speeds of 60, 80, and 100 km/h under simulated cold temperatures of 10, 15, and 20°C in a controlled cold chamber. The combustion of B10 and B20 in the diesel engine showed enhancements in power and torque of 3.9% and 4.6%, respectively, compared to Euro 2M (B7) diesel. These improvements are likely the result of the synergistic effects of the enriched oxygen levels in biodiesel and the increased density of cold air, which enhance combustion efficiency. CO_2 emissions decreased by 1.5%, 4.3%, and 11.2% with the use of B10, B20, and B30 fuels, respectively. NOx emissions decreased as biodiesel content increased at 10 and 15°C; however, the emissions increased by 17.6% and 38.2% for B20 and B30, respectively, in comparison to B10 at 20°C. B20 demonstrated good engine performance and emissions at 15°C, with improvements of 1.3% in power and 3.7% in torque, which compensated for a 3.2% increase in fuel consumption, and there were reductions of 8.9% in NOx emissions and 0.9% in CO_2 emissions compared to B7 diesel. Palm biodiesel blends ranging from 7 wt.% to 20 wt.% are capable of withstanding the moderate cold ambient temperatures of the highlands without compromising engine operation.

ARTICLE HISTORY
Received : 15th June 2023
Revised : 13th Aug. 2024
Accepted : 09th Dec. 2024
Published : 17th Dec. 2024

KEYWORDS
Palm biodiesel
Cold performance
Fuel consumption
Power
Torque
Exhaust emissions

1. INTRODUCTION

The widespread use of alternative renewable energy sources, such as biodiesel, has been prompted by concerns over limited fossil fuel reserves and their contribution to climate change, which has consequently led to a growing research interest in fuel compatibility for internal combustion (IC) engines over the past decade [1]. Biodiesel has been used either as pure or diesel blends in commercial transportation that do not require major modifications to the engine [2, 3]. Biodiesel can be derived from a diverse range of feedstocks, ranging from edible oils like rapeseed, and palm to non-edible oils such as jatropha, and rubber seed, in addition to other sources (microalgae, used cooking oil, animal fats, etc.) [4]. In fact, all forms of esterified vegetable oils are suitable for use as diesel substitutes. Nevertheless, palm oil and rapeseed oil are considered the best options among vegetable oils for use as diesel fuels, additives, or diesel fuel extenders [5]. The selection of crops used as biodiesel feedstock is influenced by climate and soil conditions, such as oil palm in Southeast Asia (notably Malaysia and Indonesia), soybean in the United States, rapeseed and sunflower in Europe, and coconut in the Philippines.

Among the world's vegetable oils, oil palm is recognized as the most efficient oil-producing crop, yielding the highest oil output per unit of cultivated land (i.e., approximately 4–5 t ha^{-1} yr^{-1}), making palm oil the most preferred feedstock for biodiesel production in terms of production cost and product reliability [3, 6]. Moreover, palm oil offers positive carbon benefits as compared to other major biodiesel sources [7], rendering it the most viable and sustainable feedstock for biodiesel production [8]. Practically, palm biodiesel emerges as a promising alternative to petroleum diesel for common rail direct injection (CRDI) engines, with advantages such as improved stability and reduced exhaust emissions, except for NOx, making it a viable and environmentally friendly option [9, 10]. Furthermore, palm biodiesel exhibits better properties than biodiesel from other feedstock, especially in terms of cetane number and iodine value [8, 11].

Most countries that have implemented biodiesel programs have gradually increased their biodiesel blending ratio to above 7% in the last decade [12]. Malaysia, being one of the major oil palm-producing countries, is moving ahead with high biodiesel blends. B20, a blend consisting of 20% palm biodiesel and 80% diesel has currently been implemented in phases beginning in January 2020 in selected regions. The B10/B20 program covers all areas in Malaysia, except Cameron Highlands and Genting Highlands in Pahang and Kundasang in Sabah. The biodiesel content for the transportation sector will further increase to 30% (B30) in the near future [13]. In the highlands, the temperature ranges from 11 to 13 °C, with the lowest recorded at 10.9 °C in December 2007 [15]. These highlands have been exempted from using B10 and continue to use B7 due to concerns regarding vehicle operability under low-temperature conditions, as highlighted by the original equipment manufacturers [13]. Previous studies have reported some unfavorable findings associated with extreme

***CORRESPONDING AUTHOR | J. Nursyairah** | nursyairah@mpob.gov.my

cold/winter conditions using biodiesel from rapeseed, sunflower, soybean, etc. However, the operability of palm biodiesel at low temperatures and its impacts under moderate cold ambient temperatures have yet to be investigated.

The presence of saturated fatty acids in vegetable oils, particularly in palm oil, would result in poor cold flow properties when used in cold climatic conditions [4, 14]. This can also compromise engine performance due to biodiesel crystallization, which impedes fuel flow in cold weather. In general, both diesel and biodiesel fuels experience low-temperature operability problems during cold weather, especially in winter, which are exacerbated by the use of biodiesel [15]. Research has shown that fuel consumption increases as ambient temperature decreases from 26 to –20 °C for all tested vehicles using diesel, attributable to increased frictional losses within the engine and longer warm-up periods in cold ambient temperatures [16]. Biodiesel's low-temperature operability can be a limitation, potentially leading to the obstruction of fuel filters and/or the disruption of injector function [17]. Palm oil, in particular, has suboptimal low-temperature operability due to its higher proportion of saturated fatty acid composition compared to other biodiesel feedstocks, which tend to form solid crystals or precipitates [18, 19]. Additionally, the high monoglyceride content in biodiesel also contributes to the formation of precipitates or solidified materials that can obstruct the flow and operation of fuel lines and filters, especially at cold temperatures [20 – 23]. Under certain conditions, palm biodiesel may even precipitate during storage at colder room temperatures of 20–23 °C [24].

The main driver for using biodiesel is to mitigate greenhouse gas emissions. The substantial oxygen content in biodiesel enhances the combustion efficiency of carbon compounds, resulting in decreased emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) [25, 26]. However, it has been reported that biodiesel contributes to higher NOx emissions than fossil diesel, raising significant environmental concerns about its use in IC engines [26, 27]. The quality of exhaust emissions deteriorates as ambient temperature decreases [16, 28]. Numerous previous studies have examined the performance of petroleum diesel under simulated conditions of extreme cold temperatures. A study on a Jaguar V6 3.0L CRDI diesel engine under idling conditions after a cold start found that NOx increased substantially by up to 150% and 50% at −20 and −7 °C, respectively, compared to 20 °C. The peak HC emissions were approximately 15 times greater than those in normal ambient environments due to inefficient fuel-air mixing and incomplete fuel combustion [28]. Another study examining 167 diesel vehicle test fleets found that HC and CO emissions were observed 1 to 4 times and 1 to 3 times greater, respectively, at -20 °C compared to 20 °C.

Meanwhile, NOx emissions varied depending on the emission control technologies used, ranging from 0.75 to 1.11 times lower or greater at -20 °C compared to 20 °C. [16]. Additionally, unburned HC emissions at −7 °C were 2.5 higher than the emissions at 20 °C using Worldwide harmonized Light-duty vehicles Test Cycles (WLTC) [29]. Testing at test temperatures of 23, 14, and −5 °C using the New European Driving Cycle (NEDC) and WLTC revealed that NOx emissions were 11 and 2.8 times higher at −5 and 14 °C than those observed at 23 °C, respectively, in the NEDC. Similarly, in the WLTC, the NOx emissions of 5 and 14 °C increased by 7 and 2.5 times, respectively, compared to 23 °C [30]. At low temperatures, both standard diesel and B20 fuel blends exhibited substantial increases in HC and CO emissions [31]. The findings of previous studies are summarized in Table 1. To the authors' knowledge, no prior research has investigated the effects of palm biodiesel on exhaust emissions under moderate cold ambient temperatures.

Verification on the impact of palm biodiesel blends in IC engines at temperatures above 0 °C, particularly under moderate cold ambient temperatures at highlands, is significant to fill in the gap of insufficient information with regard to the effect of utilizing high biodiesel blends in petroleum diesel on engine operation. This study offers valuable insights into the operational behavior of diesel engines under moderately cold environmental conditions in tropical highlands using high palm biodiesel blends. The outcomes of this research could provide a useful reference for establishing the acceptable limit of palm-based biodiesel blend fuels for use in the moderate cold temperatures prevalent in the Malaysian highlands. Fuel performance in relation to engine power, torque, fuel consumption, and exhaust emissions of the diesel engine at steady-state full load conditions was investigated using different palm biodiesel blends of B10, B20, and B30.

Table 1. Impact of cold ambient temperature on exhaust emissions

Engine Specification	Input Parameter	Emission Parameter				Ref.
		CO_2	CO	NOx	HC	
TD 313 diesel engine, 4-cylinder, & 4-stroke	• Fuel: Diesel and B20 • Temperature: −10, 0, 25, and 50 °C • Test condition: NEDC and WLTC	-	• Increased by 92.5% for diesel fuel from 50 to −10 °C	-	• Increased by 86.9% and 90.9% using diesel and B20 from 50 to −10 °C	[35]
2-L turbocharge, inline 4-cylinder, CRDI Euro 6 vehicle	• Fuel: Diesel • Temperature: 23, 14, and -5 °C • Test condition: NEDC and WLTC	• Increased at low ambient temperature, CO_2 emissions (g/km) in the WLTC were less than those in the NEDC	• Increased at low ambient temperature	• NOx at -5 and 14 °C were 11 and 2.8 times higher compared to those at 23 °C in the NEDC • NOx at -5 and 14 °C were 7 and 2.5 times higher than those at 23 °C in the WLTP	• Increased at low ambient temperature	[30]
4-cylinder, 1.6 L, turbocharged HSDI	• Fuel: Diesel • Temperature: 20 and -7 °C • Test condition: Transient state of WLTC driving cycle	-	• CO at -7 °C was lower than that at 20 °C	-	• HC at -7 °C was 2.5 greater than that at 20 °C	[29]
Jaguar V6 3.0 L CRDI diesel engine	• Fuel: Diesel • Temperature: 20, -7, and -20 °C • Test condition: NEDC and WLTC	-	-	• NOx at −20 and −7 °C were 150% and 50% higher compared to normal conditions	• HC in cold ambient were 15 times greater compared to normal conditions	[28]
Dodge Colt, Volvo, Plymouth Fury, Oldsmobile Delta 88, and VW rabbit	• Fuel: Diesel and gasoline • Temperature: 20 and -20 °C • Test condition: Urban driving cycle	-	• Increased 1–3 times at cold temperature	• Higher or lower about -0.75 to 1.11 times, depending on emission control technologies	• Increased 1–4 times at cold temperature	[16]

2. MATERIALS AND METHODS

2.1 Preparation of Test Fuels

Undistilled palm biodiesel with high monoglyceride content (>0.6 wt.%) was obtained from Bremfield Sdn. Bhd., while Euro 2M (B7) diesel containing 7 wt.% of palm biodiesel (standard fuel) was obtained from a Petron fuel station located at Genting Highlands, Pahang. The base diesel and biodiesel used for this study were similar to those used in previous investigations [32, 33]. Both palm biodiesel (B100) and standard diesel fuel meet the requirements of MS2008:2014 and MS123-4:2020, respectively [34, 35]. The blends of 10%, 20%, and 30% biodiesel (B10, B20, and B30) were prepared on a volumetric basis and stored in high-density polyethylene drums at room temperature. The blended fuels were analyzed for their density, viscosity, cloud point (CP), cold filter plugging point (CFPP), and pour point (PP) according to ASTM D4052, ASTM D445, ASTM D2500, EN 116, and ASTM D97, respectively.

2.2 Experimental Setup and Cold Performance Test Procedure

A Toyota Fortuner 2.5G (D) A/T Euro III turbocharged direct injection (DI) common rail diesel engine was utilized to perform the test in a cold chamber equipped with a chassis dynamometer (Figure 1). The vehicle specifications are provided in Table 2. The experimental configuration inside the cold chamber is depicted schematically in Figure 2. The in-pipe differential fuel flow rate before and after the fuel filter was measured using a CONTOIL® DFM 8ECO flow meter without interfering with the engine operation. A portable emission gas analyzer with a non-dispersive infrared (NDIR) detector was employed to quantify the levels of HC, CO, CO_2, O_2, and NO in the exhaust emission. The specifications of the fuel flow meter and the gas analyzer are detailed in Table 3 and Table 4, respectively.

Figure 1. Cold chamber with the chassis dynamometer and the vehicle used in the study

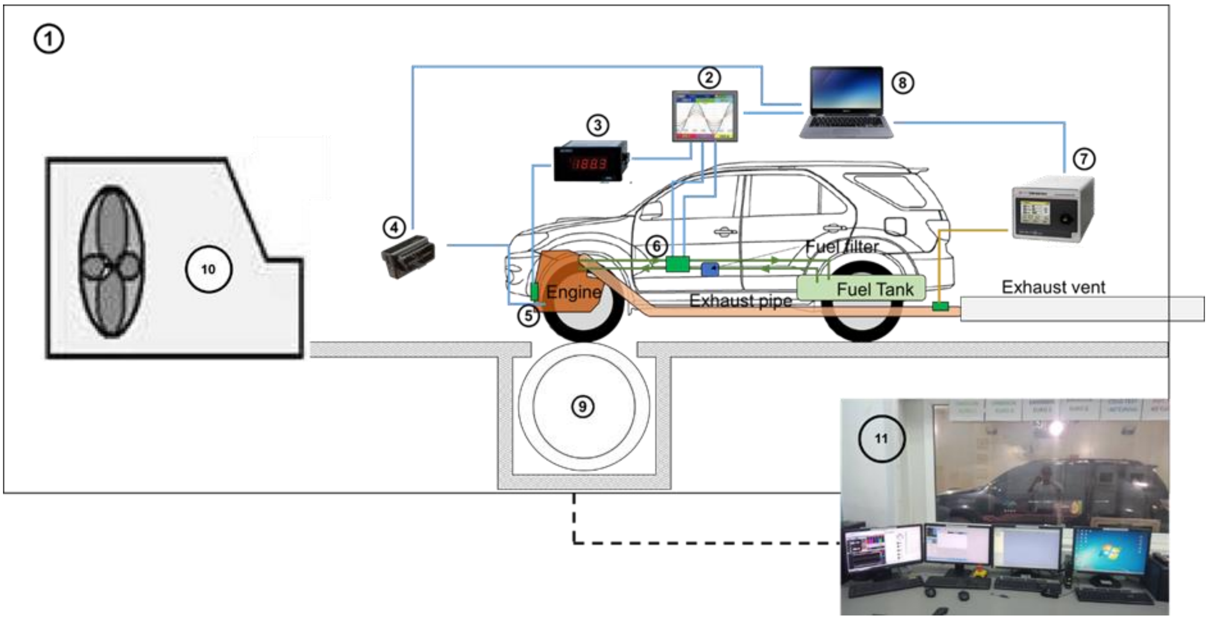


Figure 2. Experimental setup for cold performance test (1: cold chamber, 2: data logger, 3: counter (tachometer), 4: OBDII data logger, 5: IR sensor (tachometer), 6: fuel flow meter, 7: emission gas analyzer, 8: laptop, 9: chassis dynamometer, 10: wind simulator, and 11: control room)

Table 1. Vehicle specifications

Item	Specification
Model	Toyota Fortuner 2.5G (D) A/T
Type of engine	Common rail DI diesel engine
No. of cylinder	Four in line
Power (max.)	110 kW @3,400 rpm
Torque (max.)	400 Nm @1,600 rpm

Table 2. Specification of fuel flow meter

Item	Specification
Device	DFM 8ECO
Nominal pressure	16
Nominal flow rate (L/h)	200
Min. flow rate (L/h)	10
Accuracy (%)	1
Repeatability (%)	+/- 0.2
Flow sensor	Double sensor with 0.01244 l/pulse, 7 Hz (max.), pulse interval of 46 (min.), pulse width of 20 ms, 10 mA (max.)

Table 4. Specification of gas analyzer

Item	Specification
Device	Autocheck automotive emission analyzer
Method	
HC, CO, and CO_2	NDIR measurement
O_2 and NOx	Electro-chemical cell
Range	HC *n*-hexane (0~30,000 ppm), HC (0~60,000 ppm), CO (0~10%), CO_2 (0~20%), O_2 (0~25%), NOx (0~5,000 ppm)
Resolution	HC and NOx (1 ppm), CO (0.001 vol. %), CO_2 and O_2 (0.01 vol. %), RPM (10 RPM), oil temp. (1 °C)
Repeatability	
HC, CO, and CO_2	2% rel
O_2 and NOx	3% rel

The overall uncertainty associated with the results of this study was calculated using the instrument accuracy percentages provided in Table 5, according to Eq. 1. The uncertainties associated with the various parameters measured in the study were calculated following Eq. (2). The uncertainty quantified for the study is less than ±5%, aligning with the values documented in prior relevant research [32, 36].

$$\frac{U_y}{y} = \sqrt{\sum_{i=1}^{n} \left(\frac{1}{y}\frac{\partial y}{\partial xi}\right)^2} \tag{1}$$

where y represents a specific factor dependent on the parameter xi, and U_y denotes the corresponding level of uncertainty associated with y.

$$Overall\ uncertainty = \sqrt{(1)^2 + (1)^2 + (2)^2 + (2)^2 + (3)^2 + (2)^2} = \pm 4.79 \tag{2}$$

The vehicle cold testing procedure comprised four key steps: preconditioning/presoaking, soaking, cold startability test, and performance test, as illustrated in Figure 3. The test vehicle underwent a preconditioning procedure, which consisted of changing the fuel filter, oil filter, and engine oil; flushing the fuel line using standard fuel B7; refueling of new fuel and pre-driving prior to entering the cold chamber; presoaking for 1.5 h at 5 °C below the target ambient temperature; and 6 h soaking at the target temperature. The cold performance test was performed after the cold startability test, where the vehicle underwent a 5-minute ramping period at each of the specified speeds (60, 80, and 100 km/h) under full load conditions. This allowed for the assessment of variations in power, torque, fuel consumption, and exhaust emissions, including CO, CO_2, O_2, NOx, and HC. Out of 16 test conditions tested for cold start performance in the previous study, only nine test conditions were fit for the cold engine performance test, as summarized in Table 6. This was because of the vehicle's failure to start at certain test temperatures and biodiesel blending ratios, as reported in a previous study [32].

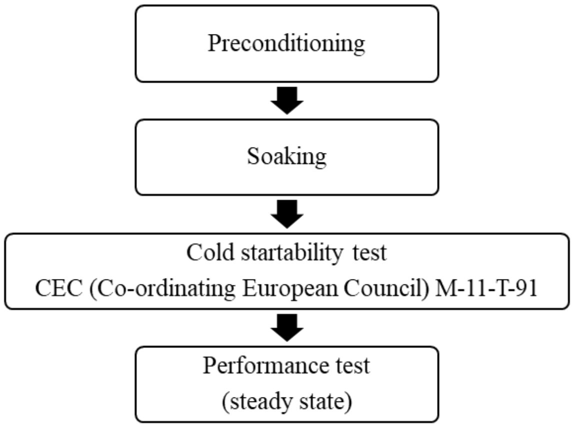


Figure 1. Cold test procedure

Table 5. Accuracy of the measurements

Parameter	Accuracy
Temperature	±1.0 °C
Fuel flow	±1.0 L/h
CO2	±2.0%
CO	±2.0%
NOx	±3.0 ppm
HC	±2.0 ppm

Table 6. Test matrix for engine cold performance

Test Temperature	Test Fuel	Test Fuel	Test Fuel	Test Fuel
	B7	B7	B7	B7
20 °C	✓	✓	✓	✓
15 °C	✓	✓	✓	X
10 °C	✓	✓	X	X
5 °C	X	X	X	X

Note: ‘X’ means failed to start and did not proceed with the cold engine performance test

2.3 Soaking Analysis and Cold Test Parameters

2.3.1 Soaking analysis

The vehicle was preconditioned in the cold chamber for 7.5 h prior to testing to guarantee the fuel temperature in the fuel tank reached the target temperature of the study. Figure 2 shows the temperature soaking profile of standard diesel B7 at 10 °C. The temperature in the vehicle was determined by monitoring engine fluids' temperatures, such as the fuel in the fuel tank and fuel line, the engine coolant in the radiator, as well as the engine lubricant in the oil sump. The surrounding temperature was influenced by both the ambient temperature and the temperature in the engine room. The temperature of the ambient, engine room and coolant in the radiator showed a drastic decline at an early stage of presoaking when the cold chamber was set at 5 °C below the targeted ambient temperature. After 30 min, these three temperatures stabilized to the targeted ambient temperature. This was because the thermocouples installed to monitor ambient and engine room temperature were directly exposed to the surroundings, while the coolant in the radiator responded immediately to changes in the environment. Other engine fluids' temperatures in the vehicles showed a slow decline, in which 5–6 h was required to approach the target temperature. This was influenced by the high heat capacity of the engine oil and fuel, resulting in long periods of cooling. In addition, the large amount of fuel in the fuel tank also slowed the cooling time. For the purpose of the test, the fuel temperature in the fuel tank was used as a reference for the target ambient temperature for all tests. During vehicle start-up, the intake manifold temperature and pressure were within ±3 °C and ±0.01 bar, respectively, of the target conditions.

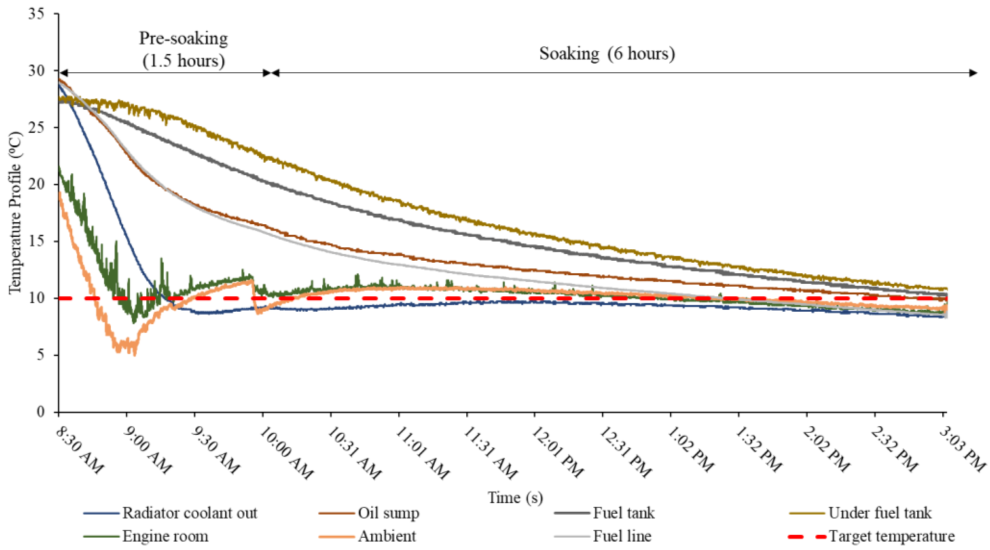


Figure 2. Temperature profile for soaking of B7 at 10 °C

2.3.2 Cold test parameters

The engine's performance was evaluated at moderate cold ambient temperature by means of four parameters: power, torque, fuel consumption, and exhaust emissions. The total power output of the vehicle at constant speed was measured by subtracting the power produced during the deceleration phase (power negative) from the engine power generated during the acceleration phase (power positive), as depicted in Figure 3. A constant power value was used to determine the power at a specific engine speed. For instance, the total power output at 100 km/h was calculated by deducting the constant value of power negative (B) from the constant value of power positive (A). The vehicle's torque was calculated based on Eq. 4 derived from Eq. 3, which involves engine power and engine speed measured by the IR sensor (tachometer) collected from the data logger.

$$Power\ (kW) = \frac{Torque\ (N \cdot m) \times Speed\ (RPM)}{9.5488} \tag{3}$$

$$Torque\ (N \cdot m) = \frac{Power\ (kW) \times 9.5488}{Speed\ (RPM)} \tag{4}$$

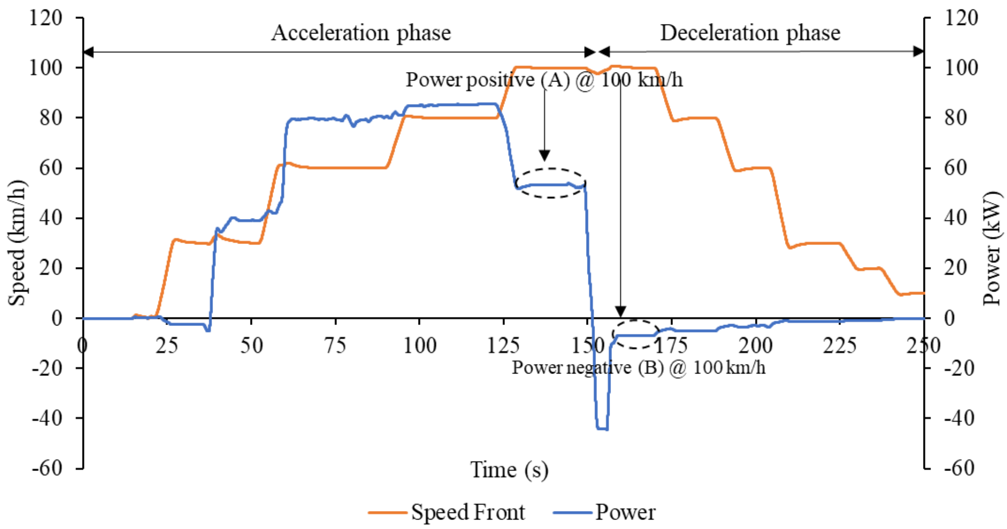


Figure 3. Example of engine power measurement under steady-state full load condition at cold ambient temperature

The fuel consumption was calculated by measuring the differential volume of the fuel entering the fuel flow meter placed before the fuel filter (fuel supply) and the returned fuel to the fuel filter (fuel return) according to Eq. 5.

$$Fuel\ consumption\ (mL/s) = Fuel\ supply\ (mL/s) - Fuel\ return\ (mL/s) \tag{5}$$

The instantaneous exhaust emissions were determined by identifying the constant value of exhaust emissions at a certain engine speed. All data presented in the graphs were obtained by averaging the measurements recorded over a 5-minute ramping period at each of the specified speeds.

3. RESULTS AND DISCUSSION

The selection of test fuels, namely B7, B10, B20, and B30, was based on Malaysia's current biodiesel implementation program. B10 and B20 blends are currently being used in the lowlands, while B7 is used in the highlands. The National Agricommodity Policy 2021–2030, published by the Ministry of Plantation and Commodities, aims to implement the B30 biodiesel blend by the year 2030 as part of the nation's initiative to increase the use of renewable fuels [37]. The properties of standard diesel B7, B10, B20, and B30 are summarized in Table 3. The palm biodiesel blends utilized in this study have density and kinematic viscosity values that fall within the limits of 0.820–0.876 g/cm^3 and 1.5–5.8 mm^2/s, respectively, as stipulated in MS123-4:2020 [34]. With an increase in biodiesel concentration in the fuel, the density and kinematic viscosity of the blended fuel increase proportionally, following the same patterns reported in previous studies. [38, 39]. The cold engine performance tests were conducted at 60, 80, and 100 km/h at temperatures of 10, 15, and 20 °C, respectively. The test speeds were set based on the WLTC, with each sub-part having a different maximum speed. During the test, four parameters were monitored and measured: power, torque, fuel consumption, and exhaust emissions.

Table 3. The properties of palm biodiesel blends for the cold performance test

Parameter	Method	Unit	Test Fuel			
			B7	B10	B20	B30
Density at 15 °C	ASTM D4052	g/cm^3	0.8376	0.8386	0.8430	0.8467
Kinematic Viscosity at 40 °C	ASTM D445	mm^2/s	3.0860	3.1179	3.2570	3.3803
Cloud Point	ASTM D2500	°C	7	8	10	10
Cold Filter Plugging Point	EN 116	°C	8	7	10	12

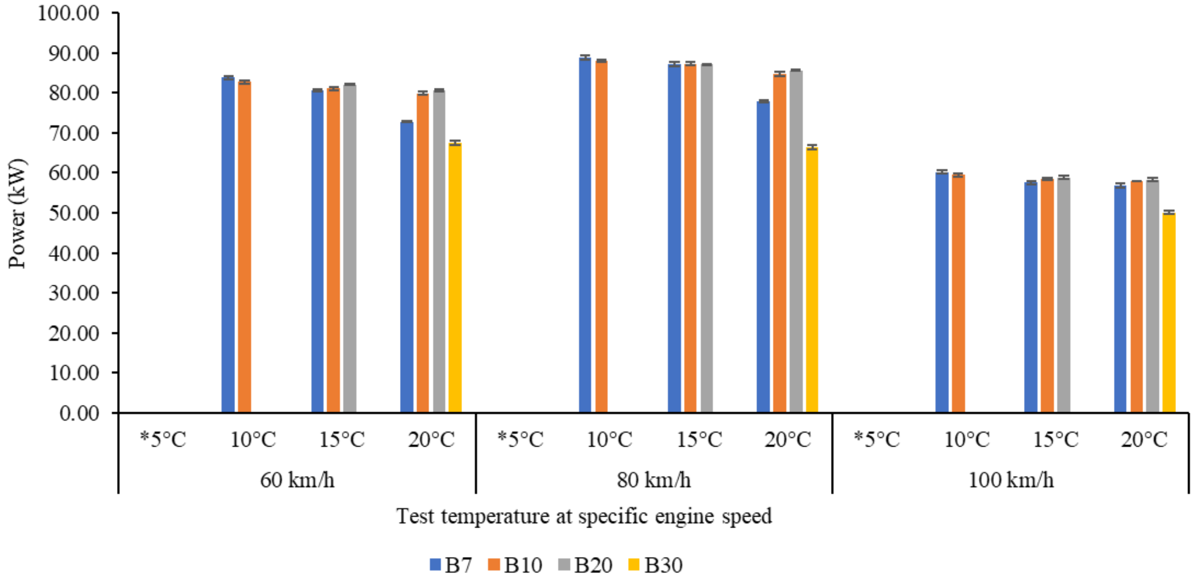
3.1 Engine Power and Torque

The most common parameters used to define an engine's performance are power and torque, which are directly proportional to each other. The changes in engine power and torque at different engine speeds, as affected by the various palm biodiesel fuel blends, and ambient temperatures, are presented in Figure 6 and Figure 7, respectively. In Figure 6, the engine power was in the order of engine speed: 80 km/h > 60 km/h > 100 km/h, with an average power of 83.70, 79.03, and 57.52 kW, respectively. The engine torque exhibited a gradual reduction as engine speed increased (Figure 7) for all palm biodiesel blends, with an average torque of 218.15, 177.27, and 100.92 N·m at 60, 80, and 100 km/h, respectively. Previous studies have also reported a similar decreasing trend in engine torque as the engine speed increased when using palm biodiesel blends in diesel engines [40].

Overall, the engine power and torque showed a consistent increase across the tested ranges of engine speed at 15 and 20 °C for B20 fuel (higher biodiesel content), which is consistent with previous studies [40, 41]. On average, engine power and torque increased by 3.6% and 3.4% for B10 and 4.2% and 5.8% for B20, at 15 and 20 °C, respectively, in comparison to B7. The enriched oxygen presence in biodiesel (i.e., 10–12 wt.%) compared to diesel may contribute to this observation. The addition of 10–12 wt.% of biodiesel into petroleum diesel could lead to better combustion, thus enhancing the power and torque of the engine [42]. Additionally, the higher density of the biodiesel blends in comparison to standard diesel led to a greater mass flow rate when an equivalent volume was supplied to the engine, which contributed to the observed increases in power and torque [43]. The differences in power and torque between B20 and B10 were relatively small, with only 0.8% and 1.9%, respectively. This suggests that the optimum power and torque were achieved with B20 and dropped when B30 was used. At 10 °C, a slight decrease in power by 1.1% and torque by 2.4% was observed for B10 compared to standard diesel B7. Similarly, studies have reported 2%–6% and 1%–8% decreases in power and torque, respectively, when using coconut oil methyl ester blended fuels (10 to 30% blending) in comparison to ultra-low sulfur diesel [44]. Engine power and torque are expected to deteriorate owing to biodiesel's lower density and energy content, considering the same mass of injected fuel. Besides, when a more viscous fuel leaves the injector, the fuel droplets are larger and do not evaporate efficiently, leading to a reduction of power and torque.

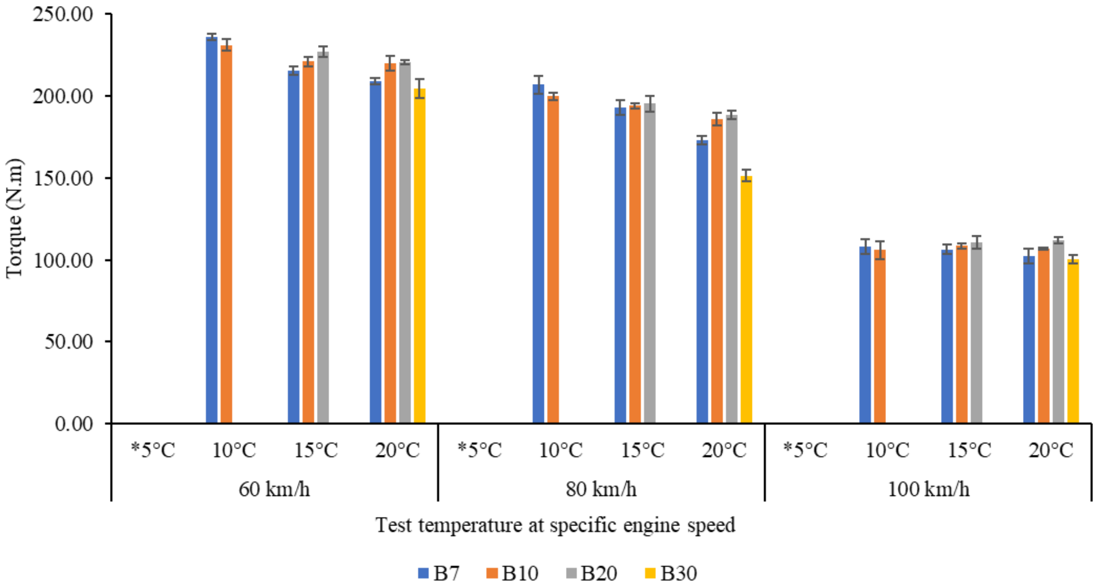
B30 fuel showed the lowest power and torque among the test fuels. On average, the reduction in power was 7.2%, 14.8%, and 11.8%, while torque decreased by 2.1%, 14.3%, and 2.0% at 60, 80, and 100 km/h, respectively, using B30 compared to standard diesel (B7). The drop in power was due to a lower volume of fuel introduced into the combustion chamber as compared to other fuels, as shown in Figure 8, resulting in reduced power output from the engine. This phenomenon was possibly caused by a clogged fuel filter from a higher biodiesel blend, which restricted the desired fuel supply to the combustion chamber, and consequently prevented the engine from performing at optimum levels. This is supported by a study on waste cooking oil, which reported a 10.9% (max.) reduction in power due to high head loss in the filter caused by clogging [45]. Nevertheless, the reduction in engine power with a consumption of 1 mL/s of B30 was <8% compared to other palm biodiesel blends, as depicted in Figure 8.

With regard to temperature, power and torque increased as ambient temperature decreased for all palm biodiesel blends, consistent with the findings of a similar study by Spence & Williams (1974) using petroleum diesel [46]. Specifically, engine power and torque increased by 1.5%–6.9% and 1.9%–8.4%, respectively, as the temperature decreased from 20 to 10 °C for B7, B10, and B20. The improved power and torque performance observed in moderately cold conditions can be ascribed to the collective influence of the enhanced density of the cooler air, which corresponds to a higher concentration of oxygen molecules per unit volume coupled with the inherent oxygen content present in the biodiesel fuel. This synergistic combination can lead to improved combustion efficiency and performance [47 - 49].



Note: *Vehicle could not be started

Figure 4. Effect of engine power at full load steady-state condition under cold ambient temperature using different blends of palm biodiesel



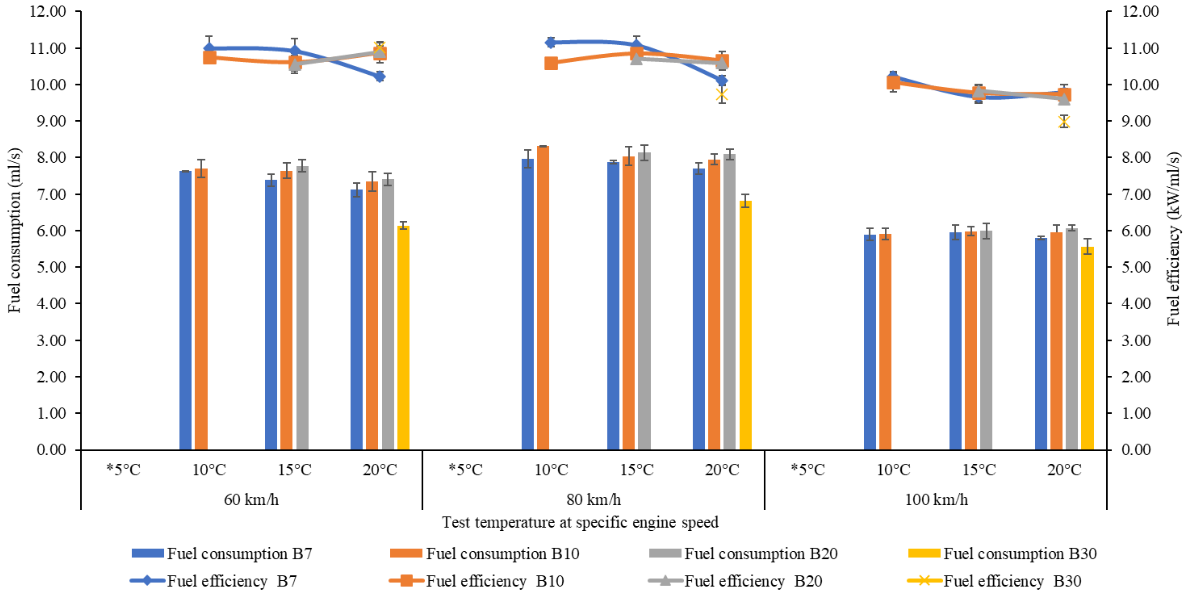
Note: *Vehicle could not be started

Figure 5. Effect of engine torque at full load steady-state condition under cold ambient temperature using different blends of palm biodiesel

3.2 Fuel Consumption

Figure 8 demonstrates the effect of palm biodiesel blends on fuel consumption at temperatures of 5, 10, 15, and 20 °C. The highest fuel consumption was observed at 80 km/h with an average of 7.85, 8.10, 8.11, and 6.82 mL/s for B7, B10, B20, and B30, respectively. In contrast, fuel consumption was the lowest at the highest speed of 100 km/h for all palm biodiesel blends, falling within the range of 5.57–6.07 mL/s. The variation in fuel consumption under constant operating conditions can be attributed to the differences in thermophysical properties between diesel and biodiesel blends.

An increase in fuel consumption by an average of 2.3% and 3.9% was observed when using B10 and B20, respectively, in comparison to B7 under all operating conditions. Previous studies have also found that fuel consumption increases proportionally with higher biodiesel content in the fuel [50 – 53]. This is linked to variations in heating values and densities of the fuel blends. The lower heating value of biodiesel, attributed to its higher oxygen content, requires a larger volume of blended fuels to achieve an equivalent heat release as diesel fuel [54, 55]. Additionally, the higher density of biodiesel in blended fuels leads to an increase in viscosity, potentially hindering fuel atomization and resulting in higher fuel consumption and gaseous emissions [40]. B30 showed a noticeable reduction in fuel flow into the combustion chamber, resulting in lower engine power output (Figure 6). Fuel consumption using B30 decreased by 16.1%, 12.9%, and 4.2% at 60, 80, and 100 km/h, respectively, compared to standard diesel (B7) at 20 °C. This could be due to fuel filter clogging, which caused low fuel pressure, leading to lean fuel condition, engine misfire, and consequently, poor fuel consumption. The possibility of clogged fuel filtration occurrences was indicated by high pressure drop across the fuel filter when B30 was used at 20 °C (Figure 9). However, the drop in pressure decreased when B20 and B10 were used compared to B7, which warrants further investigation.



Note: *Vehicle could not be started

Figure 6. Effect of fuel consumption and efficiency at full load steady-state condition under cold ambient temperature using different blends of palm biodiesel

As the temperature decreased from 20 to 10 °C, a notable rise in fuel consumption was recorded for all palm biodiesel blends over the range of engine speed, consistent with other studies [16, 56]. On average, the fuel consumption of B7, B10, and B20 increased by 2.4%, 1.8%, and 1.3%, respectively, at lower ambient temperature. This could be attributed to the changes in the viscosity of lubrication fluids, requiring more fuel to overcome friction, transmission, and other engine components [16, 56, 57]. The increased density resulting from the higher biodiesel fraction in petroleum diesel further exacerbated the problem, leading to a higher volumetric amount of fuel being injected into the engine [38, 58].

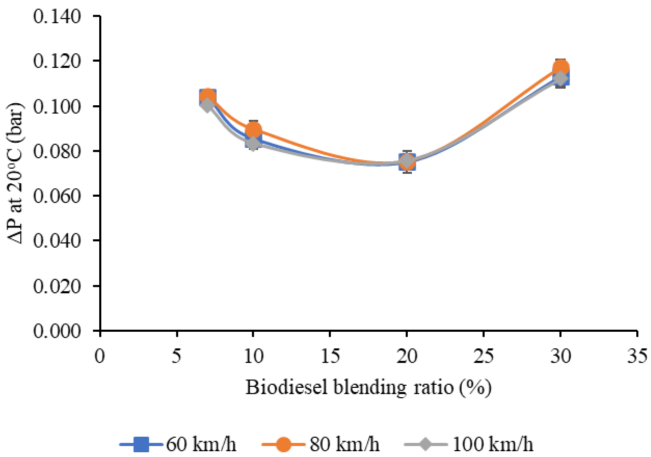


Figure 7. Pressure drop across the fuel filter at 20 °C under full load steady-state condition

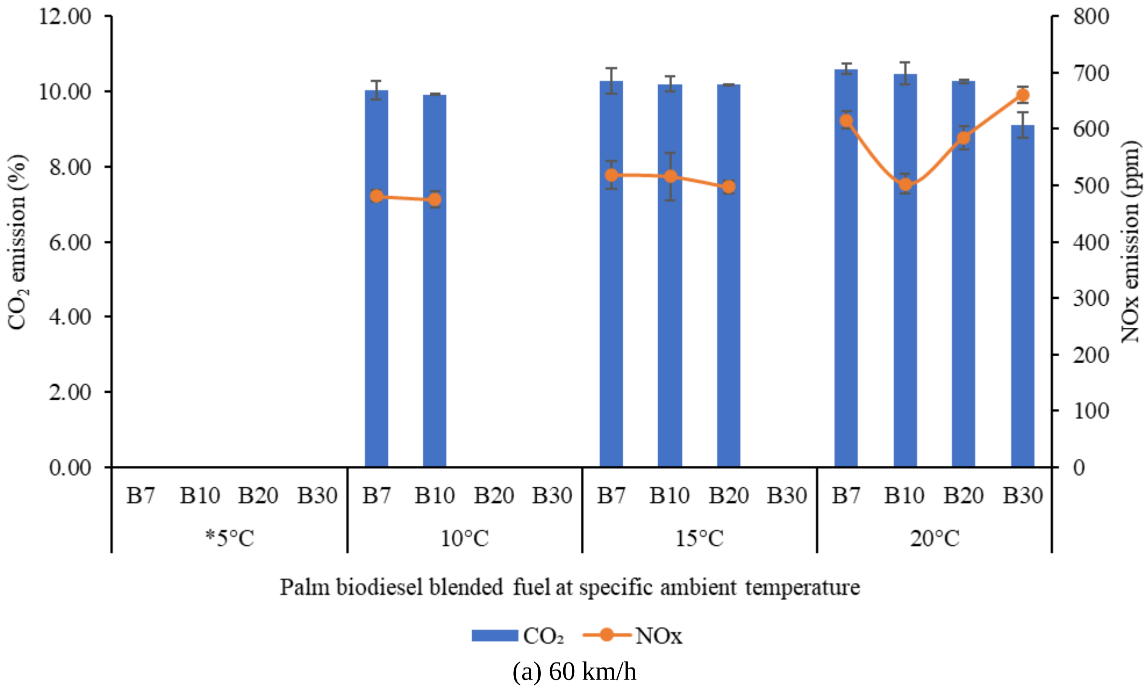
3.3 Emission Characteristics at Steady-State Engine Operation

Previous studies have shown that the pollutants emitted from engine exhaust are affected by the surrounding temperature [29, 30, 59]. In this study, the emissions of CO_2, NOx, CO, and HC were measured. Interestingly, there were no detectable levels of CO and HC emissions during steady-state driving at moderately cold ambient temperatures, suggesting complete combustion of the fuel with no partially burned or unburned fuel.

CO_2 emission is a dominant contributor to global warming. The transport sector in Malaysia contributes to 28% of the country's total CO_2 emissions, with 85% originating from road transportation [60]. Figure 10 shows the variations of CO_2 emissions for the standard diesel B7, B10, B20, and B30 at specific ambient temperatures of 10, 15, and 20 °C under steady-state conditions. Generally, CO_2 emissions were higher at lower vehicle speeds, in the order of 60 km/h > 80 km/h > 100 km/h, similar to the findings by other researchers [61]. The range of CO_2 emitted by B7, B10, B20, and B30 was between 9.11% and 10.6% at 60 km/h, 8.85% and 9.97% at 80 km/h, and 7.22% and 8.72% at 100 km/h, respectively, across the temperature of 10, 15, and 20 °C. The decrease in CO_2 emissions in the blended fuel with higher biodiesel content can be attributed to their lower carbon-to-hydrogen ratio relative to diesel [62, 63]. Specifically, CO_2 emissions decreased by 0.9% to 3.0% for B10, 0.9% to 7.8% for B20, and 11.2% for B30, when compared to B7 at 10, 15, and 20 °C, respectively, across all engine speed ranges. However, at the highest engine speed of 100 km/h, the CO_2 concentration of B30 fuel increased by 5.6% compared to B20.

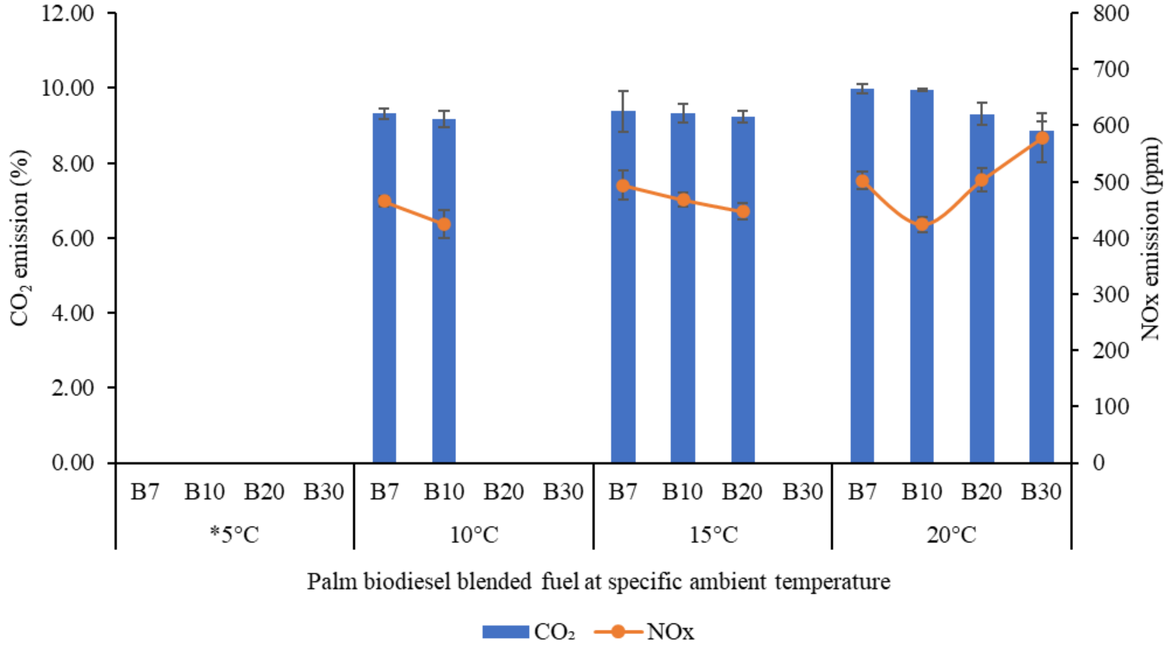
CO_2 emissions at low ambient temperatures were slightly lower compared to those at high ambient temperatures over the whole range of engine speed studied. On average, CO_2 emissions decreased by 8.4%, 6.4%, and 0.9% for B7, B10, and B20, respectively, as the temperature dropped from 20 to 10 °C. This reduction in CO_2 emissions at lower temperatures is associated with the lower overall mass of fuel combusted in the engine, as it is influenced by changes in fuel density at cold temperatures [64, 65]. Besides, the higher fuel viscosity at lower temperatures also affects fuel atomization, leading to incomplete combustion and consequently, lower CO_2 emissions [65]. There was only a minimal difference in the concentration of CO_2 emitted at each engine speed when B7, B10, and B20 were used at 10 and 15 °C, which can be considered negligible. At 20 °C, CO_2 emissions decreased substantially as the biodiesel content in the tested fuels increased, except for B30 at 100 km/h.

Biodiesel's oxygenated nature can enhance engine combustion, but it also increases NOx emissions compared to petroleum diesel. To manage and reduce these emissions, various emission control technologies, including exhaust gas recirculation, lean NOx traps, and selective catalytic reduction can be utilized. [66]. Figure 10 illustrates the impact of using palm biodiesel blends on NOx emissions at cold ambient temperatures under full-load steady-state conditions. The NOx emissions follow the sequence of 100 km/h > 60 km/h > 80 km/h, with an average of 584, 539, and 478 ppm, respectively.

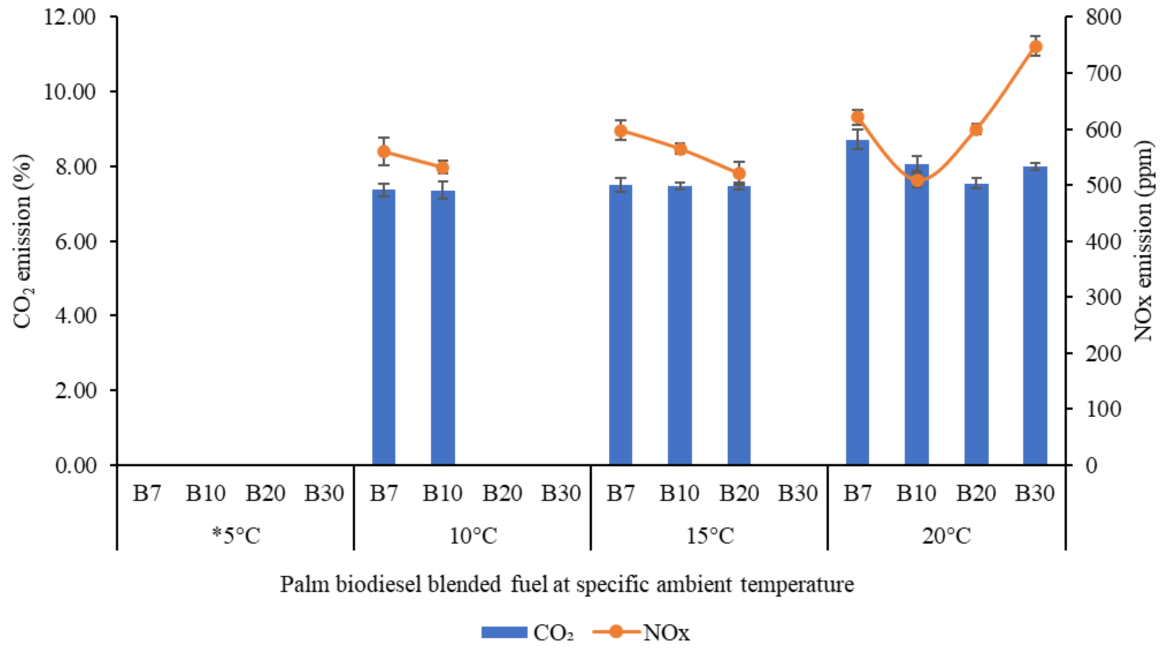


(a) 60 km/h

Figure 8. Effect of engine-out emissions of CO_2 and NOx at full load steady-state condition at (a) 60 km/h



(b) 80 km/h



(c) 100 km/h

Note: *Vehicle could not be started

Figure 9. (cont.) (b) 80 km/h, and (c) 100 km/h under cold ambient temperature using different blends of palm biodiesel

With respect to the biodiesel blending ratio, Figure 9 shows that NOx emissions increased by 17.6% and 38.2% when using B20 and B30, respectively, in comparison to B10 at 20 °C throughout all engine speeds, irrespective of the B7 diesel that showed otherwise. The additional oxygen molecules in the blended fuel increase combustion temperature due to excessive HC oxidation, resulting in higher NOx emissions [26, 27, 61]. On average, NOx emissions of standard diesel B7 were 14.3% lower at 20 °C compared to B30, while B10 and B20 recorded 17.3% and 2.7% higher emissions, respectively, for all constant speed conditions. In contrast, the NOx emissions decreased by 4.4% and 8.9% on average with the use of B10 and B20 at 10 and 15 °C, respectively, in comparison to standard diesel B7. At lower temperatures, the influential effect of the increased oxygen concentration in biodiesel blends appears to have been masked by the more severe effect of cold air on lowering the combustion temperature, resulting in the anticipated NOx reduction [67, 68].

The NOx concentration exhibited a decreasing trend with lower ambient temperatures. When using B7 fuel, the NOx concentration decreased by 7.0% and 9.8% on average at 15 and 10 °C, respectively, in comparison to 20 °C. Similarly, a 13.1% reduction in NOx emissions was observed for B20 at 15 °C compared to at 20 °C. This could possibly be due to the influence of cold air, which reduces combustion temperatures and promotes the formation of a lean premixture, ultimately lowering NOx emissions [67, 68]. NOx emissions of B10 exhibited an inconsistent relationship with the employed temperature, with the order being 15 °C > 10 °C > 20 °C.

4. CONCLUSION

This study offers valuable perspectives on the performance of diesel engines fueled by high palm-based biodiesel blends in moderately cold tropical highland conditions, in contrast to prior research that focused on extremely cold environments and diverse feedstocks. Based on the positive impact observed on engine power, torque, and exhaust emissions, biodiesel blends up to B20 have been identified as suitable for use in the Malaysian highlands. The cold performance and exhaust emissions of a common rail turbocharged engine using palm biodiesel blends of B10, B20, and B30 at full load steady-state conditions of 60, 80, and 100 km/h under simulated cold chamber conditions of 10, 15, and 20 °C were evaluated. Engine power and torque were enhanced with the use of B10 and B20, in comparison to B7 diesel at 10–20 °C, although this came with a slight increase in fuel consumption. Additionally, a notable reduction in CO_2 and NOx emissions was observed with the use of B10 and B20 at 10 and 15 °C. The inherent characteristics of palm-derived biodiesel, including higher oxygen content, kinematic viscosity, and density, together with its lower calorific value relative to conventional diesel fuel, affected the performance and exhaust emissions of diesel engines. Notably, B20 demonstrated better engine performance than B7 at 15 °C with improved engine power and torque, combined with a significant reduction in CO_2 and NOx emissions. The presence of water vapor in the cold air appears to have a cooling effect, thereby diminishing the overall combustion temperature. This reduces NOx emissions, as the thermal NOx formation process, involving the high-temperature reaction of atmospheric nitrogen and oxygen, is less prevalent under these cooler conditions. Palm biodiesel blends up to B20 and can withstand moderately cold ambient temperatures (10–20 °C) without causing any problems to diesel engines. Further field trials in highland environments are necessary to verify the effectiveness and long-term viability of fuel blends with high biodiesel content, such as B20, for practical application.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to the Director-General of the Malaysian Palm Oil Board (MPOB) for granting approval to publish this article.

CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHORS' CONTRIBUTION

Nursyairah Jalil: Investigation, data curation, writing-original draft preparation and visualization

Harrison Lau Lik Nang: Conceptualization, validation, resources, writing – review & editing and supervision

Rifqi Irzuan Abdul Jalal: Conceptualization, methodology, validation, writing - review & editing and supervision

REFERENCES

[1] S. Ramkumar and V. Kirubakaran, "Biodiesel from vegetable oil as alternate fuel for C.I engine and feasibility study of thermal cracking : A critical review," *Energy Conversion and Management*, vol. 118, no. 2016, pp. 155–169, 2016.

[2] A. Demirbas, "Importance of biodiesel as transportation fuel," *Energy Policy*, vol. 35, pp. 4661–4670, 2007.

[3] Y.M. Choo, A.N. Ma, K.W. Chan, and B. Yusof, "Palm diesel: An option for greenhouse gas mitigation in the energy sector," *Journal of Oil Palm Research*, vol. 17, no. June, pp. 47–52, 2005.

[4] P. Verma and M.P. Sharma, "Review of process parameters for biodiesel production from different feedstocks," *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 1063–1071, 2016.

[5] M. Ejaz and J. Younis, "A review of biodiesel as vehicular fuel," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, pp. 2484–2494, 2008.

[6] D.J. Murphy, "The future of oil palm as a major global crop: Opportunities and challenges," *Journal of Oil Palm Research*, vol. 26, no. 1, pp. 1–24, 2014.

[7] L. Reijnders and M.A.J. Huijbregts, "Palm oil and the emission of carbon-based greenhouse gases," *Journal of Cleaner Production*, vol. 16, pp. 477–482, 2008.

[8] K. Zahan and M. Kano, "Biodiesel production from palm oil, its by-products, and mill effluent: A review," *Energies*, vol. 11, no. 8, p. 2132, 2018.

[9] J.C. Ge, H.Y. Kim, S.K. Yoon, and N.J. Choi, "Optimization of palm oil biodiesel blends and engine operating parameters to improve performance and PM morphology in a common rail direct injection diesel engine," *Fuel*, vol. 260, no. 2020, p. 116326, 2020.

[10] D. Singh, D. Sharma, S.L. Soni, C.S. Inda, and S. Sharma, "A comprehensive review on 1st-generation biodiesel feedstock palm oil : Production, engine performance and exhaust emissions," *BioEnergy Research*, vol. 14, no. 1, pp. 1–22, 2021.

[11] A.M. Ashraful, H.H. Masjuki, M.A. Kalam, I.M. Rizwanul Fattah, S. Imtenan, S.A. Shahir et al., "Production and comparison of fuel properties, engine performance and emission characteristics of biodiesel from various non-edible vegetable oils: A review," *Energy Conversion and Management*, vol. 80, pp. 202–228, 2014.

[12] A. Sugiyono, Anindhita, I. Fitriana, L.A.M.A. Wahid, Adiarso. Indonesia Energy Outlook 2019: The Impact of Increased Utilization of New and Renewable Energy on the National Economy, Agency for the assessment and application of Technology, 2019.

[13] Ministry of International Trade and Industry Malaysia, National Automotive Policy 2020 (NAP 2020), 2020.

[14] R.D. Lanjekar and D. Deshmukh, "A review of the effect of the composition of biodiesel on NOx emission, oxidative stability and cold flow properties," *Renewable and Sustainable Energy Reviews*, vol. 54, no. 2016, pp. 1401–1411, 2016.

[15] M.A. Hazrat, M.G. Rasula, M. Mofijur, M.M.K. Khand, F. Djavanroodi, A.K. Azadd, et al., "A mini review on the cold flow properties of biodiesel and its blends," *Frontiers in Energy Research*, vol. 8, p. 598651, 2020.

[16] N. Ostrouchov, "Effect of Cold Weather on Motor Vehicle Emissions and Fuel Consumption - II," *SAE Technical Paper 790229*, 1979.

[17] G. Dwivedi, S. Jain, and M. Sharma, "Diesel engine performance and emission analysis using biodiesel from various oil sources - Review," *Journal of Materials and Environmental Sciences*, vol. 4, no. 4, pp. 434–447, 2013.

[18] S.K. Hoekman, A. Broch, C. Robbins, E. Ceniceros, and M. Natarajan, "Review of biodiesel composition, properties, and specifications," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 143–169, 2012.

[19] P. Bhale and K. Sorate, "Impact of biodiesel on fuel system materials durability," *Journal of Scientific & Industrial Research*, vol. 72, no. 1, pp. 48–57, 2013.

[20] I. Paryanto, T. Prakoso, and M. Gozan, "Determination of the upper limit of monoglyceride content in biodiesel for B30 implementation based on the measurement of the precipitate in a Biodiesel–Petrodiesel fuel blend (BXX)," *Fuel*, vol. 258, no. 2019, p. 116104, 2019.

[21] V. Plata, P. Gauthier-Maradei and V. Kafarov, "Influence of minor components on precipitate formation and filterability of palm oil biodiesel," *Fuel*, vol. 144, pp. 130–136, 2015.

[22] K. Amri, A.G. Arisanti, H.P. Putra, M. Dewi, A. Prismantoko, and M.D. Diaztuti, "Quantitative analysis of saturated monoglyerides in palm oil biodiesel by gas cromatography-mass spectrometry," *Journal of Oil Palm Research*, vol. 1, no. 3, pp. 121–128, 2018.

[23] P. Bhale, N. Deshpande, and S. Thombre, "Improving the low temperature properties of biodiesel fuel," *Renewable Energy*, vol. 34, no. 3, pp. 794–800, 2009.

[24] D. Na-Ranong and P. Kitchaiya, "Precipitation above cloud point in palm oil based biodiesel during production and storage," *Fuel*, vol. 122, pp. 287–293, 2014.

[25] S.K. Yoon, J.C. Ge, and N.J. Choi, "Influence of Fuel Injection Pressure on the Emissions Characteristics and Engine Performance in a CRDI Diesel Engine Fueled with Palm Biodiesel Blends," *Energies*, vol. 12, p. 3837, 2019.

[26] M.S. Gad, R. El-araby, K.A. Abed, N.N. El-ibiari, A.K. El Morsi, and G.I. El-diwani, "Performance and emissions characteristics of C.I. engine fueled with palm oil/palm oil methyl ester blended with diesel fuel," *Egyptian Journal of Petroleum*, vol. 27, no. 2, pp. 215–219, 2018.

[27] H. Chen, B. Xie, J. Ma, and Y. Chen, "NOx emission of biodiesel compared to diesel: Higher or lower?" *Applied Thermal Engineering*, vol. 137, no. December 2017, pp. 584–593, 2018.

[28] A.R. Sakunthalai, R. Xu, D. Liu, J. Tian, M. Wyszynski, and J. Piaszyk, "Impact of cold ambient conditions on cold start and idle emissions from diesel engines," *SAE Technical Paper*, vol. 2014-01–27, 2014.

[29] J. Luján, H. Climent, L. García-Cuevas, and A. Moratal, "Pollutant emissions and diesel oxidation catalyst performance at low ambient temperatures in transient load conditions," *Applied Thermal Engineering*, vol. 129, no. 2, pp. 1527–1537, 2018.

[30] J. Ko, D. Jin, W. Jang, C. Myung, S. Kwon, and S. Park, "Comparative investigation of NOx emission characteristics from a Euro 6-compliant diesel passenger car over the NEDC and WLTC at various ambient temperatures," *Applied Energy*, vol. 187, pp. 652–662, 2017.

[31] M. Chaichan, T. S. Gaaz, A. Al-amiery, and A.A. Kadhum, "Biodiesel blends startability and emissions during cold, warm and hot conditions," vol. 9, no. 2, pp. 75–89, 2020.

[32] J. Nursyairah, H. Lau, R. Jalal, and S. Loh, "Effect of palm biodiesel blends on cold start performance and emissions of common rail turbocharged engine at moderately cold ambient temperatures," *Environmental Progress & Sustainable Energy*, vol. 42, no. 3, p. e14037, 2022.

[33] J. Nursyairah, H. Lau, and R. Jalal, "The cold flow properties on palm biodiesel for diesel blends mandate in Malaysia's highlands," *Journal of Oil Palm Research*, vol. 34, no. 1, pp. 116–128, 2021.

[34] Department of Standards Malaysia, *MS 123-4:2020, Malaysian Standard – High PME Diesel Fuel – Specification – Euro 2M*. Malaysia: Department of Standards Malaysia, Ministry of Science, Technology and Innovation, Cyberjaya, 2020.

[35] Department of Standards Malaysia, Automotive Fuels – Palm Methyl Ester (PME) for Diesel Engines – Requirement and Test Methods (First Revision) (MS 2008:2014), 2014.

[36] M.E.M. Soudagar *et al.*, "Investigation on the effect of cottonseed oil blended with different percentages of octanol and suspended MWCNT nanoparticles on diesel engine characteristics," *Journal of Thermal Analysis and Calorimetry*, vol. 147, no. 1, pp. 525–542, 2022.

[37] Ministry of Plantation Industries and Commodities Malaysia (MPIC), "Dakn2030 Full," *National Agricommodity Policy 2021-2030*, 2021.

[38] G. Tüccar, E. Tosun, and E. Uludamar, "Investigations of effects of density and viscosity of diesel and biodiesel fuels on NOx and other emission formations," *Academic Platform-Journal of Engineering and Science*, vol. 6, no. 2, pp. 81–85, 2018.

[39] K. Bukkarapu, T. Rahul, S. Kundla, and G. Vardhan, "Effects of blending on the properties of diesel and palm biodiesel," *IOP Conference Series: Materials Science and Engineering*, vol. 330, p. 012092, 2018.

[40] S.S. Wirawan, A.H. Tambunan, M. Djamin, and H. Nabetani, "The effect of palm biodiesel fuel on the performance and emission of the automotive diesel engine," *Agricultural Engineering International: CIGR Journal*, vol. 10, pp. 1–13, 2008.

[41] W.M. Adaileh and K.S. Alqdah, "Performance of diesel engine fuelled by a biodiesel extracted from a waste cocking oil," *Energy Procedia*, vol. 18, pp. 1317–1334, 2012.

[42] A. Senatore, D. Buono, E. Frosina, M. Vittoria, and G. Valentino, "Performance and emissions of a 2-stroke diesel engine fueled with biofuel blends," *Energy Procedia*, vol. 81, pp. 918–929, 2015.

[43] D.H. Qi, L.M. Geng, H. Chen, Y.Z.H. Bian, J. Liu, and X.C.H. Ren, "Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil," *Renewable Energy*, vol. 34, no. 12, pp. 2706–2713, 2009.

[44] V. Tran, A. Le, and A. Hoang, "An experimental study on the performance characteristics of a diesel engine fueled with ULSD-biodiesel blends," *International Journal of Renewable Energy Development*, vol. 10, no. 2, pp. 183–190, 2021.

[45] S. Bari, C.W. Yu and T.H. Lim, "Filter clogging and power loss issues while running a diesel engine with waste cooking oil," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 216, no. 12, pp. 993–1001, 2002.

[46] P. Spence and T. Williams, "The influence of ambient temperature and pressure on compression-ignition engine performance," *Proceedings of the Institution of Mechanical Engineers*, vol. 188, no. 1, pp. 25–32, 1974.

[47] C.K.M. Gerulaitis, D.J. Lingg, D.A. Canato, L.A. Garcia, and G.B. De Jesus, "Diesel engine air intake temperature reduction for Euro V gaseous emissions regulation compliance," *SAE Technical Paper 2010-36-0185*, 2010.

[48] B. Last, H. Houben, M. Rottner, and I. Stotz, "Influence of modern diesel cold start systems on the cold start , warm-up and emissions of diesel engines," in *International Stuttgart Symposium — Automobile and Engine Technology*, 2008.

[49] G. Nyirenda, N. Tamaldin, and M.H. Zakaria, "The impact of biodiesel blend variation contamination to engine friction, wear, performance and emission," *International Journal of Automotive and Mechanical Engineering*, vol. 18, no. 1, pp. 8592–8600, 2021.

[50] O. Ogunkunle and N. Ahmed, "Exhaust emissions and engine performance analysis of a marine diesel engine fuelled with Parinari polyandra biodiesel – diesel blends," *Energy Reports*, vol. 6, pp. 2999–3007, 2020.

[51] O. Ogunkunle and N. Ahmed, "Performance Evaluation of a Diesel Engine Using Blends of Optimized Yields of Sand Apple (Parinari polyandra) Oil Biodiesel," *Renew. Energy*, vol. 134, pp. 1320–1331, 2018.

[52] M. Arunkumar, M. Kannan, and G. Murali, "Experimental studies on engine performance and emission characteristics using castor biodiesel as fuel in Ci engine," *Renewable Energy*, vol. 131, pp. 737–744, 2019.

[53] S. Islam, A.S. Ahmed, A. Islam, S.A. Aziz, L.C. Xian, and M. Mridha, "Study on emission and performance of diesel engine using castor biodiesel," *Journal of Chemistry*, p. 451526, 2014.

[54] A.S. Ramadhas, C. Muraleedharan, and S. Jayaraj, "Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil," *Renewable Energy*, vol. 30, pp. 1789–1800, 2005.

[55] S. Puhan, N. Vedaraman, B.V.B. Ram, G. Sankarnarayanan, and K. Jeychandran, "Mahua oil (Madhuca Indica seed oil) methyl ester as biodiesel-preparation and emission characterstics," *Biomass and Bioenergy*, vol. 28, pp. 87–93, 2005.

[56] A. Permude, M. Pathak, V. Kumar and S. Singh, "Influence of low viscosity lubricating oils on fuel economy and durability of passenger car diesel engine," *SAE Technical Paper*, vol. 5, no. 3, pp. 1426–1435, 2012.

[57] R. Gillot, M. Dempsey and A. Picarelli, "Predicting the effect of powertrain preconditioning on vehicle efficiency," *Mathematical and Computer Modelling of Dynamical Systems*, vol. 23, no. 3, pp. 301–318, 2017.

[58] O.S. Valente, M.J. Da Silva, V.M.D. Pasa, C.R.P. Belchior and J.R. Sodré, "Fuel consumption and emissions from a diesel power generator fuelled with castor oil and soybean biodiesel," *Fuel*, vol. 89, no. 12, pp. 3637–3642, 2010.

[59] J. Serrano, P. Piqueras, E. Sanchis and B. Diesel, "Analysis of the driving altitude and ambient temperature impact on the conversion efficiency of oxidation catalysts," *Applied Sciences*, vol. 11, p. 1283, 2021.

[60] S.I. Mustapa and H. Ali, "Analysis of CO2 emissions reduction in the Malaysian transportation sector: An optimisation approach," *Energy Policy*, vol. 89, pp. 171–183, 2016.

[61] E. Alptekin, "Emission, injection and combustion characteristics of biodiesel and oxygenated fuel blends in a common rail diesel engine," *Energy*, vol. 119, pp. 44–52, 2017.

[62] J. Xue, T.E. Grift and A.C. Hansen, "Effect of biodiesel on engine performances and emissions," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1098–1116, 2011.

[63] Z. Utlu and M. Koçak, "The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions," *Renewable Energy*, vol. 33, pp. 1936–1941, 2008.

[64] V. Mickūnaitis, A. Pikūnas, and I. Mackoit, "Reducing fuel consumption and CO2 emission in motor cars," *Transport*, vol. 22, no. 3, pp. 160–163, 2007.

[65] F. Liu, R. Hu, Y. Li, Z. Yang, and H. Xu, "Effects of fuel temperature on injection performance of an EUP system," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 233, no. 3, pp. 671–686, 2019.

[66] İ.A. Reşitoğlu, "NOx pollutants from diesel vehicles and trends in the control technologies," in *Diesel and Gasoline Engines*, IntechOpen, pp. 1–16, 2018.

[67] H. Omidvarborna, A. Kumar, and D.S. Kim, "NOx emissions from lowerature combustion of biodiesel made of various feedstocks and blends," *Fuel Processing Technology*, vol. 140, no. x, pp. 113–118, 2015.

[68] S.K. Hoekman and C. Robbins, "Review of the effects of biodiesel on NOx emissions," *Fuel Processing Technology*, vol. 96, pp. 237–249, 2012.