ACS OMEGA

Open Access

http://pubs.acs.org/journal/acsodf

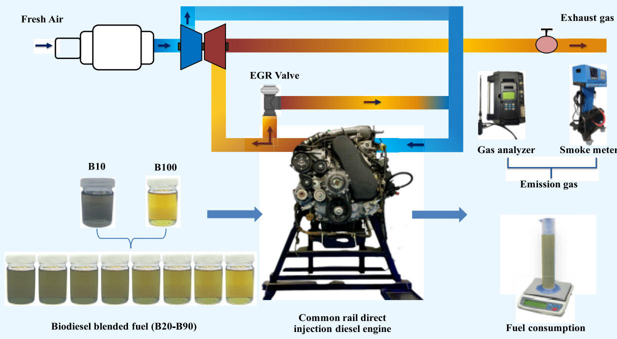
Article

Effects of Blended Diesel–Biodiesel Fuel on Emissions of a Common Rail Direct Injection Diesel Engine with Different Exhaust Gas Recirculation Rates

Aphinan Sethin, Ye Min Oo, Jarernporn Thawornprasert, and Krit Somnuk*

Cite This: *ACS Omega* 2024, 9, 20906–20918

Read Online



ABSTRACT: The aim of the study was to investigate the exhaust gas emissions and fuel consumption of a common rail direct injection (CRDI) diesel engine using mixed diesel (B10) and biodiesel (B20–B100) fuels. The study's primary objective was to determine the effects of blended diesel-biodiesel fuel on CRDI emissions based on different exhaust gas recirculation (EGR) rates, including carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxide (NO_x), and hydrocarbon (HC) emissions, smoke opacity, exhaust gas temperature, and fuel consumption. The CRDI experiments involved adjusting the different engine speeds (1400–3000 rpm) and EGR rates (0 and 12.5%), which were analyzed to determine their impact on these parameters for both blended diesel and biodiesel fuels. The results showed that under the conditions of no EGR (0%), the CO and HC emissions and the smoke opacity were lower than those with a 12.5% EGR rate for all fuel types and all cases. With 12.5% EGR rate, the O_2 emissions and the EGT of the CRDI diesel engine decreased, which resulted in significantly lower NO_x emissions because of EGR into the combustion chamber. For the maximum engine speed of 3000 rpm and with no EGR, the CO and HC emissions and the smoke opacity were lower than those with a 12.5% EGR rate for all fuel types. With a 12.5% EGR rate at 3000 rpm, the O_2 emissions and the exhaust gas temperature were reduced by 0.07% and 2.27%, respectively, and the NO_x emissions were reduced by 2.54%. However, with EGR, the CO and HC emissions and the smoke opacity increased by 7.70%, 18.61%, and 0.4%, respectively. Furthermore, the fuel consumption of pure biodiesel (B100) at 3000 rpm with a 12.5% EGR rate was reduced by 2.81% compared to that with a 0% EGR rate. Because the temperature in the combustion chamber is high enough for the engine to run, the EGR reuses a portion of the exhaust gases and can help to minimize the quantity of fuel in the combustion chamber. As a suggestion based on these observations, biodiesel fuel should not exceed B80 because the viscosity and density of fuel that are too high may affect the fuel injection system, both the injectors, and the pressure pump, causing the injectors to be unable to work correctly. These findings can contribute to the development of strategies and technologies for reducing emissions and improving fuel efficiency in CRDI diesel engines.

1. INTRODUCTION

To mitigate climate change and reduce the dependency on fossil fuels, the global community is turning rapidly to energy sources that are more renewable and sustainable. In particular, biodiesel has received much interest as a sustainable energy source and an alternative to fossil fuels.[1] In terms of the world's energy demands, biodiesel provides a cleaner and more sustainable alternative to fossil fuels while having significantly lower environmental effects.[2] Currently, global fossil fuel prices are increasing primarily because of the ongoing conflict between Russia and Ukraine, illustrating the importance of this issue. By May 2022, the average wholesale price of tallow methyl ester had reached 1112 USD per metric ton of oil equivalent, representing a remarkable increase of over 133% compared to the levels seen in 2018–2019.[3] Also, the conflict between Russia and Ukraine slowed the global economy's recovery from the COVID-19 pandemic, and this conflict-related economic limitation increased commodity prices, with disruptions to supply connections causing inflation in many regions worldwide. Despite these challenges, the biodiesel market is predicted to increase at a 6.1% compound annual growth rate (CAGR) to 49.34 billion USD by 2027, and this growth indicates the biodiesel industry's global demand. The

Received: December 18, 2023
Revised: April 18, 2024
Accepted: April 24, 2024
Published: May 1, 2024

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906–20918

global biodiesel market is expected to expand from 36.55 billion USD in 2022 to 38.93 billion USD in 2023, reflecting a 6.5% CAGR.[4] Furthermore, the world is making enormous strides toward carbon neutrality to minimize carbon emissions, and adopting alternative fuels such as biodiesel is an important part of this change.[5] Indonesia, Malaysia, and Thailand are prominent biodiesel producers in Southeast Asia, and they mostly use crude palm oil (CPO) as the primary feedstock for biodiesel production because of its high oil content. Therefore, CPO has become a significant agricultural commodity, especially in Indonesia and Malaysia, which have become key players in the regional production of CPO to date. The International Energy Agency reported that approximately 47.87 billion liters of biodiesel were produced globally in 2022.[6] In 2022, the Food and Agriculture Organization of the United Nations reported that these two nations are global palm oil giants, accounting for more than 20.6% of total world production.[7]

Indonesia is currently the leading CPO producer in the world, manufacturing 45.61 billion liters per year, and the second- and third-ranked CPO producers are Malaysia (37.96 billion L/year) and Thailand (14.40 billion L/year).[8] However, the European Union decided to ban the import of palm oil on December 2020. To resolve this problem, Indonesia, Malaysia, Philippines, Vietnam, and Thailand are implementing regulations mandating increasing biodiesel content in diesel fuel.[9] Furthermore, ASEAN member nations have accepted biofuel's potential for carbon neutral energy systems, developed biofuel standards and regulations, and taken other measures to ensure the long-term viability of biofuel production.[10] The Malaysian government is committed to the nationwide expansion of the B30 biodiesel (30% palm methyl ester with diesel fuel) program, which helps to support the palm oil industry and contributes to reducing carbon emissions.[11] B30 biodiesel is expected to bring even more significant environmental benefits, and Malaysia is planning to introduce B40 biodiesel by 2030.[12] At the same time, Indonesia—which plans to use B40 fuel—is aiming to reach a 20%−25% share of biofuels in total energy demand by 2030, and Vietnam intends to use B10 fuel for 25% of the fuel demand of the transportation sector by 2050. In Thailand, the Department of Energy Business has promoted the use of biodiesel in fuels, and based on engine suitability, B10 biodiesel will be used as the standard fuel for new pick-up vehicles and B20 fuel will be used in heavy vehicles.[13] In addition, using biodiesel instead of petroleum diesel has many environmental advantages with significantly reduced carbon emissions throughout the life cycle. Biodiesel also reduces toxic air emissions, which benefits older road vehicles and various off-road applications.[14] Recent improvements in technology and combustion methods using biodiesel and diesel blends in diesel engines have shown significant potential for sustainable energy development. Many researchers have focused on studying the combustion characteristics of biodiesel and its blends to improve engine performance, reduce emissions, and enhance combustion efficiency in conventional diesel engines. In the research of Sanli et al.[15] the results have shown that the use of biodiesel as a fuel source can positively impact combustion by improving several key parameters of emissions and performance. Biodiesel has a higher cetane number compared to petroleum diesel, leading to enhanced ignition quality and shorter ignition delays, resulting in improved combustion efficiency. The higher oxygen content in biodiesel also facilitates a more complete combustion process, reducing particulate matter (PM) emissions.[16] Moreover, researchers have explored various methodologies to modify engine parameters and optimize combustion in biodiesel engines. Techniques such as using advanced injection strategies, optimizing compression ratios, and modifying fuel injection timing have been employed to achieve better performance and lower emissions.[17] These advancements have resulted in reduced nitrogen oxide (NO_x) emissions, lower hydrocarbon (HC) and carbon monoxide (CO) emissions, and improved fuel consumption efficiency. Furthermore, several studies have investigated the combustion behavior of biodiesel and diesel blends with varying biodiesel content in conventional engines.[18,19] Their findings indicate that blending biodiesel with diesel improves fuel properties such as lubricity, viscosity, and flash point while reducing the sulfur content. These fuel properties contribute to better combustion efficiency and reduced engine wear and tear.[20] Therefore, recent developments in biodiesel and biodiesel-blended fuel technology and combustion approaches have shown significant improvements in engine performance, emissions reduction, and combustion efficiency to meet EURO 4 in 2005 and EURO 5 in 2009.[21] Therefore, the aim of the research reported herein was to assess the performance and emission characteristics of diesel fuel blended with various proportions of biodiesel in a common rail direct injection (CRDI) diesel engine.

The CRDI diesel engine was developed to increase engine efficiency and reduce emissions using a fuel injection system with electronic systems to control the engine. It works by injecting fuel directly into the combustion chamber, which helps to reduce emissions and improve fuel economy.[22] The important parts of the CRDI diesel engine are the electronic control unit (ECU), common rail system, injectors, and high-pressure pump. The common rail system relies on electronic controls and a high pressure fuel rail to precisely regulate fuel delivery from the small hole at the nozzle tip.[23] Consequently, the injection pressure can be adjusted dynamically in the range of 50−200 MPa, allowing accurate fuel delivery customization to achieve suitable engine performance.[24] Furthermore, various types of fuel injection are being developed for the CRDI diesel engine: for Euro 2 pollution control standards, there will be three fuel injections, i.e., pilot injection, main injection, and after injection; for Euro 4 and Euro 5 pollution control standards, there will be five fuel injections, i.e., pilot injection, pre-injection, main injection, after injection, and post-injection.[25] In addition, the CRDI diesel engine has an exhaust gas recirculation (EGR) system, the main objective of which is to reduce NO_x emissions by recirculating some of the exhaust gas back into the combustion chamber.[26,27] This is based on pollution control standards that require decreased engine exhaust gas emissions; the NO_x emissions from diesel engines must be less than 0.25 g/km for the European emissions standard for light-duty vehicles of Euro 4 and 0.18 g/km for Euro 5.[28] Consequently, diesel engines must be improved in terms of exhaust gas emissions by employing EGR and diesel particle filters in parallel with fuel quality improvement, this being because NO_x is a harmful pollutant that leads to smog and has a negative impact on air quality and human health.[29] As announced by Thailand's Pollution Control Department, new pick-up trucks in Thailand must meet vehicle air pollution control requirements based on Euro 4 standards, with Euro 5 standards expected to be met by 2024, the aim being to reduce air pollution even further.[30,31] The EGR system lowers the

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

Table 1. Properties of Diesel B10 and Biodiesel B20−B100

Property	Method	Diesel standard[a]	Diesel B10	B20	B30	B40	B50	B60	B70	B80	B90	B100
LHV (MJ/kg)	CHNS/O	–	40.8	40.5	40.1	39.7	39.3	38.9	38.5	38.1	37.7	37.3
Density at 15 °C (kg/L)	ASTM D1298	0.81−0.87	0.831	0.835	0.839	0.842	0.846	0.850	0.853	0.857	0.861	0.865
Viscosity at 40 °C (cSt)	ASTM D445	1.8−4.1	3.45	3.71	3.97	4.22	4.48	4.73	4.99	5.25	5.50	5.76
Pour point (°C)	ASTM D97	<10	−8	−6	−4	−2	−1	1	3	4	6	8
FAME (vol %)	EN 14078	7−10	10	20	30	40	50	60	70	80	90	100
O_2 (wt %)	CHNS/O		1.04									11.05

[a]Department of Energy Business.[37]

temperature in the combustion chamber and minimizes NO_x production during combustion by recirculating exhaust gases; therefore, combining the EGR system with a CRDI system will reduce emissions.

However, the recycled exhaust gases replace some of the fresh air used in combustion, which may lower the engine performance. Regarding the exhaust emissions and engine performance of CRDI diesel engine with an EGR system, Damodharan et al.[32] used waste plastic oil to test a single cylinder CRDI diesel engine at 1500 rpm with three injection timings (21°, 23°, and 25 °CA bTDC) with EGR rates of 10%, 20%, and 30%. They found that the lowest NO_x emissions were decreased by 52.4% under the conditions of 30% EGR and 21 °CA bTDC, and black smoke dropped to 46% and 9.5% for 10% and 20% EGR, respectively. Bhowmick et al.[33] studied the production of Calophyllum Inophyllum biodiesel (CIB) by blended fuel at 10% for testing with a single cylinder common rail diesel engine and EGR system. In addition, the engine's fuel injection settings were adjusted to 10% for pilot injection and 90% for main injection. They found that the B10@P10-M90 fuel mixture had the highest efficiency at 35.8% and lower fuel consumption. It was as low as 0.25 kg/kWh compared to those of all fuel injection tests. In terms of exhaust gas emissions, it was found that HC and CO emissions decreased. However, NO_x emissions increased by 18.9% compared to diesel fuel. Meanwhile, when EGR rates of 10% and 20% were used, NO_x emissions were reduced by 14.4% and 27.6%, respectively, compared to those without an EGR rate. Subramanian et al.[34] tested a 10% EGR rate on a CRDI diesel engine running on the *Simmondsia chinensis* biodiesel (SCB)−methyl acetate (MA) blend of DBMA20 (50% diesel, 30% SCB + 20% MA) under differing pilot injection timing (PIT) and pilot injection fuel quantity (PFIQ). When the conditions of 10% EGR, 45° PIT, and 20% PFIQ were tested, they found a 1.71% increase in brake thermal efficiency (BTE) engine efficiency and a 21.87% drop in brake specific fuel consumption. At the same time, the exhaust gas emissions of NO_x, HC, and CO were 11.34%, 47.69%, and 56.41%, respectively, when comparing DBMA20 results with 10% EGR at standard injection settings.

According to the literature review, most researchers have extensively examined the impact of biodiesel on conventional agricultural diesel engines. Studies have investigated the effect of blending a low biodiesel content with diesel on these engines. Most researchers studied the biodiesel contents in the range of 10−50 vol % for testing in the CRDI diesel engine.[35,36] However, there is currently a knowledge gap in the literature when it comes to studying the use of blended diesel (B10) and biodiesel (B20−B100) fuels on a CRDI diesel engine. Furthermore, no research has yet examined the exhaust gas emissions and fuel consumption analysis of these fuels, considering varying engine speeds (ranging from 1400−3000 rpm) and exhaust gas recirculation (EGR) rates (0% and 12.5%). This research aims to explore this knowledge gap and provide valuable insights for the testing of high contents of biodiesel in a CRDI diesel engine under those conditions. Therefore, the objective of the present study was to fill that knowledge gap by examining the effects of blended diesel−biodiesel fuel on CRDI diesel engine emissions using several accurate ranges of biodiesel fuel blends, i.e., B10, B20, B30, B40, B50, B60, B70, B80, B90, and B100. Finally, the CO, CO_2, O_2, NO_x, and HC emissions and the exhaust gas temperature (EGT), smoke opacity, and fuel consumption from diesel B10 and biodiesel−diesel blends (B20−B90) and pure biodiesel (B100) were examined to assess the feasibility of these fuel blends in a CRDI diesel engine operating at 1400−3000 rpm without engine load.

2. MATERIALS AND METHODS

2.1. Materials. Diesel B10 (90% diesel with 10% methyl ester) is Thailand's standard diesel from a petrol station. The biodiesel (>96.5 wt % purity of methyl ester) was produced from waste cooking oil purchased from the Specialized Research and Development Center for Alternative Energy from Palm Oil and Oil Crops, Faculty of Engineering, Prince of Songkla University. The fuel blends in this study were labeled as B_x, where B represents biodiesel and x represents the volume percentage of biodiesel in each fuel blend. Therefore, nine biodiesel−diesel blends of 20, 30, 40, 50, 60, 70, 80, and 90 vol % biodiesel were labeled as B20, B30, B40, B50, B60, B70, B80, and B90, respectively, while pure biodiesel was labeled as B100. These fuel blends were produced by mixing with a stirrer until a homogeneous phase appeared. The properties of diesel B10 to B100 biodiesel fuel were studied and compared with those of the baseline diesel of B10, and the results are given in Table 1. As can be seen, palm oil biodiesel has a higher density, viscosity, pour point, and lower heating value (LHV) than diesel, and this biodiesel also contains 11.05 wt % O_2. These important physical properties are related to the combustion and emission characteristics, as described in Section 3. From diesel B10 to B100 biodiesel fuel, the viscosity at 40 °C is 3.45−5.76 cSt, the density at 15 °C is 0.831−0.865 kg/L, and the LHV is 40.8−37.3 MJ/kg.

2.2. Diesel Engine Experimental Setup. The CRDI diesel engine (2KD-FTV) used in the present experiments was a four-stroke, four-cylinder, turbocharged, and water cooled diesel engine with a maximum torque of 343 N m at 2800 rpm, a maximum power of 106 kW at a maximum engine speed of 3400 rpm, a compression ratio of 15.6:1, and a power adder with the turbocharger. The specifications of the diesel engine are summarized in Table 2. In the injection system, a solenoid controlled injector with a microsac of six holes and a 0.127 mm

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

Table 2. Technical Specifications of the Test Engine

Characteristics of the engine	Specification
Engine	2.5-liter D-4D
Engine code	2KD-FTV
Cylinder arrangement	Four in-line
Capacity	2494 cc
Bore × stroke	92.0 × 93.8 mm
Compression ratio	15.6:1
Injection timing	6.5° bTDC
Stoichiometric air−fuel ratio	14.7:1[a]
Fuel type	48 cetane diesel
Fuel injection system	Common rail direct injection
Max. power	106 kW @ 3400 rpm
Max. torque	343 N m @ 2800 rpm
Power adder	Turbocharger

[a]Chatlatanagulchai et al.[38] and Shinde et al.[39]

diameter was used. It was designed as a special part of the common-rail injection system, incorporating state-of-the-art piezoelectric injectors featuring six holes in each injector, ensuring accurate fuel delivery even at high engine loads and speeds. This advanced injection system has a remarkable fuel pressure capability of up to 160 MPa, allowing it to accommodate various performance and emission criteria. Consequently, the injection pressure can be adjusted dynamically in the range of 50−160 MPa, allowing for precise adjustment of fuel delivery for optimal engine operation. The default value of 6.5° bTDC injection timing was performed for the exhaust gas emissions and fuel consumption of a CRDI diesel engine, as shown in Table 2. Furthermore, the engine's original design was changed in several important ways, including changes to the engine mounts, common-rail injection system, ECU, and electrical systems. These improvements resulted in significantly improved engine performance, taking the engine from Euro 3 to Euro 4 emission standards. To implement these improvements, a remapping process was performed on the ECU using specialized software called WinOLS, which was run on a computer platform. During the remapping process, optimizing the important engine parameters was considered by increasing the fuel pressure in the common rail system and varying the operational range of the injectors. The primary goal of this comprehensive remapping process was to improve the efficiency and responsiveness of the engine under testing settings, particularly when applied to increasing the percentage of biodiesel fuel usage.

Moreover, there were also adjustments to the EGR rate and voltage regulation in the engine throttle system. The EGR technique is controlled to reduce the temperature rise inside the combustion chamber, with the main objective being to control the generation of NO_x emissions while the density of the EGR mixture is improved at the same time. This causes a greater quantity of recirculated exhaust gases to be sent back into the intake manifold. For improved performance, the EGR cooler receives some of the exhaust gas and mixes it with fresh air before sending it into the intake manifold. The temperature of the recirculated exhaust gas is lower than that of the original exhaust gas from the engine. Opening or closing the EGR valve has a significant impact on the CO_2 concentration at the inlet. The other concentrations depend on the process of fuel combustion that occurs within the engine. This method is useful for measuring the necessary EGR rates during steady-state engine running because fuel consumption is little impacted by the EGR rate. The average EGR rate is calculated by measuring CO_2 emissions at the fresh air intake and exhaust gas outlet using an exhaust gas analyzer. The results are then used to compute the average EGR rate using eq 1.[35,40] According to the calculation, an average EGR rate of 12.5% was performed for diesel and different biodiesel blends to analyze emissions with different engine speeds.

$$\mathrm{EGR}_{\mathrm{rate}} = (\mathrm{CO}_2)_{\mathrm{intake}}/(\mathrm{CO}_2)_{\mathrm{exhaust}} \times 100 \tag{1}$$

where EGR_{rate} is the exhaust gas recirculation rate (%) and $(CO_2)_{intake}$ and $(CO_2)_{exhaust}$ are the concentrations of CO_2 in the fresh air intake (%) and exhaust gas outlet (%), respectively.

Exhaust gases from the engine for this investigation were analyzed in great detail with a gas analyzer (model: Testo 350 XL; Titisee-Neustadt; Germany) for accurate measurement of emissions, including CO, CO_2, NO_x, HC, and O_2. Table 3 provides technical information on the measurement ranges, device accuracies, and uncertainty percentages for the emission analysis, including the gas analyzer and smoke opacimeter used for the emission analysis. Following the gas analysis, measurements of combustion smoke were made using a smoke meter (model: CAPELEC; CAP3201EX-GO; Montpellier; France). A digital tachometer (model: DT2236B; Taipei; Taiwan) was used for measuring the engine speed during the experiments. A water pump (model: Mitsubishi, WCH-375S; Tokyo, Japan) circulated water throughout the system, ensuring consistent and controlled engine cooling throughout the test; this helped to regulate the inlet water temperature to maintain a steady and desired level. To monitor and measure the water

Table 3. Measurement Ranges, Device Accuracies, and Uncertainty Percentages

Measurement	Range	Device	Model	Accuracy	Uncertainty (%)
CO (ppm)	0−10 000 ppm	Gas analyzer	Testo 350 XL	±5%	±0.01
CO_2 (vol %)	0−25 vol %	Gas analyzer	Testo 350 XL	±0.8%	±0.19
NO_x (ppm)	0−3000 ppm	Gas analyzer	Testo 350 XL	±5%	±0.1
O_2 (vol %)	0−25 vol %	Gas analyzer	Testo 350 XL	±0.8%	±0.05
HC (ppm)	0−4000 ppm	Gas analyzer	Testo 350 XL	±10%	±0.22
EGT (°C)	0−1000 °C	Temperature sensor	Testo 350 XL	±2.6%	±2.01
Smoke (%)	0−99.9%	Opacimeter	CAP3201EX-GO	±0.1%	±0.12
Speed (rpm)	0−3000 rpm	Digital tachometer	DT2236B	±0.05%	±0.002
Weight (g)	0−300 g	Digital balancing scale	EK-3000i	±0.02 g	±0.01
Time (s)	−	Digital stopwatch	−	±0.1 s	±0.1
LHV (kJ/kg)	−	CHNS/O analyzer	−	−	±2.1

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

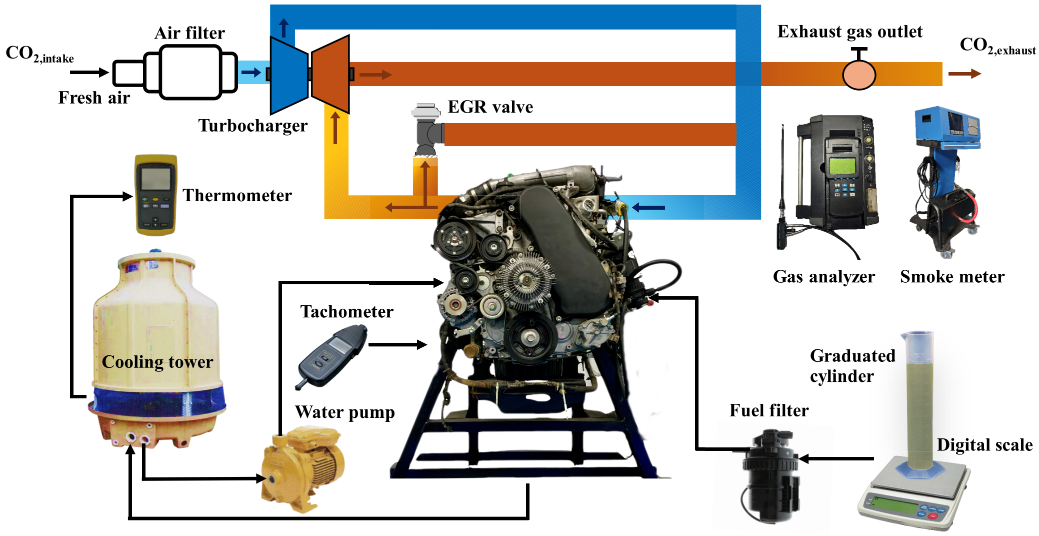


Figure 1. Schematic of the experimental setup for testing the CRDI diesel engine.

temperature at the cooling tower reservoir, a thermometer (model: Fluke 51 II; Washington, USA) was used. The fuel consumption was measured using an electronic weighing scale (model: EK-3000i; Tokyo, Japan) with an accuracy of ±0.1 g. The fuel consumption (FC) was determined by using eq 2.

$$FC = W/t \tag{2}$$

where FC (kg/h) is the fuel consumption, W (kg) is the mass of fuel and t (h) is time.

All of the measuring equipment provided accurate monitoring results from each test, thereby providing valuable insights and reliable results. Before the engine tests, all of the relevant measuring tools and recording equipment were readied, and checks were made of the different fuel types from diesel B10 to B100 biodiesel fuel and the circulation system, engine electrical system, and exhaust ventilation system.

2.3. Experimental Procedure. In this study, the engine was a four-stroke, four-cylinder, turbocharged, and water-cooled diesel engine with a maximum torque of 343 N m at 2800 rpm, a maximum power of 106 kW at the maximum engine speed of 3400 rpm, a compression ratio of 15.6:1, and power added with the turbocharger. The experiments were conducted on a diesel engine equipped with a common-rail fuel injection system capable of delivering up to 160 MPa of fuel pressure. The engine had an external water pump for cooling the engine and maintaining it at a constant temperature for steady-state testing, as shown in Figure 1. The first step was to turn on the circulating water system to cool the engine at the cooling tower by using a pump (WCH-375S) and maintain a constant engine output water temperature of 30 °C. The water temperature at the cooling tower reservoir was measured using a thermocouple thermometer. The engine was first run with diesel B10, which was the reference fuel for this study, and the baseline data were recorded; according to the Thai government, B10—a blend of 10% biodiesel—is a standard fuel that promotes energy sustainability in Thailand. After that, the engine used biodiesel (B20 to B100) at different engine speeds (1400, 1600, 1800, 2000, 2200, 2400, 2600, and 3000 rpm). The fuel in the graduated cylinder was fed into the engine by a high pressure pump and passed through the fuel filter into the common rail and to the injectors with a pressure in the common rail of 160 MPa, making the fuel droplet size smaller and allowing the fuel to burn better. Before the biodiesel was used, the engine was warmed up by running it at 900 rpm for 30 min. The temperature of the lubricating oil was controlled at 75−80 °C by detection with a type-K thermocouple. The exhaust emissions, smoke, and fuel consumption were measured after a 15 min stabilization running period for each engine speed. Also, the continuously varying EGR rate caused by the opening of the EGR valve was recorded. The EGR rate varied between 0% and 12.5% for performing diesel B10 to B100 biodiesel fuel tests in a diesel engine. After completing the 15 min run-in period, the engine speed was slowly increased to 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, and 3000 rpm by the electronic throttle system and tachometer. During diesel engine operation, the fuel consumption of biodiesel was measured and calculated using a graduated cylinder and digital scale. A gas analyzer was used to measure the CO, CO_2, NO_x, and HC emissions and the O_2 in the exhaust gas. In addition, a smoke detector was used to determine the smoke opacity of the engine. The data collection was repeated three times to calculate the mean of the test results. After the experiment was completed, the engine speed was reduced to 900 rpm for 30 min before the engine was switched off. In addition, the engine's fuel lines were cleaned for every test to ensure that the fuel from previous tests had been removed. The engine was then run with diesel B10 again for 30 min to clean the internal system of the common-rail pump and injection system.

2.4. Uncertainty Analysis. The experiments were subjected to uncertainty analysis to assess the accuracies and uncertainties of the results, and the percentage uncertainties of the exhaust emissions are reported in Table 3. The values of LHV were also used to calculate the percentage uncertainties of the fuel blends; these percentage uncertainties were considered using those for several instruments, such as the digital balancing scale, digital stopwatch, smoke meter, and gas analyzer, as reported in Table 3. The overall experimental uncertainty was computed using eq 3.[41,42]

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

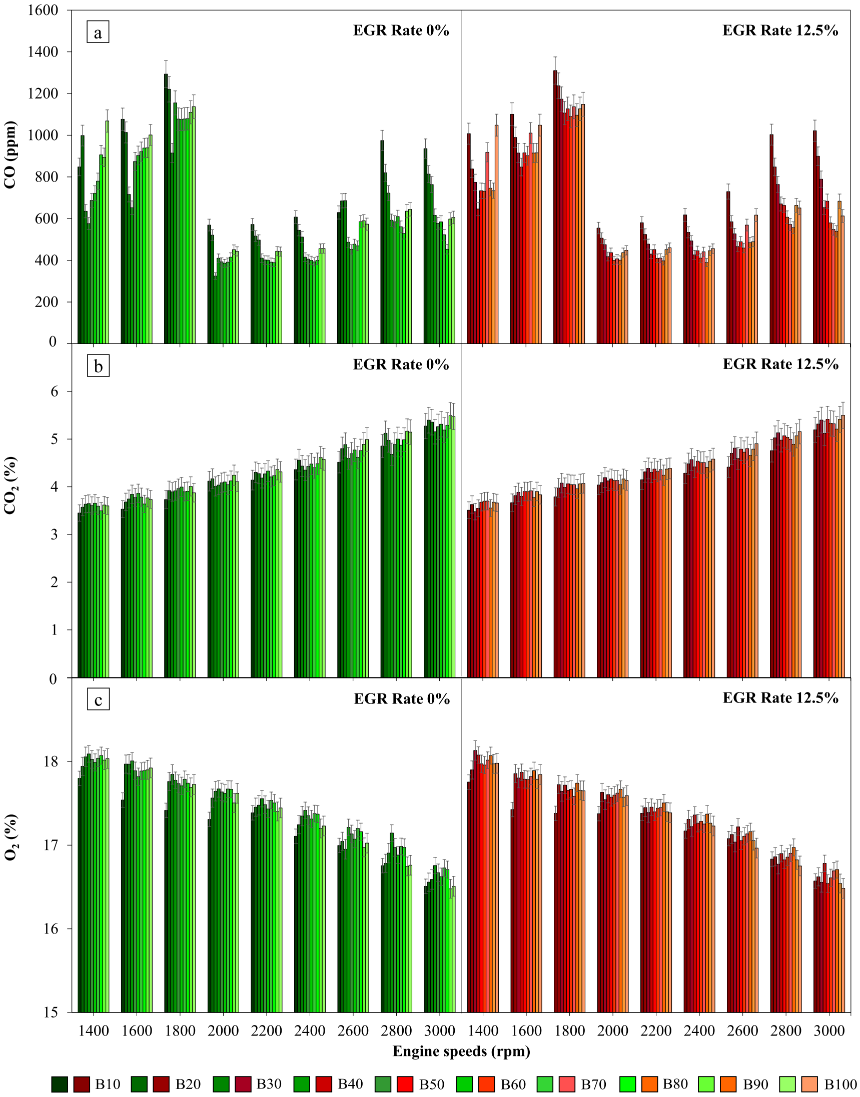


Figure 2. Effects of emissions on combustion in a diesel engine: (a) CO; (b) CO_2; (c) O_2.

$$
\begin{aligned}
&= \sqrt{\text{uncertainty of}\{(\mathrm{CO})^2 + (\mathrm{CO_2})^2 + (\mathrm{O_2})^2 + (\mathrm{NO_x})^2 + (\mathrm{HC})^2 + (\mathrm{EGT})^2 + (\mathrm{Smoke})^2\}} \\
&= \sqrt{\text{uncertainty of}\{(0.01)^2 + (0.19)^2 + (0.01)^2 + (0.05)^2 + (0.22)^2 + (2.01)^2 + (0.002)^2\}} \\
&= \pm 2.03\% \qquad (3)
\end{aligned}
$$

3. RESULTS AND DISCUSSION

3.1. Carbon Monoxide Emissions. CO emission originates from incomplete combustion, which takes place when there is not enough oxygen or when the fuel and air are not adequately mixed, resulting in poor combustion in the engine cylinders. This research tested the engine performance with and without the EGR system at different engine speeds. When the efficiency of EGR is studied, it is crucial to consider that the concentration of CO in the combustion system can increase if some of the exhaust gas is recirculated back into the intake. The CO emissions are presented in Figure 2a for diesel B10 to biodiesel B100 while operating at 0% and 12.5% EGR. To analyze the better emission conditions, the CRDI diesel engine speed is divided into three ranges: the low-speed range of 1400−1800 rpm, the medium-speed range of 2000−2400 rpm, and the high-speed range of 2600−3000 rpm. At 0% EGR rate, B30 had the lowest CO emissions (914.83 ppm) in the low-speed range (1800 rpm maximum speed), B70 had the lowest CO emissions (392.67 ppm) in the medium-speed range (2400 rpm maximum speed), and B80 had the lowest CO emissions (453.17 ppm) in the high-speed range (3000 rpm maximum speed). Comparing these lowest CO emission results from different engine speed ranges to those for diesel B10 fuel shows that there were decreases of 29.27%, 35.36%, and 51.57% in CO emissions at the maximum speeds of the low-speed, medium-speed, and high-speed ranges, respectively. At 12.5% EGR rate, B60 had the lowest CO emissions (1090.17 ppm) in the low-speed range (1800 rpm maximum speed), B80 had the lowest CO emissions (389.50 ppm) in the

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

medium-speed range (2400 rpm maximum speed), and B80 had the lowest CO emissions (538.83 ppm) in the high-speed range (3000 rpm maximum speed). Comparing these lowest CO emission results from different engine speed ranges to those for diesel B10 fuel shows that there were decreases of 16.79%, 36.94%, and 47.24% in CO emissions at the maximum speeds of the low-speed, medium-speed, and high-speed ranges, respectively.

Going from 0% to 12.5% EGR rate, the average CO emissions increased by 3.56%, 1.64%, and 7.70% for the top speed in the low-speed, medium-speed, and high-speed range, respectively. The CO emissions in the medium-speed range were the lowest because the air−fuel ratio and heat inside the cylinder are substantially adequate in that range. The CO emissions were slightly higher in the high-speed range than in the medium-speed range for both 0% and 12.5% EGR rate; this is because the air−fuel ratio becomes more concentrated as engine speed increases, leading to increased CO emissions.[43] Also, fuels with a high biodiesel concentration between B10 and B80 resulted in lower CO emissions, this being because increasing the amount of biodiesel increases the O_2 supply, allowing for more complete fuel burning, and so CO emissions decrease.[44] However, a biodiesel proportion greater than B90 leads to an increase in CO emissions. Higher viscosity and poorer spray properties compared to those of conventional diesel fuel are two major drawbacks of using biodiesel in excessive amounts. These differences can affect the fuel−air mixing process, leading to insufficient combustion and increased CO emissions. Ge et al.[36] described similar results, reporting that when the fuel density and viscosity are too high, the pilot injection is slow, resulting in low cylinder temperature and pressure and leading to incomplete combustion. As a result of incomplete combustion, more CO is emitted into the atmosphere.

3.2. Carbon Dioxide Emissions. CO_2 is emitted into the atmosphere when carbon containing fuels are burned. Figure 2b shows the CO_2 emissions of diesel B10 and biodiesel fuel blend B20 to B100 at 0% and 12.5% EGR rate. At 0% EGR rate, B90 produced the highest CO_2 emissions (4.04%) in the low-speed range (1800 rpm maximum speed), B90 produced the highest CO_2 emissions (6.73%) in the medium-speed range (2400 rpm maximum speed), and B90 produced the highest CO_2 emissions (5.49%) in the high-speed range (3000 rpm maximum speed). Compared to the values for diesel B10 fuel, there were increases of 0.27% for maximum speed in the low-speed range, 0.25% for maximum speed in the medium-speed range, and 0.22% for maximum speed in the high-speed range. At 12.5% EGR rate, B100 produced the highest CO_2 emissions in all engine speed ranges, i.e., 4.07% in the low-speed range (1800 rpm maximum speed), 4.53% in the medium-speed range (2400 rpm maximum speed), and 5.50% in the high-speed range (3000 rpm maximum speed). Compared to diesel B10 fuel, there were increases of 0.22%, 0.12%, and 0.08% in the CO_2 emissions at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively.

Going from 0% to 12.5% EGR rate, the average CO_2 emissions decreased by 0.05%, 0.15%, and 0.14% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. It was observed that increasing the percentage of biodiesel in the fuel led to higher CO_2 emissions across the range of engine speeds. How et al.[45] reported similar findings; they tested various biodiesel fuels against diesel fuel in a CRDI diesel engine and found that biodiesel B10, B20, B30, and B50 at all speeds produced lower CO_2 emissions than diesel fuel. In addition, the use of EGR during testing led to less CO_2 being released into the atmosphere. EGR is a technology that is beneficial to the environment because it lowers the level of the O_2 content of the air that is present in the combustion chamber by exchanging the incoming fresh air with the exhaust gas. Because of the decreased O_2 level, the combustion process is impacted and the peak combustion temperature is reduced. As a result, the fuel burns less completely, reducing the level of CO_2 emissions. More complete combustion and higher CO_2 emissions occur in engines without EGR because O_2 availability is higher. Similar results were described by Gong et al.,[46] who reported that using EGR in engines slows down combustion, which reduces CO_2 emissions because it lowers the combustion temperature and reduces the heat that causes CO_2 emissions.

3.3. Oxygen Gas. O_2 gas is essential in the process of combustion, during which the fuel must react chemically with O_2 to release energy. Figure 2c shows the O_2 gas with diesel B10 and a biodiesel fuel blend from B20 to B100 at 0% and 12.5% EGR rate. At 0% EGR rate, B40 had the highest O_2 gas concentration (16.76%) in the high-speed range (3000 rpm maximum speed), whereas B30 had the highest O_2 gas concentration (17.85% and 17.42%) in the low-speed range (1800 rpm maximum speed) and medium-speed range (2400 rpm maximum speed), respectively. Compared to those for diesel B10 fuel, the values were increased by 0.43%, 0.315%, and 0.25% at the maximum speed in the low-speed, medium-speed, and high-speed range, respectively. At 12.5% EGR rate, B40 had the highest O_2 gas concentration (17.72%) in the low-speed range (1800 rpm maximum speed), B40 had the highest O_2 gas concentration (17.36%) in the medium-speed range (2400 rpm maximum speed), and B40 had the highest O_2 gas concentration (16.78%) in the high-speed range (3000 rpm maximum speed). Compared to the values for diesel B10 fuel, there were increases of 0.34%, 0.19%, and 0.21% in the O_2 gas concentration at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively.

The average O_2 emissions were 0.05% lower at low speeds, 0.15% lower at medium speeds, and 0.14% lower at high speeds when the EGR rate was 0% compared to 12.5%. The highest O_2 emissions were found with the B30 biodiesel fuel blend at the maximum speed in the high-speed range for both 0% and 12.5% EGR rates. Moreover, increasing the amount of biodiesel in the fuel increased the O_2 gas because biodiesel fuel has a higher O_2 content than diesel fuel. Also, when increasing the speed of the test, the O_2 gas decreased; this is because higher engine speeds often correspond to increased airflow and improved combustion efficiency.[47] The increased airflow ensures better availability of the O_2 for combustion, leading to more complete fuel combustion within the cylinders. More efficient combustion results in less O_2 being released with the exhaust gases and more heat being produced.[48] When using EGR, the resulting O_2 emissions are slightly lower because of the EGR systems, which recirculate some exhaust gases back into the intake air and help reduce the NO_x emissions and the O_2 gas in the combustion chambers. Similar results were described by Raja et al.,[49] who reported that testing with EGR reduced the O_2 gas as the exhaust gases were recirculated into the engine system; as a result, NO_x emissions were also reduced.

3.4. Nitrogen Oxide Emissions. NO_x refers to the collective emissions of nitrogen oxide compounds, primarily

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

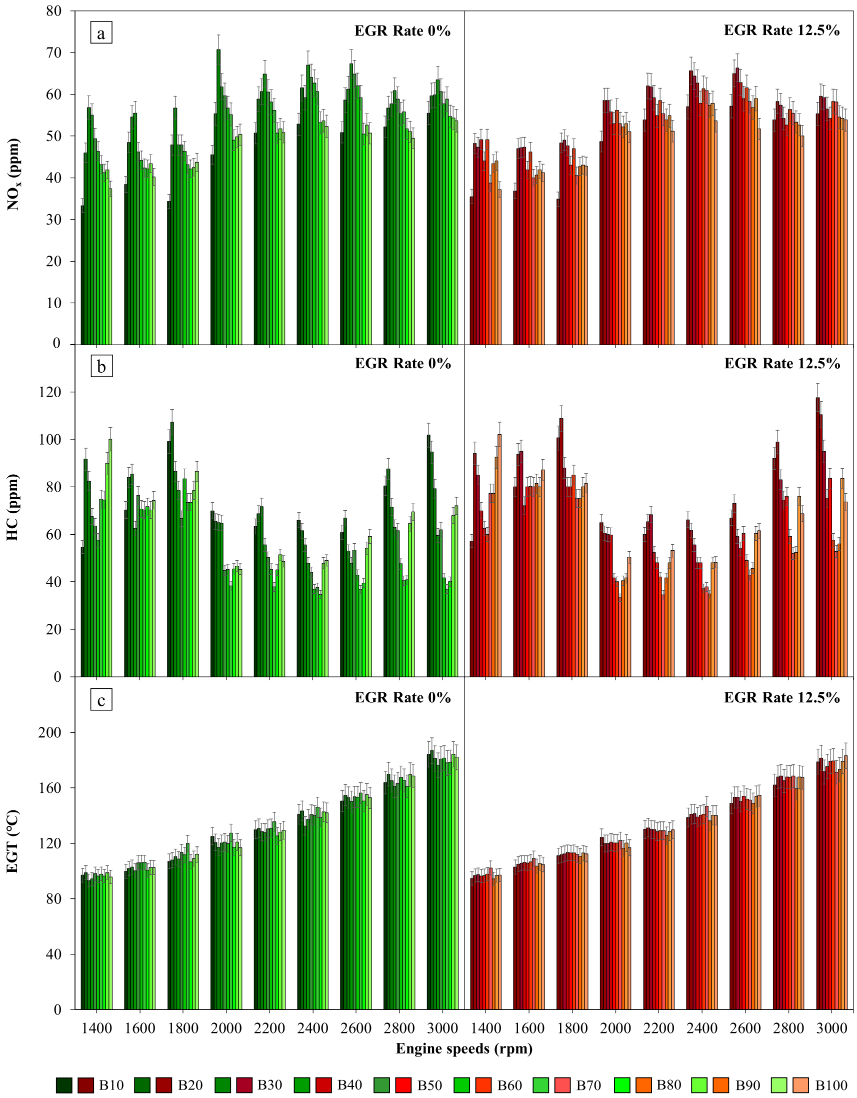


Figure 3. Effects of emissions on combustion in a diesel engine: (a) NO_x; (b) HC; (c) EGT.

nitric oxide and nitrogen dioxide. NO_x emissions are generated during combustion processes, particularly in engine combustion systems. Figure 3a shows the NO_x emissions with diesel B10 and biodiesel fuel blend B20 to B100 when using 0% and 12.5% EGR rates. At the 0% EGR rate, B30 emitted the most NO_x (49 ppm) in the low-speed range (1800 rpm maximum speed), B40 emitted the most NO_x (67 ppm) in the medium-speed range (2400 rpm maximum speed), and B40 emitted the most NO_x (63.5 ppm) in the high-speed range (3000 rpm maximum speed). The lowest NO_x emission results in the different engine speed ranges were 28.92%, 14.93%, and 12.87% higher than with diesel B10 fuel at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. At 12.5% EGR rate, B40 had the highest NO_x emissions (47.67 ppm) in the low-speed range (1800 rpm maximum speed), B40 had the highest NO_x emissions (62.67 ppm) in the medium-speed range (2400 rpm maximum speed), and B30 had the highest NO_x emissions (59.83 ppm) in the high-speed range (3000 rpm maximum speed). Compared to diesel B10 fuel, there were increases of 27.98%, 15.70%, and 7.66% in the NO_x emissions at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively.

Going from 0% to 12.5% EGR rates, the average NO_x emissions decreased by 2.28%, 2.58%, and 2.19% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. The highest NO_x emissions were found in the B30 and B40 biodiesel fuel blends at all conditions for both 0% and 12.5% EGR rate. This is similar to the effect of the O_2 gas described previously. The increased levels of NO_x emissions at higher engine speeds could be due to the corresponding increase in airflow, which leads to higher combustion temperatures, especially in the medium- and high-speed ranges. At higher temperatures, combustion is more effective, but the release of NO_x is increased, which contributes to air pollution.[50] When more fuel is injected into the combustion chamber, NO_x emissions increase because nitrogen and O_2 from the air react faster. With the increased mass of fuel and air, the fuel has a higher biodiesel content, and this higher O_2 content affects the combustion process by reducing the temperature, thereby inhibiting the formation of NO_x and resulting in reduced NO_x emissions.[51,52] Moreover, the EGR system recirculates some of the engine exhaust gases back into the intake air, which reduces the concentration of O_2 in the combustion chamber. This reduced O_2 concentration makes the air−fuel mixture thinner, and the combustion process slows

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

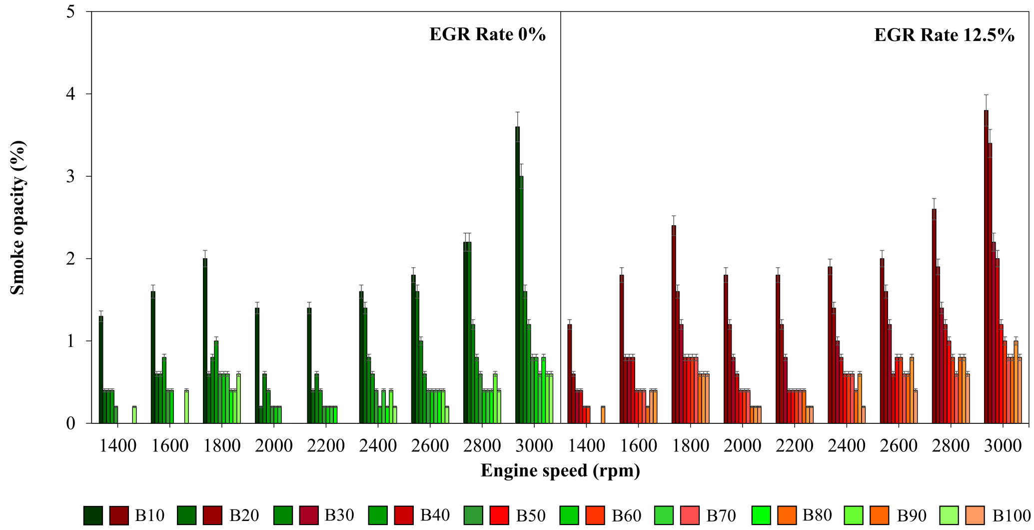


Figure 4. Effects of smoke opacity on combustion in a diesel engine.

down, which inhibits the production of NO_x. Similar results were described by Esakki et al.,[53] who tested biodiesel blends in comparison with diesel in a CRDI diesel engine with EGR; they found that NO_x decreased after applying EGR, which happens because EGR lowers the O_2 in the cylinder, and so the temperature drops in the combustion chamber.

3.5. Hydrocarbon Emissions. HC emissions are a significant environmental concern because of their role in releasing unburned or partially burned HC compounds into the atmosphere. These emissions are a direct consequence of incomplete combustion of fuels, particularly in diesel engines. Also, HCs are involved in forming particulate matter and contribute to air pollution. Figure 3b shows the HC emissions with diesel B10 and biodiesel fuel blends B20 to B100 under the conditions of 0% and 12.5% EGR rates. At 0% EGR, B50 had the lowest HC emissions (66.67 ppm) in the low-speed range (1800 rpm maximum speed), B80 had the lowest HC emissions (34.67 ppm) in the medium-speed range (2400 rpm maximum speed), and B70 had the lowest HC emissions (37.00 ppm) in the high-speed range (3000 rpm maximum speed). The lowest HC emission results in the different engine speed ranges were lower than those from diesel B10 fuel by 32.77%, 48.25%, and 63.66% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. At 12.5% EGR rate, B80 had the lowest HC emissions (75.00, 34.83, and 52.83 ppm) in the low-speed range (1800 rpm maximum speed), medium-speed range (2400 rpm maximum speed), and high-speed range (3000 rpm maximum speed), respectively. Compared to diesel B10 fuel, there were decreases in the lowest HC emissions in the different engine speed ranges by 25.50%, 47.36%, and 55.11% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively.

Going from 0% to 12.5% EGR rate, the average HC emissions were 9.46%, 3.95%, and 18.61% higher at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. The results showed that the highest HC emissions at a 12.5% EGR rate were found with the B20 biodiesel fuel; the values decreased gradually from B30 to B70 and then rose again from B90 to B100. In the low-speed range, HC emissions have high discharge values because the fuel−air mixture may not be suitable for combustion. When a more concentrated mixture contains more fuel than the available O_2, incomplete combustion and higher HC emissions are found in the low-speed range compared to the medium-speed and high-speed ranges.[54] A higher engine speed results in better fuel−air mixing, which results in a more suitable air−fuel mixture for improved combustion efficiency and hence a higher proportion of fuel burned and reduced HC emissions.[55] In addition, biodiesel fuels have a higher O_2 content than diesel fuel, which helps to make combustion more complete and hence efficient.[56] This results in lower unburned HCs and reduced HC emissions. On the other hand, increased viscosity can affect the atomization of the fuel and the nature of its spray during the injection process, which results in incomplete combustion and inefficient fuel consumption. This leads to increased emissions of unburned HC.[57] Moreover, the EGR system may cause incomplete combustion due to the reduced O_2 content, which results in the release of unburned HC and the accumulation of these deposits of carbon in the intake manifold. Similar results were described by Sogbesan et al.,[58] who tested biodiesel fuel with a CRDI. They found that the use of biodiesel fuel reduced HC emissions. However, for high EGR rates, HC emissions increase with increasing fuel volume because of longer ignition delays, and an increasing fuel volume corresponds with combustion distance.

3.6. Exhaust Gas Temperature. For both diesel B10 and biodiesel B20 to B100, the EGT increased when the engine speed increased for both 0% and 12.5% EGR rates, as shown in Figure 3c. When the engine was running at 1400−3000 rpm, the EGT was 95−187 °C for both 0% and 12.5% EGR rates. The average EGT for diesel B10 to biodiesel B100 at the maximum engine speed of 3000 rpm was 181.39 and 177.27 °C for 0% and 12.5% EGR rates, respectively. The experimental results show that using EGR reduced the EGT by 2.27% at the maximum engine speed of 3000 rpm, this being because the EGR system reduces the O_2 concentration in the intake air. Therefore, the lower O_2 concentration hinders combustion, leading to a reduction in the overall temperature of the mixture and, hence, less heat released during combustion. Consequently, this leads to a decrease in the temperature of the exhaust gas.[59]

3.7. Smoke Opacity. Indicative of air quality and environmental effects, smoke opacity is the extent to which

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

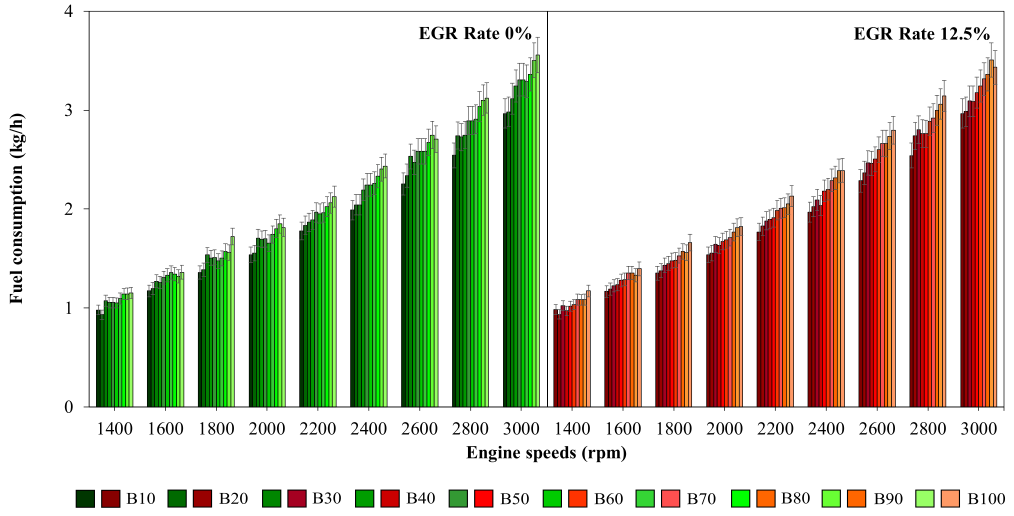


Figure 5. Effects of fuel consumption on combustion in a diesel engine.

smoke from a combustion source blocks visible light. Decreasing light visibility is typically because of the incomplete combustion of fuels, which produces fine particulate matter and hazardous pollutants. Smoke opacity meters and smoke scales are two of the most common means of measuring smoke opacity precisely, and Figure 4 shows the smoke opacity with diesel B10 and biodiesel fuel blend B20 to B100 under the conditions of 0% and 12.5% EGR rates. At 0% EGR rate, B90 had the lowest smoke opacity (0.4% and 0.6%) in the low-speed range (1800 rpm maximum speed) and high-speed range (3000 rpm maximum speed), respectively, whereas B80 had the lowest smoke opacity (0.3%) in the medium-speed range (2400 rpm maximum speed). Compared to diesel B10 fuel, there were decreases of 1.6%, 1.3%, and 3.0% in the smoke opacity at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. At 12.5% EGR rate, B80 had the lowest smoke opacity (0.6%) in the low-speed range (1800 rpm maximum speed), B100 had the lowest smoke opacity (0.3%) in the medium-speed range (2400 rpm maximum speed), and B100 had the lowest smoke opacity (0.8%) in the high-speed range (3000 rpm maximum speed). Compared to diesel B10 fuel, there were decreases of 1.8%, 1.3%, and 3.0% in the smoke opacity at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively.

Going from 0% to 12.5% EGR rate, the average smoke opacity increased by 0.22%, 0.14%, and 0.25% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. The highest smoke opacity was found for diesel B10, followed by biodiesel B20 in all of the engine speed ranges for both 0% and 12.5% EGR rates. At low speeds, black smoke was released at higher speeds than at medium speeds. At low engine speeds, the combustion process becomes less efficient because of factors such as reduced airflow. Insufficient fuel atomization or an insufficient mixture of fuel and air leads to incomplete combustion, which results in the release of unburned HC and soot particles, which contribute to the formation of smoke.[60] Moreover, the emission of black smoke increased at high speed, because the fuel delivery system was unable to supply the proper amount of fuel within the limited time for each combustion cycle at high engine speed. This can result in overfilling in the combustion process. Excess fuel can lead to incomplete combustion, causing the formation of smoke.[61] In addition, the smoke opacity at a 12.5% EGR rate was slightly higher than that at a 0% EGR rate. Similar results were described by Kumar et al.,[62] who tested a CRDI diesel engine with three biodiesel fuel blends using different EGR rates. Their results showed that when the engine was run with a higher EGR rate, the smoke emissions increased compared to that with a lower EGR rate. However, biodiesel fuel blends can help reduce smoke emissions. Biodiesel fuel has a higher O_2 content than diesel fuel, which helps to make combustion more complete because of better fuel–air mixing, resulting in even better reduction of the formation of smoke.[63]

3.8. Fuel Consumption. The fuel consumptions of diesel B10 and biodiesel fuel blends B20 to B100 under 0% and 12.5% EGR rates are shown in Figure 5. In all the engine speed ranges, the higher the biodiesel content in the fuel, the higher the fuel consumption. This is because fuel with higher biodiesel content has lower energy content because biodiesel contains O_2, which lowers its energy density.[64] Table 1 shows that the consumptions of these alternative fuels are higher when using a fuel mixture with a higher proportion of biodiesel, this being because of the LHV of these fuels in comparison to that of diesel. Meanwhile, the results show that using EGR was effective in reducing fuel consumption. Going from 0% to 12.5% EGR rate, the average fuel consumption decreased by 1.59%, 1.35%, and 1.41% at the maximum speed in the low-speed, medium-speed, and high-speed ranges, respectively. This is because EGR reuses some of the exhaust gases, thereby reducing the amount of fresh air entering the combustion chamber and making it simpler to maintain a constant temperature therein.[65]

4. CONCLUSIONS

This study examined the CO, CO_2, O_2, NO_x, and HC emissions and the EGT, smoke opacity, and fuel consumption of a CRDI diesel engine. The fuels investigated were diesel B10, various biodiesel–diesel blends ranging from B20 to B90, and pure biodiesel B100. The CRDI experiments involved adjusting the engine speed from 1400 to 3000 rpm and examining the effects of the EGR system by comparing the results obtained with and without its use. In all cases, under the conditions of no EGR (0%), the CO and HC emissions and

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918

the smoke opacity were lower than those with a 12.5% EGR rate for all fuel types. With 12.5% EGR rate, the O_2 emissions and the EGT of the CRDI diesel engine decreased, which resulted in significantly lower NO_x emissions because of EGR into the combustion chamber. As a result, the amount of O_2 gas from the combustion chamber's fresh air also decreased. Meanwhile, when EGR was used, the CO and HC emissions and the smoke opacity increased, but the fuel consumption of all of the blended fuels decreased. EGR reuses some of the exhaust gases because the temperature in the combustion chamber is high enough for engine operation, and this helps to reduce fuel consumption. For further research and development, the impact of diesel B10 to diesel B100 can also be investigated in terms of brake power, brake thermal efficiency, and brake specific fuel consumption by using a dynamometer to evaluate the performance and emissions of the CRDI diesel engine under various engine loads. Moreover, different EGR rates are an interesting point in studying the performance of CRDI diesel engines when using B10 to B100 fuels.

AUTHOR INFORMATION

Corresponding Author

Krit Somnuk – *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand;* orcid.org/0000-0002-1771-5120; Email: krit.s@psu.ac.th

Authors

Aphinan Sethin – *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*

Ye Min Oo – *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*

Jarernporn Thawornprasert – *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c10125

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was funded by the National Research Council of Thailand (NRCT), Grant No. NRCT5-RSA63022-04.

ABBREVIATIONS

BTE brake thermal efficiency
CO Carbon monoxide
CO_2 Carbon dioxide
CPO Crude palm oil
CRDI Common rail direct injection
ECU Electronic control unit
EGR Exhaust gas recirculation
EGT Exhaust gas temperature
EURO European emission standards
FC Fuel consumption
FFA Free fatty acid
HC Hydrocarbon
LHV Lower heating value
NO_x Nitrogen oxides
O_2 Oxygen
PM Particulate matter
ppm Parts per million
rpm Revolutions per minute
vol % Percentage by volume
wt % Percentage by weight

REFERENCES

(1) Wang, Y. T.; Cong, W. J.; Zeng, Y. N.; Zhang, Y. Q.; Liang, J. L.; Li, J. G.; Jiang, L. Q.; Fang, Z. Direct production of biodiesel via simultaneous esterification and transesterification of renewable oils using calcined blast furnace dust. *Renew. Energy* **2021**, *175*, 1001–1011.

(2) Priya; Deora, P. S.; Verma, Y.; Muhal, R. A.; Goswami, C.; Singh, T. Biofuels: An alternative to conventional fuel and energy source. *Mater. Today: Proc.* **2022**, *48*, 1178–1184.

(3) Arndt, C.; Diao, X.; Dorosh, P.; Pauw, K.; Thurlow, J. The Ukraine war and rising commodity prices: Implications for developing countries. *Global Food Secur.* **2023**, *36*, 100680.

(4) LinkedIn, World, Research reports. *Global advanced biofuels market [2023–2030]: Unlock the power of data with research report.* https://www.linkedin.com/pulse/global-advanced-biofuels-market-2023-2030-unlock (accessed September 27, 2023).

(5) Sadvakasova, A. K.; Kossalbayev, B. D.; Bauenova, M. O.; Balouch, H.; Leong, Y. K.; Zayadan, B. K.; Huang, Z.; Alharby, H. F.; Tomo, T.; Chang, J. S.; Allakhverdiev, S. I. Microalgae as a key tool in achieving carbon neutrality for bioproduct production. *Algal Res.* **2023**, *72*, 103096.

(6) Renewable energy market, IEA. *Will energy security concerns drive biofuel growth in 2023 and 2024.* https://www.iea.org/reports/renewable-energy-market-update-june-2023/will-energy-security-concerns-drive-biofuel-growth-in-2023-and-2024 (accessed October 5, 2023).

(7) OECD iLibrary, OECD-FAO. *Agricultural outlook 2023–2032: Biofuels.* https://www.oecd-ilibrary.org/sites/cdc97c88-en/index.html?itemId=%2Fcontent%2Fcomponent%2Fcdc97c88-en (accessed October 6, 2023).

(8) IndexMundi. *Biodiesel production by country.* https://www.indexmundi.com/energy/?product=biodiesel&graph=production&display=rank (accessed October 7, 2023).

(9) Le Monde, Le Monde with AFP. *EU bans import of products that are 'main drivers of deforestation'.* https://www.lemonde.fr/en/european-union/article/2022/12/06/eu-bans-import-of-products-that-are-main-drivers-of-deforestation_6006733_156.html (accessed October 3, 2023).

(10) China dialogue. *The place of biodiesel as China eyes carbon neutrality.* https://chinadialogue.net/en/energy/the-place-of-biodiesel-as-china-eyes-carbon-neutrality/ (accessed October 3, 2023).

(11) Biofuels international. *B30 biodiesel mandate pencilled in for 2030 in Malaysia.* https://biofuels-news.com/news/b30-biodiesel-mandate-pencilled-in-for-2030-in-malaysia/ (accessed October 14, 2023).

(12) Paul Tan's automotive news. *National energy transition roadmap: b30 biodiesel mandate for heavy vehicles in Malaysia by 2030.* https://paultan.org/2023/08/29/national-energy-transition-roadmap-b30-biodiesel-mandate-to-be-implemented-for-heavy-vehicles-by-2030// (accessed October 14, 2023).

(13) Krungsri research. *Industry outlook 2021–2023: Biodiesel.* https://www.krungsri.com/en/research/industry/industry-outlook/Energy-Utilities/Biodiesel/IO/io-biodiesel-21 (accessed October 8, 2023).

(14) Niyas, M. M.; Shaija, A. Effect of repeated heating of coconut, sunflower, and palm oils on their fatty acid profiles, biodiesel properties and performance, combustion, and emission, characteristics of a diesel engine fueled with their biodiesel blends. *Fuel* **2022**, *328*, 125242.

(15) Sanli, H. An experimental investigation on the usage of waste frying oil-diesel fuel blends with low viscosity in a Common Rail DI-diesel engine. *Fuel* **2018**, *222*, 434−443.
(16) Gali, N. K.; Yang, F.; Cheung, C. S.; Ning, Z. A comparative analysis of chemical components and cell toxicity properties of solid and semi-volatile PM from diesel and biodiesel blend. *J. Aerosol Sci.* **2017**, *111*, 51−64.
(17) Kim, H. J.; Jo, S.; Lee, J. T.; Park, S. Biodiesel fueled combustion performance and emission characteristics under various intake air temperature and injection timing conditions. *Energy* **2020**, *206*, 118154.
(18) Alptekin, E. Emission, injection and combustion characteristics of biodiesel and oxygenated fuel blends in a common rail diesel engine. *Energy* **2017**, *119*, 44−52.
(19) Asokan, M. A.; Prabu, S. S.; Prathiba, S.; Mishra, S.; Mittal, H.; Verma, V. Emission and performance behavior of safflower oil biodiesel/diesel blends in DI diesel engine. *Mater. Today: Proc.* **2021**, *46*, 8266−8270.
(20) Karpanai Selvan, B.; Das, S.; Chandrasekar, M.; Girija, R.; Vennison, S. J.; Jaya, N.; Saravanan, P.; Rajasimman, M.; Vasseghian, Y.; Rajamohan, N. Utilization of biodiesel blended fuel in a diesel engine-Combustion engine performance and emission characteristics study. *Fuel* **2022**, *311*, 122621.
(21) Louis, C.; Liu, Y.; Tassel, P.; Perret, P.; Chaumond, A.; André, M. PAH, BTEX, carbonyl compound, black-carbon, NO_2 and ultrafine particle dynamometer bench emissions for Euro 4 and Euro 5 diesel and gasoline passenger cars. *Atmos. Environ.* **2016**, *141*, 80−95.
(22) Zhang, Y.; Boehman, A. L. Impact of biodiesel on NO x emissions in a common rail direct injection diesel engine. *Energy Fuels* **2007**, *21* (4), 2003−2012.
(23) Babu, D.; Anand, R. Influence of fuel injection timing and nozzle opening pressure on a CRDI-assisted diesel engine fueled with biodiesel-diesel-alcohol fuel, In Advances in Eco-Fuels for a Sustainable Environment. *Woodhead Publ.* **2019**, 353−390.
(24) Aalam, C. S.; Saravanan, C. G.; Anand, B. P. Impact of high fuel injection pressure on the characteristics of CRDI diesel engine powered by mahua methyl ester blend. *Appl. Therm. Eng.* **2016**, *106*, 702−711.
(25) Agarwal, A. K.; Singh, A. P.; Maurya, R. K.; Shukla, P. C.; Dhar, A.; Srivastava, D. K. Combustion characteristics of a common rail direct injection engine using different fuel injection strategies. *Int. J. Therm. Sci.* **2018**, *134*, 475−484.
(26) Roy, S.; Banerjee, R.; Bose, P. K. Performance and exhaust emissions prediction of a CRDI assisted single cylinder diesel engine coupled with EGR using artificial neural network. *Appl. Energy* **2014**, *119*, 330−340.
(27) Jaliliantabar, F.; Ghobadian, B.; Carlucci, A. P.; Najafi, G.; Mamat, R.; Ficarella, A.; Strafella, L.; Santino, A.; De Domenico, S. A comprehensive study on the effect of pilot injection, EG. R. rate, IMEP and biodiesel characteristics on a CRDI diesel engine. *Energy* **2020**, *194*, 116860.
(28) Gondim, F. d. L.; Moura, M. F.; Ferreira, R. M.; Serra, D. S.; Araujo, R. S.; Oliveira, M. L. M. d.; Cavalcante, F. S. A. Exposure to total particulate matter obtained from combustion of diesel vehicles (EURO 3 and EURO 5): effects on the respiratory systems of emphysematous mice. *Environ. Toxicol. Pharmacol.* **2021**, *83*, 103583.
(29) Mahla, S. K.; Dhir, A.; Gill, K. J.; Cho, H. M.; Lim, H. C.; Chauhan, B. S. Influence of EGR on the simultaneous reduction of NO_x-smoke emissions trade-off under CNG-biodiesel dual fuel engine. *Energy* **2018**, *152*, 303−312.
(30) Chinadaily.com.cn. *Thailand approves delay on imposing euro 5 emission standard on new vehicles*. https://global.chinadaily.com.cn/a/202302/22/WS63f5b9c9a31057c47ebb0361.html (accessed October 8, 2023).
(31) Cédric, L.; Goriaux, M.; Tassel, P.; Perret, P.; André, M.; Liu, Y. Impact of aftertreatment device and driving conditions on black carbon, ultrafine particle and NOx emissions for Euro 5 diesel and gasoline vehicles. *Transp. Res. Procedia.* **2016**, *14*, 3079−3088.
(32) Damodharan, D.; Sathiyagnanam, A. P.; Rana, D.; Kumar, B. R.; Saravanan, S. Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fueled with neat waste plastic oil. *Energy Convers. Manage.* **2018**, *161*, 294−305.
(33) Bhowmick, P.; Jeevanantham, A. K.; Ashok, B.; Nanthagopal, K.; Perumal, D. A.; Karthickeyan, V.; Vora, K. C.; Jain, A. Effect of fuel injection strategies and EGR on biodiesel blend in a CRDI engine. *Energy* **2019**, *181*, 1094−1113.
(34) Subramanian, K.; Paramasivam, S. A.; Dillikannan, D.; Jayabal, R. Effect of pilot fuel injection strategies and EGR on a CRDI diesel engine powered by simmondsia chinensis seed biodiesel-methyl acetate blend. *Sustain. Energy Technol. Assess.* **2023**, *58*, 103345.
(35) Qi, D.; Ma, L.; Chen, R.; Jin, X.; Xie, M. Effects of EGR rate on the combustion and emission characteristics of diesel-palm oil-ethanol ternary blends used in a CRDI diesel engine with double injection strategy. *Appl. Therm. Eng.* **2021**, *199*, 117530.
(36) Ge, J. C.; Kim, H. Y.; Yoon, S. K.; Choi, N. J. 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* **2020**, *260*, 116326.
(37) Department of energy business, Ministry of energy. *Determine the nature and quality of diesel fuel in Thailand*. http://elaw.doeb.go.th/document_doeb/TH/771TH_0001.pdf (accessed September 28, 2023).
(38) Chatlatanagulchai, W.; Yaovaja, K.; Rhienprayoon, S.; Wannatong, K. *Air-fuel ratio regulation with optimum throttle opening in diesel-dual-fuel engine*; SAE Technical Paper No. 2010-01-1574; SAE: 2010.
(39) Shinde, S.; Yadav, S. D. Theoretical properties prediction of diesel-biodiesel-DEE blend as a fuel for CI engine with required modifications for optimum performance. *Int. J. Curr. Eng. Technol.* **2016**, *6* (5), 1562−1567.
(40) Rajesh kumar, B.; Saravanan, S. Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends. *Fuel* **2015**, *160*, 217−226.
(41) González, A. G.; Herrador, M. Á.; Asuero, A. G.; Martín, J. A practical way to ISO/ GUM measurement uncertainty for analytical assays including in-house validation data: Quality Control in Laboratory. *InTech* **2018**, 109−148.
(42) Thawornprasert, J.; Duangsuwan, W.; Somnuk, K. Investigating the effect of a diesel-refined crude palm oil methyl ester-hydrous ethanol blend on the performance and emissions of an unmodified direct injection diesel engine. *ACS Omega* **2023**, *8* (10), 9275−9290.
(43) Sayin, C.; Gumus, M. Impact of compression ratio and injection parameters on the performance and emissions of a DI diesel engine fueled with biodiesel-blended diesel fuel. *Appl. Therm. Eng.* **2011**, *31* (16), 3182−3188.
(44) Nageswara Rao, D.; Sreenivasulu Reddy, A. Effects on the performance and emission characteristics of CRDI diesel engine fueled with ethanol, acid oil methyl ester biodiesel and diesel blends. *Mater. Today: Proc.* **2023**, DOI: 10.1016/j.matpr.2023.06.065.
(45) How, H. G.; Masjuki, H. H.; Kalam, M. A.; Teoh, Y. H.; Chuah, H. G. Effect of Calophyllum Inophyllum biodiesel-diesel blends on combustion, performance, exhaust particulate matter and gaseous emissions in a multi-cylinder diesel engine. *Fuel* **2018**, *227*, 154−164.
(46) Gong, C.; Si, X.; Liu, F. Combined effects of excess air ratio and EGR rate on combustion and emissions behaviors of a GDI engine with CO_2 as simulated EGR (CO_2) at low load. *Fuel* **2021**, *293*, 120442.
(47) Mariani, F.; Grimaldi, C. N.; Battistoni, M. Diesel engine NO_x emissions control: An advanced method for the O_2 evaluation in the intake flow. *Appl. Energy* **2014**, *113*, 576−588.
(48) Jafarmadar, S.; Nemati, P. Multidimensional modeling of the effect of exhaust gas recirculation on exergy terms in a homogenous charge compression ignition engine fueled by diesel/biodiesel. *J. Clean. Prod.* **2017**, *161*, 720−734.

(49) Raja, E.; Premjeyakumar, M. Potent effect of prosopis juliflora (biodiesel+ isopropanol+ diesel) fueled with diesel engine and egr alteration. *Clean. Eng. Technol.* **2021**, *4*, 100205.
(50) Gomaa, M.; Alimin, A. J.; Kamarudin, K. A. The effect of EGR rates on NO_x and smoke emissions of an IDI diesel engine fuelled with Jatropha biodiesel blends. *Int. J. Energy Environ. Eng.* **2011**, *2* (3), 477−490.
(51) Maiboom, A.; Tauzia, X. NO_x and PM emissions reduction on an automotive HSDI Diesel engine with water-in-diesel emulsion and EGR: An experimental study. *Fuel* **2011**, *90* (11), 3179−3192.
(52) Rajesh; Kumar, V.; Mahla, S. K. Influence of EGR on a CI engine running on 20% blend of jatropha biodiesel. *Mater. Today: Proc.* **2021**, *43*, 273−280.
(53) Esakki, T.; Rangaswamy, S. M.; Jayabal, R. An experimental study on biodiesel production and impact of EGR in a CRDI diesel engine propelled with leather industry waste fat biodiesel. *Fuel* **2022**, *321*, 123995.
(54) Patil, V.; Thirumalini, S. Effect of cooled EGR on performance and emission characteristics of diesel engine with diesel and diesel-karanja blend. *Mater. Today: Proc.* **2021**, *46*, 4720−4727.
(55) Duda, K.; Wierzbicki, S.; Śmieja, M.; Mikulski, M. Comparison of performance and emissions of a CRDI diesel engine fuelled with biodiesel of different origin. *Fuel* **2018**, *212*, 202−222.
(56) Jayabal, R.; Thangavelu, L.; Subramani, S. Combined effect of oxygenated additives, injection timing and EGR on combustion, performance and emission characteristics of a CRDi diesel engine powered by sapota biodiesel/diesel blends. *Fuel* **2020**, *276*, 118020.
(57) Singh, M.; Sandhu, S. S. Performance, emission and combustion characteristics of multi-cylinder CRDI engine fueled with argemone biodiesel/diesel blends. *Fuel* **2020**, *265*, 117024.
(58) Sogbesan, O.; Garner, C. P.; Davy, M. H. The effects of increasing FAME biodiesel content on combustion characteristics and HC emissions in high-EGR low temperature combustion. *Fuel* **2021**, *302*, 121055.
(59) Thawornprasert, J.; Somnuk, K.; Oo, Y. M.; Prateepchaikul, G. Feasibility of using diesel-palm fatty acid distillate ethyl ester-hydrous ethanol blend in an unmodified direct injection diesel engine: An assessment of stability, fuel properties, and emissions. *ACS Omega* **2020**, *5* (32), 20021−20033.
(60) Kiplimo, R.; Tomita, E.; Kawahara, N.; Yokobe, S. Effects of spray impingement, injection parameters, and EGR on the combustion and emission characteristics of a PCCI diesel engine. *Appl. Therm. Eng.* **2012**, *37*, 165−175.
(61) Rashed, M. M.; Kalam, M. A.; Masjuki, H. H.; Mofijur, M.; Rasul, M. G.; Zulkifli, N. W. M. Performance and emission characteristics of a diesel engine fueled with palm, jatropha, and moringa oil methyl ester. *Ind. Crops Prod* **2016**, *79*, 70−76.
(62) Rajesh Kumar, B.; Saravanan, S.; Niranjan Kumar, R.; Nishanth, B.; Rana, D.; Nagendran, A. Effect of lignin-derived cyclohexanol on combustion, performance and emissions of a direct-injection agricultural diesel engine under naturally aspirated and exhaust gas recirculation (EGR) modes. *Fuel* **2016**, *181*, 630−642.
(63) Mahla, S. K.; Dhir, A.; Gill, K. J.; Cho, H. M.; Lim, H. C.; Chauhan, B. S. Influence of EGR on the simultaneous reduction of NO_x-smoke emissions trade-off under CNG-biodiesel dual fuel engine. *Energy* **2018**, *152*, 303−312.
(64) Millo, F.; Debnath, B. K.; Vlachos, T.; Ciaravino, C.; Postrioti, L.; Buitoni, G. Effects of different biofuels blends on performance and emissions of an automotive diesel engine. *Fuel* **2015**, *159*, 614−627.
(65) Zamboni, G.; Moggia, S.; Capobianco, M. Hybrid EGR and turbocharging systems control for low NO_x and fuel consumption in an automotive diesel engine. *Appl. Energy* **2016**, *165*, 839−848.

https://doi.org/10.1021/acsomega.3c10125
ACS Omega 2024, 9, 20906−20918