Investigation on the Performance and Exhaust Gas Emissions of Diesel Engine Fueled with Waste Rubber Bio-Oil

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Abstract

This research investigated the performance and emission characteristics of a Kubota ET115 agricultural diesel engine by using waste rubber bio-oil from the pyrolysis process blended with diesel. The blended ratios of the fuels (waste rubber bio-oil: diesel) were 0:100, 5:95, 15:85, 25:75, and 35:65 by volume. For the investigation, a water brake dynamometer was used for evaluation. Following this, the experimental results showed that an increase in the proportion of waste rubber bio-oil resulted in a decrease in engine torque and power by approximately 2.74–15.74% and 2.96–15.74%, respectively. On the other hand, BSFC and BSEC increased by 39.18–66.67% and 39.91–62.70%, respectively. BTE decreased by 30.56–53.73%. In terms of emissions, the findings showed that CO_2 and soot emissions had decreased by 0.89%–6.48% and 1.22%–36.13%, respectively. However, there was a significant increase in CO and NO_x emissions, where CO rose by 8.87–66.21% and NO_x by 28.57–123.97%. However, this investigation provides evidence supporting the valorization of waste rubber bio-oil into an alternative fuel.

Keywords: Alternative Energy, Bio-Oil, Performance, Emissions, Waste Rubber Bio-Oil

1. Introduction

The reliance on diesel engines in the agricultural sector has increasingly contributed to fuel consumption and environmental impact growth [1-2]. This situation, Thailand's national energy policy aims to promote reducing the use of fossil energy and switching to alternative energy, achieving a share of no less than 36% by 2037 [3-4]. Previous studies have used of agricultural crops for conversion to alternative energy sources, including palm oil, sugarcane, cassava, etc. [5-6]. In addition to these crops, it has been studied that rubber cup lump can be used to produce oil fuel by the pyrolysis process [7]. This process converts biomass or organic waste into biofuels under anaerobic conditions. One of the products obtained from this process is a liquid fuel called pyrolysis oil, which belongs to the group of bio-oils that can be used to replace fossil fuels [8]. Therefore, rubber is another motivating alternative.

From an economic outlook, Rubber is a major economic crop that plays a significant role in Thailand [9]. The price of cup lump rubber fluctuates according to domestic and international market conditions. From early November 2023 to 2025, the price changed as follows: it averaged 45 baht/kg in 2023, rose to 58 baht/kg in 2024, then decreased to approximately 51 baht/kg in 2025 [10]. Such variations have led to the accumulation of excess or waste rubber cup lumps at certain times, which cannot be sold commercially, presenting an opportunity to use these raw materials to produce biofuels.

Although bio-oil is an energy source that can replace fossil fuels, it still has limitations in its chemical properties, such as a low heating value, high water, soot and oxygen content, as well as chemical instability due to its numerous organic constituents. Therefore, it cannot be used directly in engines in the long term. It must be blended with gasoline or diesel fuel first [11-12]. However, previous research reported that blending bio-oil derived from rubber pyrolysis with diesel at an appropriate ratio can maintain the smooth operation of agricultural diesel engines [7]. This reflects not only an approach to agricultural waste management but also an alternative to reduce fuel costs for farmers and promote a sustainable circular economy, thereby enhancing the country's long-term energy security.

Based on these concepts, the researchers are interested in studying the performance and exhaust gas composition of small diesel engines powered by bio-oil pyrolyzed from waste rubber cup lumps without engine modification. In order to perform the analysis of the effects of different fuel blends on engine performance. Most previous research has focused on fuels from other plants, and the performance of rubber has not been studied in depth. The results of this study are expected to contribute to engineering understanding of the potential of bio-oil from waste rubber cup lumps as a renewable fuel and serve as a guideline for efficient and sustainable future usability.

2. Materials and methods

2.1 Test fuels

In this study, the properties of bio-oil derived from waste rubber cup lump were analyzed based on the data reported by Youngpattana et al. [7], Which has been produced the oil through a fast pyrolysis process conducted at a temperature of 500 °C. The obtained data were used to calculate the properties of the blended fuels according to the mixing rule. The viscosity of the blended fuel was determined using the logarithmic mixing rule, as expressed in equation (1), where P_{mix} represent the viscosity of the fuel blend, V_i represent the volumetric fraction of each component, and P_i are the viscosity of each individual fuel.

$$In(P_{mix}) = \sum(V_i \times In(P_i)) \qquad (1)$$

The properties of the blended fuels were calculated using the Linear Mixing Rule as expressed in equation (2), where P_{mix}

represent the property of the mixture, V_i are the volumetric fraction of the fuel, and P_i are the corresponding property of that fuel.

$$P_{mix} = \sum (V_i \times P_i) \tag{2}$$

When comparing the properties of bio-oil derived from waste rubber cup lump with those of diesel fuel according to the Department of Energy Business specification titled "Characteristics and Quality of Diesel Fuel B.E. 2567 (2024)" [13] and ASTM standards, the summarized results are presented in the Table. 1. To assess the suitability of such fuels for use in diesel engines, the abbreviation "RB" is used to represent waste rubber cup lump bio-oil blend, with the number following indicating the blending ratio with diesel fuel. This bio-oil has a lower cetane number, cause prolonged ignition delay, which could lead to incomplete combustion and more CO emissions. Additionally, the lower heating value of bio-oil results in reduced energy release during combustion, directly impacting engine torque and braking power. Although the viscosity of bio-oil is lower than diesel fuel, allowing for better atomization, these characteristics are expected to influence combustion temperature, thermal efficiency, and exhaust emission characteristics, particularly regarding NO_x and soot formation [14].

2.2 Test engine

A Kubota ET 115 was a small four-stroke diesel engine, which is a single-cylinder, water-cooled, and swirl chamber type [15]. This engine was used in the study without modification. The test engine's technical information is shown in the following Table. 2, the engine is connected to a water brake dynamometer, which is shown in Figure 1.

Table 1 Properties of fuel comparison according to the ASTM standards.

Fuel Type	Fuel properties				
	Flash Point (°C) ASTM D93	Viscosity (cSt) ASTM D445	Density @ 15.6 °C (g/cm^3) ASTM D1298	Cetane Index ASTM D976	HeatingValue (MJ/kg) ASTM D240
Diesel	64.00	3.39	0.85	56.99	47.47
Waste Rubber Cup Lump Oil	28.50	1.32	0.85	30.88	40.60
RB5	58.42	3.23	0.85	55.68	47.12
RB15	55.27	2.94	0.85	53.07	46.43
RB25	52.12	2.67	0.85	50.46	45.75
RB35	48.98	2.43	0.85	47.85	45.06

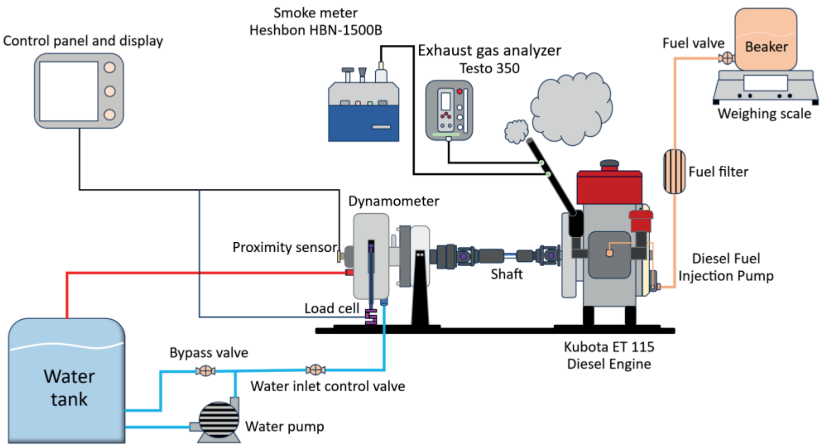

Figure. 1 Schematic diagram of the experimental setup.

Table 2 Technical information of the engine

Details	Technical Information
Model	Kubota ET 115
Engine type	Horizontal water cooled 4-stroke 1 cylinder
Combustion type	Swirl chamber
Cylinder width × stroke	94×92 mm
Cylinder volume	624 cm^3
Maximum horsepower	11.50 hp at 2400 rpm
Continuous horsepower	10.50 hp at 2400 rpm
Maximum torque	34.32 Nm at 1800 rpm
Compression ratio	21:1
Fuel consumption	210 g/hp-h

2.3 Test procedure

2.3.1 Performance testing

Engine performance and emissions tests were conducted over a five-speed range from 800 to 2400 rpm. These tests were performed at 80%, 90%, and 100% throttle positions, due to average the engine load at the maximum throttle position of the fuel pump valve that similar testing has been performed in previous study [16]. The test apparatus details, as shown in Table 3, included a Stuska Dyno water brake dynamometer and a Zega S-Beam strain gauge load cell that margin of error from the actual measurement is ±1%. The load cell receives force from the engine via a driveshaft connected to the flywheel. Fuel consumption was measured during the engine performance tests. The mass of fuel consumed in 5 minutes was measured with a digital scale Tiny FEH-5000. Brake specific fuel consumption (BSFC) was then calculated as the mass of fuel consumed per unit of brake power produced, expressed in kilograms per kilowatt hour (kg/kWh) according to equation (3). This allows direct comparison of engine efficiency for each fuel type, where $\dot{m}_f$ represents fuel flow rate in kg/h, and P_B represents engine brake power in watt (W).

$$Bsfc = \frac{\dot{m}_f}{P_B} \tag{3}$$

Table 3 Details of the engine performance and emission instruments.

Dynamometer set		
Instruments	Ranges	Accuracy
Load cell Zega	1-100 kg	±0.02 %FS
Proximity Sensor	0.80-35.00 mm	Repeatability ±0.10 mm
Scale Tiny FEH-5000	1-5000 g	±1 g
Exhaust gas analyzer, Testo 350		
Gas type	Ranges	Accuracy
CO	0–10,000 ppm	±10 ppm < 200 ppm
CO_2	0–50 vol.%	±0.30% < 25 vol.%
NO_x	0–500 ppm	±5 ppm < 100 ppm
Smoke meter, Heshbon HBN-1500B		
Ranges	Accuracy	
0-100%	±1%	

From engine performance testing, energy efficiency should be evaluated by brake specific energy consumption (BSEC), by considering the heating value of the fuel as well. In calculating BSFC, the unit is kilogram per kilowatt hour (kg/kWh). The heating value of the fuel is in megajoules per kilogram (MJ/kg), resulting in BSEC in megajoules per kilowatt hour (MJ/kWh), as specified in equation (4). The BSEC value represents the amount of energy from the fuel the engine uses to produce per unit of mechanical energy. When comparing the efficiency of alternative fuels with various energy properties, a low BSEC value is crucial because it shows that the engine can use the fuel's energy more effectively [17].

$$Bsec = Bsfc \times HeatingValue \tag{4}$$

Brake Thermal Efficiency (BTE), which reflects the proportion of energy from the fuel that is converted to mechanical power of the engine [18], is shown in equation (5), where P_B is the engine power in kW and $\dot{m}_f$ represents the fuel mass flow rate expressed in (kg/h).

$$BTE = \frac{P_B \times 3600}{\dot{m}_f \times HeatingValue} \times 100 \tag{5}$$

2.3.2 Exhaust gas emissions testing

The exhaust gas composition emitted from the engine during testing was measured using a TESTO 350 exhaust gas analyzer. The probe was installed at the exhaust pipe outlet to measure the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), as shown in the technical specifications presented in Table 3. Subsequently, the pollutant concentrations obtained from the TESTO 350 in volumetric terms (parts per million, ppm) were converted into mass-specific emissions per unit of energy output (g/kWh). This conversion could not be achieved solely through mathematical unit transformation but required several additional parameters, including the measured exhaust gas content, exhaust gas mass flow rate, engine power output, molecular weights of each pollutant species, average molecular weight of the exhaust gas, as well as exhaust gas temperature and pressure during measurement [19]. Onward, the calculation procedure is as follows: the mass concentration (mg/m³) was first determined according to Equation (6), where MW represents the molecular weight of the gas (NO_x = 44 g/mol, CO = 28 g/mol, CO_2 = 44 g/mol), p denotes the exhaust gas pressure, 0.0821 is the universal gas constant, and T indicates the exhaust gas temperature in °K.

$$mg/m^3 = \frac{ppm \times MW \times p}{0.0821 \times T} \quad (6)$$

The mass flow rate was then calculated using equation (7), where $ExhaustFlowRate$ expressed in cubic meters per hour (m³/h).

$$Mass\ Flow = \frac{mg/m^3 \times Exhaust\ Flow\ Rate}{1000} \quad (7)$$

For the calculation of the mass-based emission rate per unit of engine power output (g/kWh), equation (8) applied, where the emission rate is determined from the ratio of the mass flow rate of the exhaust gases to the engine power, P_B expressed in kilowatts (kW).

$$Emission = \frac{Mass\ Flow}{P_B} \quad (8)$$

The measurement of black smoke opacity or soot was conducted while the engine operated under load at a speed of 1,600 rpm. The exhaust gas opacity, expressed as smoke opacity, was measured using a Heshbon HBN-1500B smoke meter. The results are presented in Table 3 on the previous pages.

3. Experimental results and discussion

During the engine performance and emissions tests, the environmental conditions at the test site were continuously monitored and recorded, including an air temperature of approximately 32.24 °C, a relative humidity of approximately 57.32 %, and an atmospheric pressure of approximately 990.99 hPa, as measured by the BME 280 weather station module. The results of the performance test and exhaust gas composition of a small diesel engine using bio-oil from waste rubber cup lumps will be presented in sequence in the following sections.

3.1 Analysis of the engine performance

This test evaluated engine performance in terms of brake torque, brake power, brake specific fuel and energy consumption, and brake thermal efficiency. The test results revealed that the engine using bio-oil blend had lower torque and brake power compared to diesel. These were mainly due to the lower heating value of the bio-oil, resulting in less energy combustion. Furthermore, the specific fuel consumption of the bio-oil blend was higher than that of diesel, indicating a decrease in energy efficiency from BSEC and BTE assessments compared to using standard diesel.

3.1.1 Torque

Figure 2 shows the torque variation of the engine running on different fuel blends. It was found that the torque decreased with increasing bio-oil concentration. On average, the engine running on waste rubber cup lump oil had slightly lower torque than a diesel. For low blending ratios, the torque

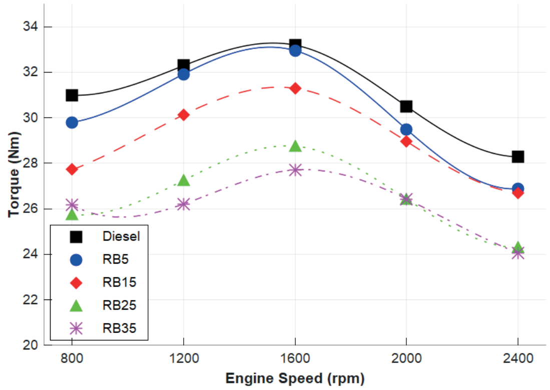

Figure 2 Torque of the engine by using mixed fuel at different rates

variation was not significant, but there was a clear change when the bio-oil concentration was increased.

The test results showed that the RB5 and RB15 blends provided engine torque values close to those of standard diesel. The maximum torque of the diesel was 33.19 Nm at 1,600 rpm, while the RB5 blend had a maximum torque of 32.95 Nm at the same speed. There is an occurrence of incomplete combustion, which was found due to the physical characteristics of the oil, that are low viscosity, low cetane number, and low heating value, which comparable to previous research [20].

3.1.2 Brake power

Figure. 3 shows the variation of brake power with respect to engine speed for bio-oil blends. The test results showed that engine brake power decreased with increasing bio-oil concentration, which was due to the decreased heating value of the blend between bio-oil and standard diesel.

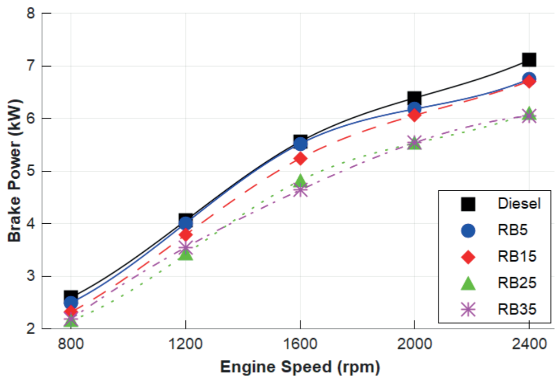

Figure 3 Brake power of the engine by using mixed fuel at different rates.

The test results indicated that the maximum brake power of the engine using standard diesel fuel was 7.11 kW at 2,400 rpm, while the engine using RB5 blend had a maximum brake power of 6.75 kW at the same rpm, which was slightly lower than the maximum brake power of standard diesel fuel by approximately 5.19%. For RB15, RB25, and RB35 blends, the maximum brake power decreased by 5.78%, 15.29%, and 16.11%, respectively. The reduction in brake power in the low concentration blend ratios, which is consistent with previous research [21], which are related to the behavior of torque.

3.1.3 Brake specific fuel consumption

Figure. 4 shows the study results of the variation of specific fuel consumption (BSFC) with engine speed when using bio-oil in different blend proportions. The tendency of BSFC to decrease with increasing engine speed was found in all tested conditions. The engine showed the highest BSFC value at the speed range of 800–1,200 rpm. And the test found that diesel gave the lowest BSFC values of 0.33 kg/kWh at 2400 rpm, while RB35 had the highest BSFC value of 1.32 kg/kWh at 800 rpm. For the blended oil,

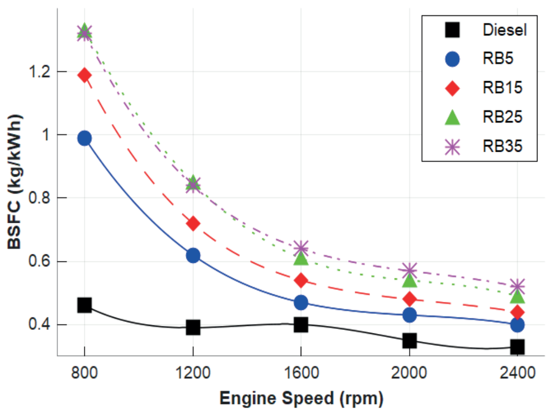

Figure 4 Brake specific fuel consumption of the engine by using mixed fuel at different rates that explained that this phenomenon is due to the lower heating value of bio-oil, resulting in a higher fuel consumption rate to maintain the energy level.

the average BSFC was higher than that of diesel by 39.18 (RB5), 52.83 (RB15), 64.35 (RB25), and 66.67 (RB35), respectively. This is consistent with the research reference [22].

3.1.4 Brake specific energy consumption

Figure 5 shows the trend of brake specific energy consumption (BSEC) values with respect to engine speed for bio-oil blends. The analysis results indicate that diesel has the lowest BSEC value in all speed ranges, following its higher energy efficiency than the blends [23]. The BSEC value tends to be highest at low engine speeds in all blends, especially for RB25 and RB35 blends, which give the highest BSEC values of 60.72 and 71.28 MJ/kWh at 800 rpm, respectively, and the average BSEC of standard diesel and RP35 is significantly different by 62.70%. With the behavior of BSEC is consistent with BSFC. However, as the engine speed increases, the BSEC of the blends decreases and tends to approach the BSEC of standard diesel.

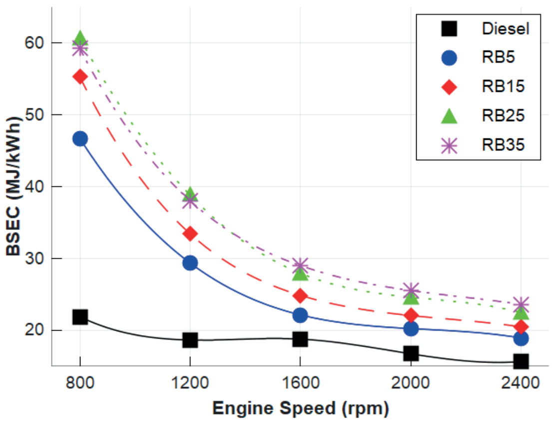

Figure 5 Brake Specific energy consumption of the engine by using mixed fuel at different rates.

3.1.5 Brake thermal efficiency

Figure 6 shows the variation of Brake Thermal Efficiency (BTE) with engine speed for bio-oil blends. The evaluation results showed that BTE decreased with increasing bio-oil concentration, which was due to the decreased heating value indicating the engine's ability to convert thermal energy from fuel combustion into work [24]. The average BTE of the engine using standard diesel was 19.88%, while the engine using RB5 blend had an average BTE of 14.61%, which was approximately 30.56% lower than the average BTE of the diesel, and tends to increase with the concentration of bio-oil. For RB15, RB25, and RB35 blends, the BTE decreased by 40.90%, 51.49%, and 53.73%, respectively. This indicates that the engine converts less heat energy from the fuel into mechanical work than diesel.

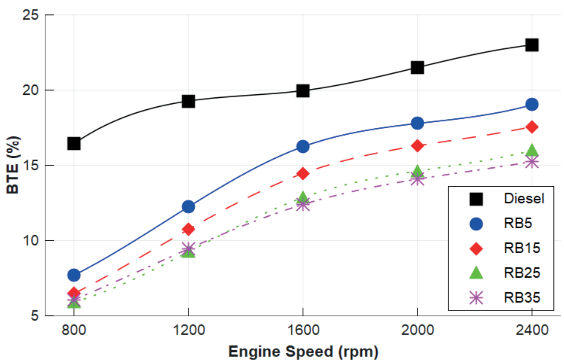

Figure 6 Brake thermal efficiency of the engine by using mixed fuel at different rates.

3.2 Analysis of exhaust emissions

The emission analysis results showed that the use of bio-oil blends significantly affected diesel engine emissions. The bio-oil blends were found to produce lower CO_2 emissions than standard diesel. Conversely, the use of bio-oil blends produced higher CO and NO_x emissions than diesel, which may be due to the higher combustion temperature and the reduced of cetane number. In terms of soot, a lower trends.

3.2.1 Carbon dioxide emissions

Carbon dioxide emissions (CO_2) are a common outcome of the combustion process of all fuel types. However, the results showed decrease in CO_2 emissions when using higher ratios of bio-oil. This can be explained by the higher intramolecular oxygen content of bio-oil than diesel, resulting in higher combustion temperatures and lower carbon emissions in the form of CO_2 compared to diesel [25]. On average, the use of bio-oil in proportions of RB5, RB15, RB25, and RB35 resulted in CO_2 emissions reductions in average of 0.89, 2.44, 3.42, and 6.48%, respectively, as shown in Figure 7.

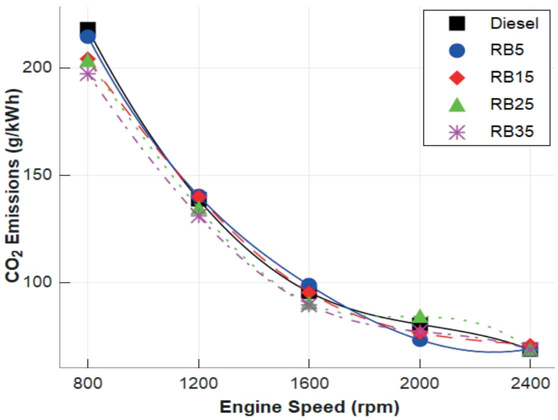

Figure 7 Effect of CO_2 from the engine by using mixed fuel at different rates.

3.2.2 Carbon monoxide emissions

The results showed that the carbon monoxide (CO) emissions of diesel engines had an increasing trend when the blending percentage was increased in average by 8.87%, 23.64%, and 43.55% for RB5, RB15, and RB25, respectively, especially at the RB35 ratio, which gave the highest increment of CO emission of 66.21% compared to the standard diesel, as shown in Figure. 8. This case can be explained by the increased oxygen content in the combustion process resulting in incomplete oxidation of carbon molecules, and the change of physical properties of the blended fuel, such as the reduced cetane number and heating value, which is consistent with the indication from the previous research [26] that indicated the relationship between the oxygen (O_2) composition of the fuel and the CO formation under incomplete combustion conditions.

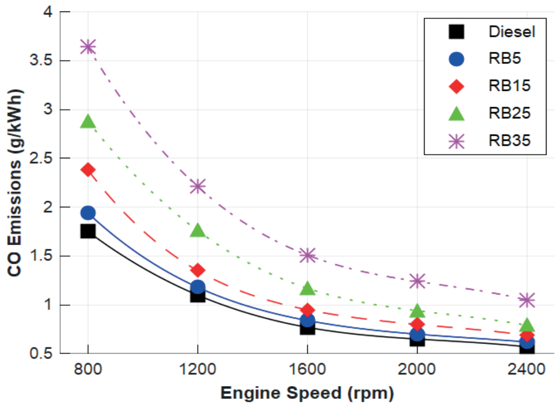

Figure 8 Effect of CO from the engine by using mixed fuel at different rates.

3.2.3 Nitric oxide emissions

The test results showed the increase in nitric oxide (NO_x) emissions with all bio-oil blend proportions, with the NO_x contents increasing by 28.57, 66.67, 95.53, and 123.97% for RB5, RB15, RB25, and RB35 blends, respectively, as shown in Figure 9. This increase was directly related to the high oxygen content of the biofuels and the higher combustion temperature. The NO_x generation mechanism was explained by the Zeldovich Mechanism, in which nitrogen in the air reacts with oxygen to form NO_x. This result is consistent with the previous research [27].

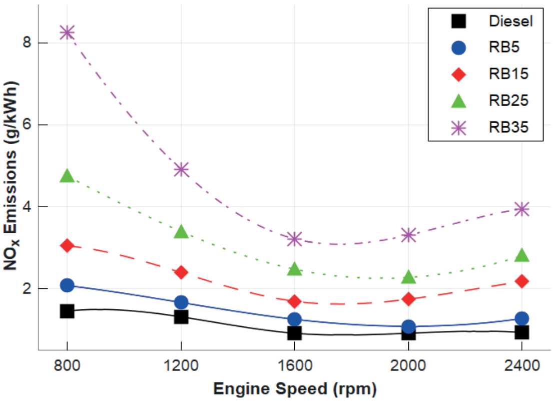

Fig. 9 Effect of NO_x from the engine by using mixed fuel at different rates.

3.2.4 Soot emissions

The results showed that the smoke opacity was inversely relational to the bio-oil blending ratio, showing a decreasing trend with increasing biofuel ratio. At 1,600 rpm, the smoke opacity of standard diesel was 57.77%, while waste cup lump rubber bio-oil gave lower smoke opacity at all blending ratios, reducing smoke by 1.22–36.13% compared to standard diesel, as shown in Figure 10. This phenomenon could be explained by the higher oxygen content in biofuel, promoting higher combustion temperature, which causes the reduction of particulate matter (PM) compounds of the exhaust, which is consistent with previous studies [28-30] that reported the relationship between fuel molecular structure and soot formation. This has beneficial effects on both the environment and public health. Furthermore, it leads to cleaner components within the combustion system.

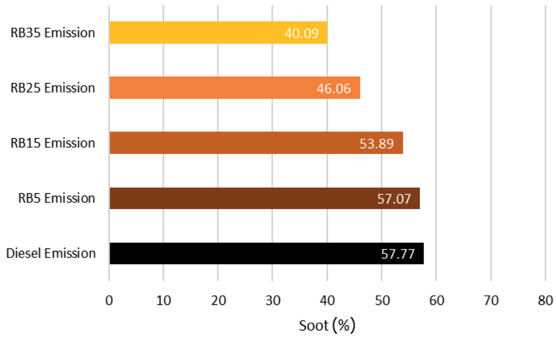

Figure 10 Effect of soot from the engine by using mixed fuel at different rates.

4. Conclusions

In this study, the bio-oil produced from waste rubber cup lump which has not yet undergone the distillation process or quality improvement, was used as blended fuel in a four-stroke diesel engine throughout the tests. With the test results were compared with diesel and blended fuel, assessing average performance and exhaust emissions, as shown in Table. 4. By the results demonstrated that bio-oil from the waste rubber cup lump “RB” which at the highest blend ratio tested (RB35), it provided an average brake torque of only 15.74% lower than diesel fuel, despite an average BSFC increase of 66.67%, it represents an alternative energy option due to Thailand's high rubber production capacity and its potential to reduce greenhouse gas emissions especially CO_2 by 0.89-6.48% generated by engine combustion. Finally, future research should focus on improving fuel properties, particularly cetane rating, and injection timing optimization to reduce emissions and enhance engine performance to be appropriate to the tested fuel. Furthermore, it is recommended to include

Table 4 The percentage difference in engine performance and emissions utilizing bio-oil at varying blending ratios.

Ratios	Average performance									
	T (Nm)	% diff.	P (kW)	% diff.	BSFC (kg/kWh)	% diff.	BSEC (MJ/kWh)	% diff.	BTE (%)	% diff.
Diesel	31.05	-	5.14	-	0.39	-	18.35	-	19.88	-
RB5	30.21	2.74	4.99	2.96	0.58	39.18	27.50	39.91	14.61	30.56
RB15	28.96	6.97	4.82	6.43	0.67	52.83	31.25	52.02	13.13	40.90
RB25	26.49	15.85	4.41	15.29	0.76	64.35	34.93	62.24	11.74	51.49
RB35	26.52	15.74	4.39	15.74	0.78	66.67	35.11	62.70	11.46	53.73

Ratios	Average emission							
	CO_2 (g/kWh)	% diff.	CO (g/kWh)	% diff.	NO_x (g/kWh)	% diff.	Soot %	% diff.
Diesel	120.20	-	0.97	-	1.11	-	57.77	-
RB5	119.14	0.89	1.06	8.87	1.48	28.57	57.07	1.22
RB15	117.30	2.44	1.23	23.64	2.22	66.67	53.89	6.95
RB25	116.16	3.42	1.51	43.55	3.14	95.53	46.06	22.56
RB35	112.65	6.48	1.93	66.21	4.73	123.97	40.09	36.13

detailed combustion analysis, including in-cylinder pressure measurements and heat release rate evaluation, to clarify the relationship between ignition delay, combustion temperature, and gas formation when using waste rubber bio-oil. Future research should improve fuel properties, especially the cetane index. Optimizing injection timing is also important to lower emissions and enhance engine performance for the tested fuel. It is also recommended to include a detailed combustion analysis. In-cylinder pressure measurements and heat release rate evaluation would clarify the links among ignition delay, combustion temperature, and gas formation when using waste rubber bio-oil.

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