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# Evaluation of diesel engine performance and emissions fueled with waste cooking oil biodiesel-plastic pyrolysis oil blends.

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**Abstract**

The depletion of petroleum reserves, rising fossil fuel demand, and increasing plastic waste pollution highlight the need for alternative fuels. This study investigated the performance and exhaust emissions of a direct-injection diesel engine fueled with waste cooking oil biodiesel blended with plastic pyrolysis oil at concentrations of 5%, 10%, 15%, and 20% (B+A5 to B+A20). Biodiesel was produced through degumming, esterification, and transesterification, while plastic pyrolysis oil was obtained via thermal cracking. Engine tests under a constant load across a range of engine speeds evaluated brake power, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust emissions. The results indicate that increasing the proportion of plastic pyrolysis oil improved engine performance compared to pure biodiesel. The B+A20 blend provided the best overall performance, with 44.4% higher power output, 39.6% higher BTE, and 30% lower BSFC than biodiesel, although performance remained below conventional diesel. Regarding emissions, B+A20 reduced CO by 16.3% relative to biodiesel and slightly reduced $CO_2$ (<1%), while NOx increased by 59.7%, highlighting a trade-off between improved performance and NOx control. Overall, blending waste cooking oil biodiesel with plastic pyrolysis oil enhances renewable fuel performance and valorizes plastic waste, but further measures are needed to mitigate NOx emissions.

**Keywords:**
Biodiesel, diesel engine, plastic pyrolysis oil, waste cooking oil

## 1 Introduction

The challenges in meeting global energy needs are projected to become increasingly complex due to population growth and rising energy demand in the transportation and industrial sectors. Currently, more than 80% of the world's primary energy supply still depends on fossil fuels such as oil, natural gas, and coal [1]. This dependence persists because fossil fuel–based technologies are considered more efficient and well-established than alternative energy systems [2]. However, the limited availability of fossil fuel reserves and the environmental impacts of their combustion pose serious socioeconomic and environmental challenges. As a result, extensive research efforts have focused on biodiesel as a sustainable alternative to conventional diesel fuel [3–5]. In addition, the demand for petroleum as a refinery input is projected to increase significantly, while limited domestic supply continues to drive dependence on imported fuels, including diesel [6].

In parallel with energy-related challenges, the rapid growth in plastic consumption since its invention in 1907 has created a major environmental problem [7]. The favorable properties of plastic, including durability, flexibility, and low cost, have led to its widespread use across industrial and household applications. Consequently, global plastic consumption has reached hundreds of millions of tons annually and is expected to continue increasing [8]. In Indonesia, plastic waste accounts for approximately 14% of total waste generation [9]. Improper management of this waste contributes to severe environmental pollution in soil, water, and marine ecosystems, as well as increased carbon emissions from landfilling and open burning.

From the perspective of hydrocarbon composition, plastic waste offers strong potential as an alternative energy source. Pyrolysis can thermally decompose plastic materials into liquid fuel under oxygen-free conditions at around 400 °C [10,11]. Previous studies have reported that plastic pyrolysis oil can be utilized in compression-ignition engines, either as a primary fuel or blended with conventional diesel [12,13]. However, the direct use of plastic pyrolysis oil is often associated with relatively high emissions of nitrogen oxides (NOx) and carbon monoxide (CO), raising concerns regarding its environmental performance [14].

On the other hand, biodiesel derived from waste cooking oil has been extensively investigated as a renewable and environmentally friendly fuel. Despite its advantages, waste cooking oil biodiesel generally exhibits lower engine performance and higher fuel consumption compared to fossil diesel. Therefore, integrating plastic pyrolysis oil as a biodiesel additive offers a promising synergistic solution to mitigate the limitations of both fuels. Nevertheless, most existing studies have focused either on biodiesel alone or on plastic pyrolysis oil blended with fossil diesel. Research that systematically examines the integration of waste cooking oil biodiesel with plastic pyrolysis oil as an additive, particularly with respect to engine performance and exhaust emissions across different blend ratios, remains very limited. Accordingly, the present study aims to address this research gap by evaluating the performance and emission characteristics of a direct-injection diesel engine fueled with blends of waste cooking oil biodiesel and plastic pyrolysis oil. This approach integrates two major waste streams into a single fuel system and provides new insights into the development of sustainable alternative fuels while highlighting the associated performance improvements and emission trade-offs.

## 2 Research methodology

### 2.1 Material preparation and characterization of biodiesel fuel

The biodiesel used in this study was produced from waste cooking oil biodiesel (WCOB) collected from local food vendors.

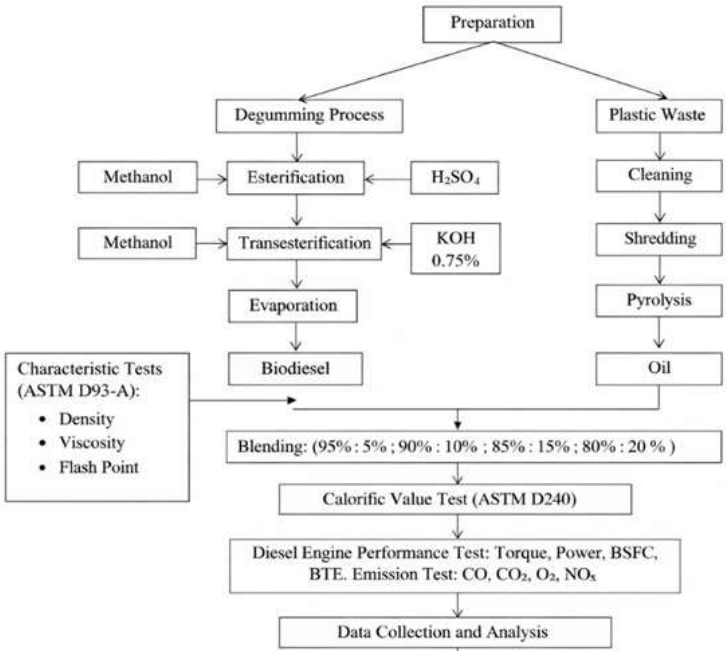


**Fig. 1.** Flowchart of diesel engine performance and emission analysis using biodiesel–plastic pyrolysis oil blends.

Prior to conversion, the waste cooking oil was filtered and characterized for free fatty acid (FFA) content, water content, and

density, as these parameters critically influence the esterification and transesterification processes. Analytical-grade chemicals, including sulfuric acid ($H_2SO_4$), methanol ($CH_3OH$, ≥99.5% purity), and sodium hydroxide (NaOH, ≥98% purity, pellets), were used during biodiesel production, while waste cooking oil served as the primary feedstock.

The characterization results were used to determine suitable reaction conditions and to ensure that the produced biodiesel met the requirements for subsequent fuel blending, engine performance, and exhaust emission testing. The overall experimental workflow of the study, including feedstock preparation, biodiesel and plastic pyrolysis oil production, fuel blending, and engine testing, is summarized in the flowchart shown in Fig. 1.

### 2.1.1 Biodiesel production process

Waste cooking oil biodiesel (WCOB) was produced from used cooking oil collected from local food vendors. The oil was filtered and heated at approximately 105 °C to remove moisture, and its free fatty acid (FFA) content was analyzed prior to processing. Due to the relatively high FFA level, a two-step process comprising esterification followed by transesterification was used.

During esterification, the oil was reacted with methanol at a 6:1 (methanol: oil) molar ratio, using 1% (v/v) sulfuric acid ($H_2SO_4$) as the catalyst at around 60 °C for 60 minutes under continuous stirring. The transesterification step was then conducted using 1% (w/w) sodium hydroxide (NaOH) as the catalyst with a 6:1 methanol-to-oil ratio, at approximately 60 °C for 60 minutes. After the reaction, the mixture was allowed to settle for phase separation, and glycerol was removed. The crude biodiesel was washed with warm distilled water until neutral, then dried by gentle heating at about 105 °C to remove residual moisture.

### 2.1.2 Fuel characterization

The produced biodiesel (WCOB), conventional diesel fuel, and biodiesel–waste plastic pyrolysis oil blends (B+A5, B+A10, B+A15, and B+A20) were characterized prior to engine testing. Key fuel properties, including calorific value, density, and viscosity, were determined using standard laboratory methods to ensure fuel quality and consistency. The measured fuel properties were used to support the analysis of engine performance and exhaust emission characteristics.

## 2.2 Preparation of plastic waste oil

The collected plastic waste was first cleaned to remove adhering particles such as dust and sand, then dried to eliminate moisture, and subsequently shredded to reduce particle size. The plastic feedstock consisted of a mixed composition of low-density polyethylene (LDPE), polyethylene (PE), and polystyrene (PS). The shredded plastics were subjected to fast pyrolysis in a 2 L-capacity reactor heated by the conventional combustion of unused wood branches. The process temperature was maintained between 450 °C and 550 °C, with the heating rate controlled to ensure complete thermal decomposition. Upon reaching the target temperature, the plastic material began to decompose, and the generated volatile compounds were condensed into liquid form through a condensation system. The resulting liquid fuel, hereafter referred to as waste plastic pyrolysis oil (WPPO), was collected in a 1 L glass container. The yields of WPPO, solid residues, and their physical characteristics are summarized in Table 1.

Table 1. Results of the plastic waste pyrolysis process

| Plastic Waste Type | Pyrolysis Oil (%) | Solid (%) | Mass (kg) | Color |
|---|---|---|---|---|
| LDPE | 56 | 10 | 2 | Black |
| PE | 62 | 12.2 | 2 | Yellow |
| PS | 70 | 3 | 2 | Dark brown |
| Mixture | 47 | 25 | 2 | Clear yellow |

As shown in Table 1, polystyrene produced the highest oil yield at 70%, whereas the mixed plastic feedstock yielded the lowest oil fraction at 47% and generated the largest proportion of solid residues. Variations in oil color indicate differences in hydrocarbon composition and impurity content among the feedstocks. To improve WPPO quality prior to blending, the liquid collected from the condenser outlet was filtered using filter paper to remove residual impurities. The appearance of the filtered WPPO obtained from different plastic feedstocks is shown in Fig. 2.

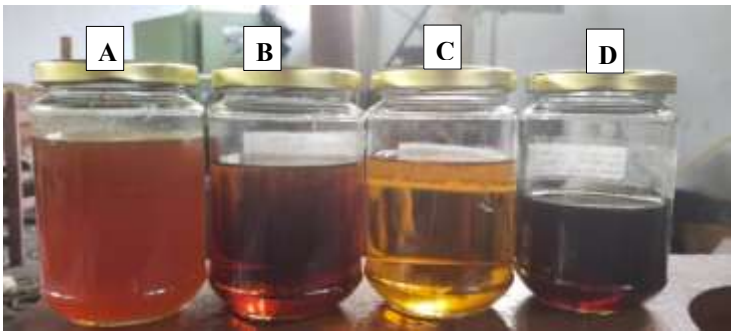


**Fig 2.** Pyrolysis oils obtained from different plastic feedstocks: (A) polystyrene (PS, orange brown), (B) polyethylene (PE, dark brown), (C) mixed plastic (clear yellow), and (D) low-density polyethylene (LDPE, black).

The waste plastic pyrolysis oil (WPPO) was subsequently blended with waste cooking oil biodiesel (WCOB) at volumetric ratios of 95:5, 90:10, 85:15, and 80:20, designated B+A5, B+A10, B+A15, and B+A20, respectively. In these designations, B represents WCOB, and A represents WPPO, with the numerical value indicating the volumetric percentage of WPPO in the blend. Fuel blending was carried out using an electric stirrer for approximately 10-15 minutes, followed by storage for 24 hours to ensure homogeneity. Prior to engine testing, each fuel blend was characterized for its calorific value.

## 2.3 Diesel engine performance and emission testing

Diesel engine performance and emission testing requires a controlled experimental setup to ensure data accuracy and reproducibility. In this study, engine power, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust emissions, including carbon monoxide (CO), carbon dioxide ($CO_2$), and nitrogen oxides (NOx), were evaluated through the integrated operation of the fuel supply system, cooling system, dynamometer, and exhaust gas measurement instruments. A schematic representation of the experimental configuration, showing fuel flow and data-acquisition points, is shown in Fig. 3.

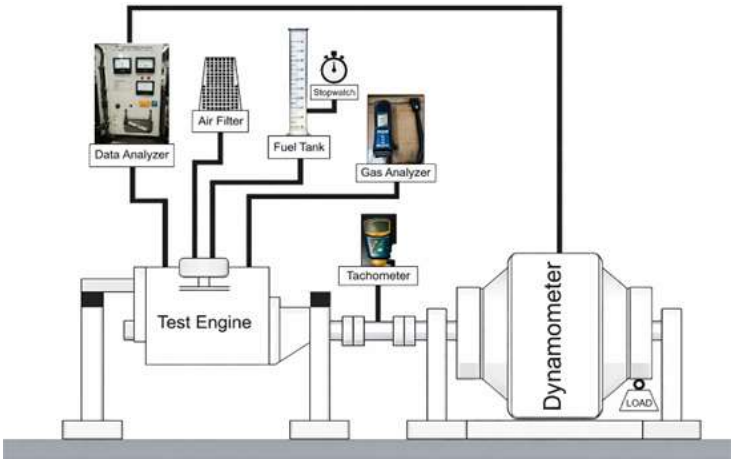


**Fig 3.** Schematic diagram of the engine testing setup

All fuel blend tests were conducted using a fully preheated engine to achieve stable operating conditions. A reference fuel volume of 8 mL was used for each test cycle, and the elapsed time was measured with a stopwatch. Engine performance measurements were performed using a dynamometer under a constant load of 2 kg,

with cooling water supplied through the engine testing unit to maintain consistent operating temperatures.

Experiments were conducted at engine speeds of 1500, 1800, 2100, 2400, and 2700 rpm for all fuel samples. The results were compared with those obtained using neat biodiesel (B100) and conventional diesel fuel. All measurements were conducted in duplicate to ensure data reliability. Performance parameters, including brake power, brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust emissions (CO, $CO_2$, and NOx), were recorded using calibrated instrumentation and gas analyzers integrated with the engine testing setup. The specifications of the diesel engine used in this study are summarized in Table 2.

Table 2. Specifications of the diesel engine

| Parameter | Specification |
|---|---|
| Engine Type | ROBIN – FUJI DY23D |
| Number of Cylinders | 1 |
| Bore × Stroke | 70 mm x 60 mm |
| Displacement | 230 $cm^3$ |
| Fuel Injection Timing | $23^0$ BTDC |
| Maximum Power | 3.5 kW/3600 rpm |
| Maximum Engine Speed | 3600 rpm |
| Compression Ratio | 21: 1 |
| Dry Weight | 45 kg |

## 3 Result and discussion

### 3.1 Characterization of waste cooking oil biodiesel and plastic waste oil

#### 3.1.1 Basic physicochemical properties

Fuel characterization is essential to ensure compliance with quality standards, as properties such as density, kinematic viscosity, calorific value, cetane number, and sulfur content directly affect combustion and emission behavior. In this study, biodiesel produced from waste cooking oil and oil derived from plastic pyrolysis was analyzed and compared with the Indonesian National Standard (SNI 7182:2015). The comparative results of these fuel properties with the national standard are summarized in Table 3.

Table 3. Fuel characteristics based on Indonesian National Standard (SNI 7182:2015)

| No | Test | WCOB | WPPO | SNI | Unit | Reference Method |
|---|---|---|---|---|---|---|
| 1. | Flash Point | 143 | - | 100 | °C Min | ASTM D93-A |
| 2. | Viscosity | 4.4775 | 1.58 | 2.3-6.0 | $mm^2/s$ | ASTM D93-A |
| 3. | Density | 858.15 | 811.9 | 850-890 | $kg/m^3$ | ASTM D93-A |
| 4. | Calorific Value | 39965 | 45274 | 46200 | J/g | ASTM D240 |

The characterization of the test samples in this study revealed that the flash point, kinematic viscosity, and density of biodiesel derived from waste cooking oil (WCO) complied with the requirements of SNI 7182:2015, while the calorific value was close to the standard. Biodiesel from waste plastic oil exhibited overall properties approaching the standard, but its lower viscosity and density could potentially impact the Brake Specific Fuel Consumption (BSFC) [15]. Furthermore, the physicochemical properties of biodiesel produced from WCO, and sunflower oil indicated only minor differences. Specifically, the density of WCO-based biodiesel was 870 $kg/m^3$, compared to 873 $kg/m^3$ for biodiesel from fresh sunflower oil, a difference that can likely be attributed to their similar molecular structures [16].

#### 3.1.2 Calorific value of biodiesel and blended fuels

The calorific value is a crucial indicator of a fuel's energy potential. In this study, the higher heating value (HHV) and lower heating value (LHV) were determined for pure waste cooking oil (WCO) biodiesel and for biodiesel blended with plastic pyrolysis oil (WPPO) at varying proportions. As shown in Table 4, the addition of WPPO increased both HHV and LHV, indicating improved energy density of the blended fuels.

Table 4. Calorific values of waste cooking oil (WCO) biodiesel and WPPO blends.

| No | Fuel Sample | HHV (J/g) | LHV (J/g) |
|---|---|---|---|
| 1. | WCO Biodiesel 100% (B100) | 39.965 | 36.725 |
| 2. | WCO Biodiesel 95% + WPPO 5% (B+A5%) | 40.062 | 36.822 |
| 3. | WCO Biodiesel 90% + WPPO 10% (B+A10%) | 40.695 | 37.455 |
| 4. | WCO Biodiesel 85% + WPPO 15% (B+A15%) | 40.744 | 37.504 |
| 5. | WCO Biodiesel 80% + WPPO 20% (B+A20%) | 40.806 | 37.566 |

As shown in Table 4, pure WCO biodiesel exhibited the lowest calorific value at 39,965 J/g. The addition of WPPO progressively increased the calorific value, reaching its highest level at a blend of WCO 80% + WPPO 20%, with a value of 40,806 J/g. This trend indicates that WPPO acts as an effective additive in enhancing the energy content of biodiesel. The results also confirm that higher proportions of WPPO lead to greater energy yield per unit mass of fuel, suggesting that WCO–WPPO blends have the potential to deliver improved combustion performance compared with pure biodiesel.

#### 3.1.3 Characterization of plastic pyrolysis oil compared with fossil fuels

Plastic pyrolysis oils obtained from LDPE, PE, PS, and mixed plastic feedstocks were characterized and compared with conventional fossil fuels (gasoline and diesel). As presented in Table 4, the calorific values of pyrolysis oils were generally higher than those of gasoline and close to those of diesel, while viscosity and density values ranged between those of gasoline and diesel. This indicates their potential as blending components for alternative fuels.

Table 5. Properties of plastic pyrolysis oils compared with fossil fuels

| Properties | Mixed | LDPE | PE | PS | Gasoline | Diesel |
|---|---|---|---|---|---|---|
| Calorific value (kJ/kg) | 45.274 | 44.053 | 45.925 | 42.795 | 47.300 | 46.500 |
| Viscosity (cP) | 0.7292 | 0.9584 | 1.0199 | 1.2916 | 0.652 | 2.000 |
| Density ($kg/m^3$) | 777.6 | 837.9 | 818.5 | 811.9 | 775.0 | 807.0 |

The highest calorific value of plastic pyrolysis oil was obtained from PE (45.925 kJ/kg), while the lowest was from PS (42.795 kJ/kg), with an average of 44.047 kJ/kg. The calorific values of PE and Mixed oils were close to that of diesel (46.5 kJ/kg), whereas LDPE and PS showed lower values. The oils still contained fine particles that required further filtration, and PE oil tended to solidify upon standing, unlike Mixed oil, which remained liquid. Consequently, the Mixed plastic pyrolysis oil was selected as the most suitable additive for WCO biodiesel.

### 3.2 Performance characteristics of the engine

#### 3.2.1 Brake Power (Shaft Power Output)

Brake power is the effective power at the engine shaft, often called shaft power, and corresponds to the usable power available to overcome the applied load. This parameter is a crucial indicator of engine performance because it reflects the actual power delivered by the engine after accounting for mechanical losses. Brake power can be expressed mathematically as:

$$P_B = \frac{2\,\pi n T}{60X1000}\,T \qquad (1)$$

where
$P_B$ : brake power (kW),
$n$ : engine speed (rpm),
$T$: torque (Nm).

The variation in brake power for different fuel blends, specifically biodiesel–waste plastic oil (WPO) blends and conventional diesel fuel, was evaluated using a single-cylinder, direct-injection diesel engine. The comparative brake power results under various engine operating conditions are presented in Fig. 4.

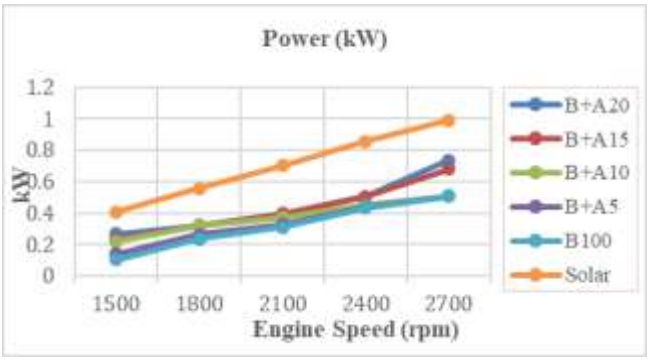


**Fig 4.** Brake power versus engine speed

The maximum brake power was obtained with diesel fuel at 0.9891 kW. In comparison, B100, B+WPO5, B+WPO10, B+WPO15, and B+WPO20 exhibited reductions of 48.57%, 48.57%, 48.57%, 31.42%, and 25.71%, respectively. The incorporation of waste plastic oil into biodiesel was observed to improve brake power relative to neat biodiesel, although the enhancement remained moderate.

In general, brake power increased with engine speed, reaching a maximum at 2700 rpm, then declined at higher biodiesel proportions. This reduction in power output can be attributed to increased fuel viscosity, higher flow resistance, and less effective air–fuel mixing, which adversely affect fuel atomization and combustion efficiency [17–19]. Conversely, higher fuel viscosity may reduce internal leakage in the fuel injection pump [20]. Additionally, the increased fuel mass flow rate partially compensates for the lower calorific value of biodiesel–WPO blends [21,22]. Overall, although biodiesel–WPO blends exhibit lower brake power than diesel fuel, the addition of waste plastic oil helps maintain more stable engine performance compared to neat biodiesel.

#### 3.2.2 Brake thermal efficiency (BTE)

The useful work produced by an engine is always lower than the total energy generated by the piston due to unavoidable mechanical losses. From an economic perspective, it is therefore essential to maximize the useful work that can be obtained from the combustion of a given amount of fuel. When the brake power (PB) is expressed in kW and the fuel mass flow rate (ṁf) in kg/h, the brake thermal efficiency can be determined using the following equation:

$$\eta b = \frac{PB}{\dot{m}_f.CV}\,x\,3600 \qquad (2)$$

where:
ηb : brake thermal efficiency (dimensionless, often expressed in %)
$P_B$ : brake power (W),
$\dot{m}f$ : fuel mass flow rate (kg/h),
$CV$ : calorific value of the fuel (kJ/kg).

Brake thermal efficiency is the engine's ability to convert the thermal energy released during fuel combustion into useful mechanical output. The variation of BTE with engine speed for biodiesel–waste plastic oil (WPO) blends and diesel fuel is illustrated in Fig. 5

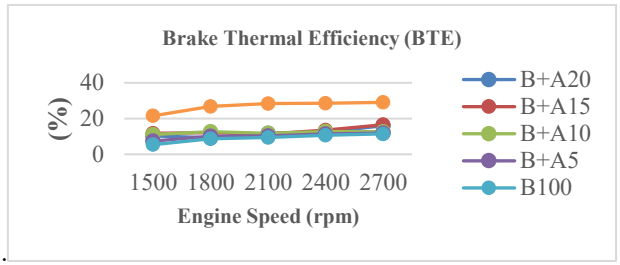


**Fig 5.** Brake thermal efficiency versus engine speed

The experimental results show that BTE increased with engine speed and reached its maximum at 2700 rpm. The highest BTE was achieved with diesel fuel (29.03%), which was approximately 13% higher than that of B+WPO15 (16.52%). The maximum BTE values for B+WPO20, B+WPO10, B+WPO5, and B100 were 15.97%, 12.60%, 11.88%, and 11.44%, respectively, all of which were lower than that of diesel fuel. The improvement in BTE observed in biodiesel–WPO blends relative to neat biodiesel is primarily due to WPO's higher calorific value. Previous studies on diesel engines fueled with waste frying oil methyl ester (WFOME) have reported a decrease in BTE with increasing biodiesel content, with B50 exhibiting a 6.5% reduction compared to diesel [23]. Similarly, increasing the proportion of waste plastic oil in diesel-based blends has been reported to reduce BTE due to higher density and viscosity relative to diesel fuel, which are linked to the dominance of heavier hydrocarbon chains (C15–C30) and the greater energy required to break aromatic bonds [24,25]. Furthermore, blending waste cooking oil biodiesel with diesel significantly influences spray atomization, flame stability, and temperature distribution in diffusion combustion, thereby affecting overall combustion efficiency and BTE [26]. The combined effects of lower calorific value, higher exhaust gas temperature, and higher heat release rates accelerate heat losses, ultimately leading to reduced BTE in WPO-containing fuel blends [27].

#### 3.2.3 Brake specific fuel consumption (BSFC)

Brake Specific Fuel Consumption (BSFC) is a crucial parameter for assessing the impact of fuel blend variations on diesel engine performance [28]. BSFC values tend to increase when two fuels with differing calorific values and densities are blended. The relationship between BSFC and engine speed for each fuel condition is shown in Fig. 6.

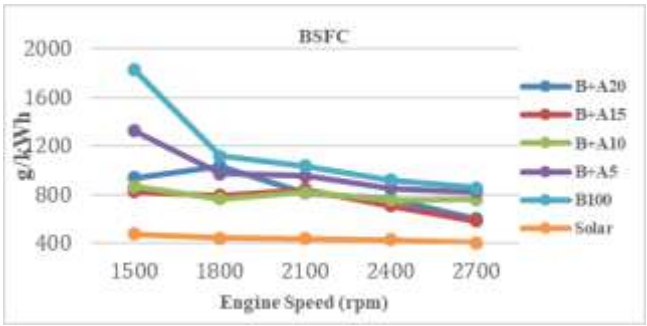


**Fig 6.** Relationship between brake specific fuel consumption and engine speed

The results indicated that BSFC for B+A20, B+A15, B+A10, B+A5, and B100 increased by 48.14%, 43.45%, 88.39%, 103.2%, and 111.6%, respectively, compared to conventional diesel fuel (405 g/kWh). A decrease in BSFC was observed for all tested fuels as engine speed increased from 1500 to 1800 rpm, then rose slightly to 2100 rpm, and subsequently declined. Diesel fuel consistently exhibited the lowest BSFC across all engine speeds compared to biodiesel blended with pyrolysis plastic oil additives. Overall, an increase in average engine speed led to a reduction in BSFC, attributed to shorter combustion duration and faster fuel consumption. Additionally, increasing the proportion of plastic waste oil additives in biodiesel reduced BSFC. This effect is associated with higher calorific values, increased biodiesel viscosity, and slower air–fuel mixing rates.

Brake-specific fuel consumption (BSFC) increased with a higher WFOME content in the fuel blend, consistent with previous studies that reported a higher proportion of waste frying oil methyl ester (WFOME) in the mixture leads to greater BSFC increases, with B50 reaching up to 12.98% under certain operating conditions [29]. Similarly, BSFC for waste cooking oil biodiesel (WCOB) blends also increased with increasing biodiesel content, resulting in higher BSFC for B10, B20, and B30 than for ULSD, as the lower calorific value of biodiesel required the engine to consume more fuel to produce the same power [30]. Among the tested fuels, BSFC increased with higher WCOB blend ratios. On average, BSFC rose by approximately 0.4–4% for WCOB5, WCOB10, WCOB20, and WCOB30 blends. The higher BSFC for biodiesel blends is primarily due to biodiesel's lower calorific value. However, this increase is partially offset by the higher biodiesel density in the volumetric injection system, which reduces the difference in volumetric fuel consumption between diesel and biodiesel. Furthermore, the increase in BSFC with higher WCOB content is related to the greater density of the biodiesel blends, as well as the kinematic viscosity, which affects atomization and slows the fuel–air mixing rate [31].

### 3.3 Exhaust gas emissions

#### 3.3.1 Carbon monoxide (CO) concentration analysis

Carbon monoxide (CO) is formed from the reaction between carbon and oxygen as a product of incomplete combustion. CO is colorless, odorless, and tasteless, yet highly toxic. This gas is generated when the engine operates with a fuel–air mixture that is rich in fuel [32]. CO is produced when the carbon content of the fuel (approximately 85% by weight, with the remainder hydrogen) undergoes incomplete combustion due to insufficient oxygen. This condition typically occurs when the fuel–air mixture is richer than the stoichiometric ratio, such as during idling at low load or at maximum output. Carbon monoxide cannot be eliminated under rich mixture conditions, whereas CO formation does not occur in lean mixtures. The CO emissions observed in this study are presented in the graph shown in Fig 7.

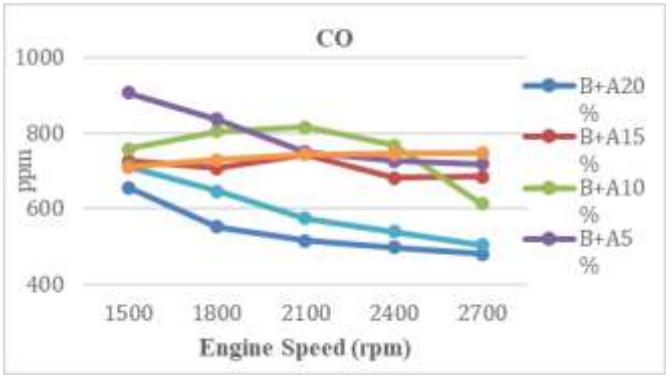


**Fig 7.** CO Emission versus engine speed

As shown in Fig 7, the minimum CO emissions were observed at an engine speed of 2700 rpm. For the test fuels B100, B+A5, B+A10, B+A15, and B+A20, CO emissions decreased by 32.49%, 29.7%, 17.93%, 8.29%, and 35.87%, respectively, compared to diesel fuel (747 ppm), which exhibited the highest CO concentration. Although CO emissions fluctuated with different additives, increasing engine speed generally reduced CO levels across all fuels. [33] Found that B30, the use of a fuel preheater, reduced fuel consumption by 20% and CO emissions by 7.6%, indicating that both fuel blending and technical engine modifications are effective strategies for reducing CO emissions. The higher CO concentrations in some blends were attributed to elevated fuel consumption and the presence of non-oxygenated compounds in plastic waste oil, which hindered complete combustion. Moreover, CO emissions were influenced by combustion temperature, air–fuel ratio, fuel physicochemical properties, oxygen deficiency at higher engine speeds, and limited time for complete oxidation [34]. CO emissions are also highly dependent on the air–fuel ratio relative to the stoichiometric proportion and the combustion performance in gasoline engine cylinders. When the air–fuel ratio shifted from rich to lean (λ increasing from 0.85 to 1.2), CO emissions drastically decreased to about one-tenth of the initial values, and under lean conditions (λ > 1), CO remained low due to the abundance of oxygen for complete oxidation [35].

#### 3.3.2 Carbon dioxide ($CO_2$) concentration

$CO_2$ is naturally present in the environment and is a key product of hydrocarbon combustion. They are considered an important parameter for evaluating the effects of different fuel blends on diesel engine performance [36]. The $CO_2$ emission results obtained in this study are presented in Fig 8.

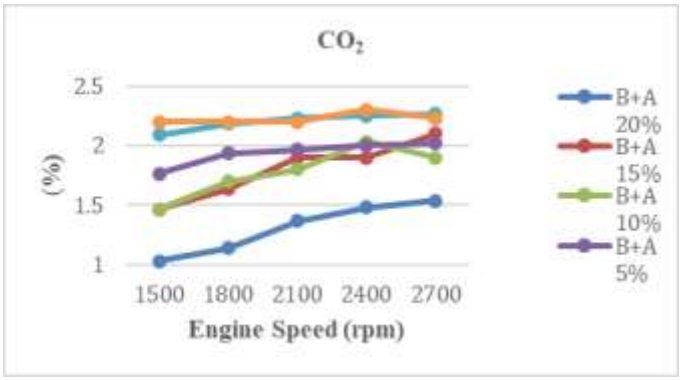


**Fig 8**. $CO_2$ Concentration versus engine speed

Based on the data, the peak $CO_2$ emissions occurred at an engine speed of 2700 rpm. For the test fuels B+A5, B+A10, B+A15, and B+A20, $CO_2$ levels were lower by 0.21%, 0.33%, 0.13%, and 0.69%, respectively, compared to diesel fuel (2.23%), which exhibited $CO_2$ concentrations close to those of biodiesel (2.26%). The results indicate that adding additives to biodiesel can significantly reduce $CO_2$ emissions, likely due to the enhanced calorific value, which improves combustion efficiency. In contrast, [37] reported a slight increase in NO and $CO_2$ emissions when biodiesel was blended with a fuel-borne catalyst (FBC) compared to biodiesel under optimized operating conditions. Consistently, lower $CO_2$ emissions were observed for biodiesel without FBC across various operating conditions, attributed to its lower carbon content [38]. Moreover, a smaller reduction in $CO_2$ emissions was noted when antioxidants such as BHA and BHT were incorporated into the B20 blend [39].

#### 3.3.3 Nitrogen oxides (NOx) emissions

NOx emissions represent a critical performance indicator for oxygenated fuels, as the fuel's oxygen content strongly influences them. The formation of NOx is governed by the complex interactions between air and fuel in the combustion chamber, as well as the local oxygen concentration and in-cylinder temperature [40]. The observed fluctuations in NOx concentrations under different test conditions are illustrated in Fig 9.

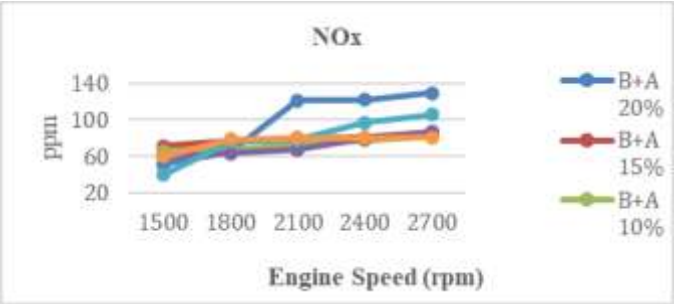


**Fig 9.** NOx Emissions versus Engine Speed

As shown in the data, peak NOx emissions occurred at 2700 rpm. For the test fuels B100, B+A5, B+A10, B+A15, and B+A20, NOx levels increased by 30.86%, 7.00%, 1.23%, 6.17%, and 59.67%, respectively, compared to diesel fuel (81 ppm), which exhibited the lowest NOx concentration. Between 1500 and 2400 rpm, fluctuations in NOx emissions were observed for biodiesel blended with plastic waste oil additives, with certain engine speeds exhibiting lower NOx levels than those of diesel. The subsequent increase in NOx for the plastic waste oil additives is attributed to higher in-cylinder pressures and ignition delays, which enhance heat release compared to diesel fuel. Additionally, the higher aromatic content in plastic waste oil increases the adiabatic flame temperature, further enhancing heat release and increasing NOx formation in the exhaust. The test fuels showed a general trend of increasing $NO_x$ emissions with rising engine speed, indicating improved combustion efficiency at higher speeds. The elevated $NO_x$ emissions observed for plastic waste oil additives and their blends were primarily associated with the higher premixed combustion rate of these fuels. [41] Found that blending kerosene with diesel and biodiesel reduces fuel viscosity and density, increases the calorific value, and decreases emissions of $CO_2$, CO, HC, particulates, and opacity. However, the use of biodiesel tends to increase $NO_x$ emissions, mainly because of its higher oxygen content, which elevates combustion temperatures and consequently promotes $NO_x$ formation.

NOx emissions are generally higher for biodiesel due to its chemically bound oxygen content, which promotes NOx formation [42]. In addition, the increase in NOx emissions can be attributed to higher adiabatic flame temperatures. Biodiesel typically contains a higher proportion of unsaturated fatty acids, leading to elevated adiabatic flame temperatures that further enhance NOx formation [43]. Moreover, the combination of higher oxygen content, higher in-cylinder temperatures, and longer residence times results in higher NOx emissions from biodiesel than from conventional diesel across almost all engine speeds [44].

## 4 Conclusion

In summary, the study demonstrates that blending waste plastic pyrolysis oil with waste cooking oil biodiesel (B+A20) can enhance engine performance and reduce certain emissions, while highlighting some trade-offs that require further attention:

1. The B+A20 blend significantly improved engine performance compared to neat biodiesel, with a 44.4% increase in power output, a 39.6% increase in brake thermal efficiency (BTE), and a 30% reduction in brake-specific fuel consumption (BSFC). Performance, however, remained lower than conventional diesel.
2. The addition of waste plastic pyrolysis oil improved the combustion characteristics of biodiesel, contributing to better BTE and lower BSFC, in line with the measured experimental data.
3. The B+A20 blend reduced CO emissions by 16.3% compared to biodiesel and 40.4% compared to diesel, while $CO_2$ emissions decreased slightly (<1%), indicating cleaner combustion.
4. NOx emissions increased by 59.7% compared to diesel, highlighting the trade-off between enhanced performance and NOx control.

Overall, B+A20 demonstrates potential as an alternative fuel that supports circular energy systems by valorizing plastic waste. Future research should focus on mitigating NOx emissions using strategies such as exhaust gas recirculation (EGR), aftertreatment technologies, or testing under varying engine loads and operating conditions.

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**References**

[1] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, and R. Valdez, "A global assessment: Can renewable energy replace fossil fuels by 2050?," *Sustainability*, vol. 14, no. 8, p. 4792, 2022. doi: 10.3390/su14084792.

[2] Badan Pengkajian dan Penerapan, T., Outlook Energi Indonesia 2021: Tenaga Surya Untuk Penyediaan Energi Charging Station, 2021.

[3] S. Abel, L. Jule, L. Gudata, N. Nagaraj, R. Shanmugam, L. Dwarampudi, B. Stalin, and K. Ramaswamy, "Preparation and characterization of biofuel from Ricinus communis seed extracts," Sci. Rep., vol. 12, p. 10684, 2022. doi: 10.1038/s41598-022-14403-7.

[4] B. N. Kale and S. Patle, "State of art review of algal biodiesel and its blends influence on CI engine performance and emissions," Clean. Eng. Technol., p. 100431, 2022. doi: 10.1016/j.clet.2022.100431.

[5] T. M. I. Riayatsyah, R. Thaib, A. S. Silitonga, J. Milano, A. H. Shamsuddin, A. H. Sebayang, J. Sutrisno, and T. M. I. Mahlia, "Biodiesel production from Reutealis Trisperma oil using conventional and ultrasonication esterification and transesterification," Sustainability, vol. 13, p. 3350, 2021. doi: 10.3390/su13063350

[6] J. Sekretariat, Laporan Hasil Analisis Neraca Energi Nasional 2021, Dewan Energi Nasional, 2021.

[7] Y. Nofendri and A. Haryanto, "Perancangan alat pirolisis sampah plastik menjadi bahan bakar," J. Kaj. Tek. Mesin, vol. 6, pp. 1–11, 2021. doi: 10.52447/jktm.v6i1.4454

[8] D. Iswadi, F. Nurisa, and E. Liastuti, "Pemanfaatan sampah plastik LDPE dan PET menjadi BBM dengan pirolisis," J. Ilm. Tek. Kim. Unpam, vol. 1, pp. 1–9, 2017. doi: 10.32493/jitk.v1i2.718

[9] P. Purwaningrum, "Upaya mengurangi timbulan sampah plastik di lingkungan," Indon. J. Urban Environ. Technol., vol. 8, pp. 141–147, 2016. doi: 10.25105/urbanenvirotech.v8i2.1421

[10] S. Salamah and A. Aktawan, "Pemurnian hasil cair pirolisis sampah plastik dengan distilasi batch," J. Chemica, vol. 3, pp. 31–34, 2016. doi: 10.26555/chemica.v3i1.4990

[11] A. R. Lukitobudi, M. S. R. Sugiyarto, and D. A. Qolbi, "Kaji eksperimental sistem distilasi asap pembakaran sampah plastik menjadi bahan bakar alternatif dengan pendinginan sistem refrigerasi kompresi uap," Kurvatek, vol. 5, pp. 87–94, 2020. doi: 10.33579/krvtk.v5i2.2081

[12] B. Kaewbuddee, E. Sukjit, J. Srisertpol, S. Maithomklang, K. Wathakit, N. Klinkaew, P. Liplap, and W. Arjharn, "Evaluation of waste plastic oil-biodiesel blends as alternative fuels for diesel engines," Energies, vol. 13, no. 11, p. 2823, 2020. doi: 10.3390/en13112823

[13] N. Ndiaye, N. Derkyi, and E. Amankwah, "Pyrolysis of plastic waste into diesel engine-grade oil," Sci. Afr., vol. 20, p. e01836, 2023. doi: 10.1016/j.sciaf.2023.e01836.

[14] K. Landwehr, A. Larcombe, A. Reid, and B. Mullins, “Critical review of diesel exhaust exposure health impact research relevant to occupational settings: Are we controlling the wrong pollutants?,” Exposure Health, vol. 13, pp. 141–171, 2020. doi: 10.1007/s12403-020-00379-0
[15] S. Maithomklang, E. Sukjit, J. Srisertpol, N. Klinkaew, and K. Wathakit, “Pyrolysis oil derived from plastic bottle caps: Characterization of combustion and emissions in a diesel engine,” Energies, vol. 16, no. 5, p. 2492, 2023. doi: 10.3390/en16052492
[16] A. Mathew and K. Anand, “Comparison of engine characteristics with biodiesels produced from fresh and waste cooking oils,” Biofuels, vol. 12, pp. 663–671, 2021. doi: 10.1080/17597269.2018.1519761
[17] S. O. Bitire and T. C. Jen, “Performance and emission analysis of a CI engine fueled with parsley biodiesel–diesel blend,” Mater. Renew. Sustain. Energy, vol. 11, no. 2, pp. 143–153, 2022. doi: 10.1007/s40243-022-00213-4
[18] F. Ma, R. Xu, and X. Liu, “Fuel injection performance and spray characteristic of high-pressure common rail systems at low temperatures,” Energy Sci. Eng., vol. 12, no. 3, pp. 1233–1241, 2024. doi: 10.1002/ese3.1713
[19] S. Slavinskas, “An experimental study on the injection characteristics and macroscopic spray characteristics of rapeseed oil–diesel fuel blends,” Appl. Sci., vol. 13, no. 10, p. 5944, 2023. doi: 10.3390/app13105944
[20] B. Binyamin and O. Lim, “Numerical analysis of the structural and flow rate characteristics of the fuel injection pump in a marine diesel engine,” Sustainability, vol. 15, no. 11, p. 8948, 2023. doi: 10.3390/su15118948
[21] S. Das and A. Chowdhury, “An exploration of biodiesel for application in aviation and automobile sector,” Energy Nexus, vol. 10, p. 100204, 2023. doi: 10.1016/j.nexus.2023.100204.
[22] M. A. Mujtaba, H. H. Masjuki, M. A. Kalam, F. Noor, M. Farooq, H. C. Ong, M. Gul, M. E. M. Soudagar, S. Bashir, I. M. R. Fattah, and L. Razzaq, “Effect of additivized biodiesel blends on diesel engine performance, emission, tribological characteristics, and lubricant tribology,” Energies, vol. 13, no. 13, p. 3375, 2020. doi: 10.3390/en13133375.
[23] M. S. Gad and H. E. Fawaz, “Artificial neural network based forecasting of diesel engine performance and emissions utilizing waste cooking biodiesel,” Sci. Rep., vol. 14, p. 21980, 2024. doi: 10.1038/s41598-024-71675-x.
[24] F. Faisal, M. G. Rasul, M. I. Jahirul, and A. A. Chowdhury, “Waste plastics pyrolytic oil as a source of diesel fuel: A recent review on diesel engine performance, emissions, and combustion characteristics,” Sci. Total Environ., vol. 886, p. 163756, 2023. doi: 10.1016/j.scitotenv.2023.163756.
[25] M. Mariappan, M. Panithasan, and G. Venkadesan, “Pyrolysis plastic oil production and optimisation followed by maximum possible replacement of diesel with bio-oil/methanol blends in a CRDI engine,” J. Clean. Prod., vol. 312, p. 127687, 2021. doi: 10.1016/j.jclepro.2021.127687
[26] S. Sukri, M. N. Sasongko, and T. D. Widodo, “Pengaruh campuran bahan bakar biodiesel WCO-diesel terhadap karakteristik api hasil pembakaran spray difusi pada concentric jet burner,” J. Rekayasa Mesin, vol. 12, no. 2, pp. 459–466, 2021. doi: 10.21776/ub.jrm.2021.012.02.22
[27] S. Vellaiyan, D. Chandran, R. Venkatachalam, K. Ramalingam, R. Rao, and R. Raviadaran, “Maximizing waste plastic oil yield and enhancing energy and environmental metrics through pyrolysis process optimization and fuel modification,” Results Eng., vol. 22, p. 102066, 2024. doi: 10.1016/j.rineng.2024.102066
[28] S. Simsek and S. Uslu, “Investigation of the effects of biodiesel/2-ethylhexyl nitrate (EHN) fuel blends on diesel engine performance and emissions by response surface methodology (RSM),” Fuel, vol. 275, p. 118005, 2020. doi: 10.1016/j.fuel.2020.118005
[29] C. Kaya and G. Kokkulunk, “Biodiesel as alternative additive fuel for diesel engines: An experimental and theoretical investigation on emissions and performance characteristics,” Energy Sources, Part A, vol. 45, pp. 10741–10763, 2020. doi: 10.1080/15567036.2020.1774685
[30] L. Razzaq, S. Imran, Z. Anwar, M. Farooq, M. Abbas, H. Khan, T. Asif, M. Amjad, M. Soudagar, N. Shaukat, I. Fattah, and S. Rahman, “Maximising yield and engine efficiency using optimised waste cooking oil biodiesel,” Energies, vol. 13, no. 22, p. 25941, 2020. doi: 10.3390/en13225941
[31] A. F. Fareed, A. S. El-Shafay, M. A. Mujtaba, F. Riaz, and M. S. Gad, “Investigation of waste cooking and castor biodiesel blends effects on diesel engine performance, emissions, and combustion characteristics,” Fuel, vol. 387, p. 118005, 2024. doi: 10.1016/j.fuel.2024.118005
[32] Majstorovic, V. Babic, and M. Todic, “Carbon monoxide in the process of uncontrolled combustion: Occurrence, hazards and first aid,” J. Phys. Conf. Ser., vol. 1426, no. 1, p. 012008, 2020. doi: 10.1088/1742-6596/1426/1/012008
[33] L. N. Komariah, E. Salindra, M. A. Ray, and M. Rendana, “Effect of technical modifications on the fuel consumption and emission level of biodiesel-diesel blended (B30) fuel engine,” J. Rekayasa Mesin, vol. 12, no. 3, pp. 717–724, 2021. doi: 10.21776/ub.jrm.2021.012.03.21
[34] R. Cole, C. D. A. Jimenez, D. Wu, T. Lieuwen, and B. Emerson, “Carbon monoxide emissions from combustion of non-carbon-containing fuels,” Combust. Flame, vol. 273, p. 113913, 2025. doi: 10.1016/j.combustflame.2024.113913
[35] Deng, Q. Li, Y. Chen, M. Li, A. Liu, J. Ran, Y. Xu, X. Liu, J. Fu, and R. Feng, “The effect of air/fuel ratio on the CO and NOx emissions for a twin-spark motorcycle gasoline engine under a wide range of operating conditions,” Energy, vol. 69, pp. 1202–1213, 2019. doi: 10.1016/j.energy.2018.12.113
[36] M. Elkelawy, E. El Shenawy, S. Khalaf Abd Almonem, M. Nasef, H. Panchal, H. A.-E. Bastawissi, K. K. Sadasivuni, A. K. Choudhary, D. Sharma, and M. Khalid, “Experimental study on combustion, performance, and emission behaviours of diesel/WCO biodiesel/cyclohexane blends in DI-CI engine,” Process Saf. Environ. Prot., vol. 149, pp. 684–697, 2021. doi: 10.1088/1742-6596/2616/1/012018
[37] Bibin, K. P. Seeni, and P. K. Devan, “Performance, emission and combustion characteristics of a direct injection diesel engine using blends of punnai oil biodiesel and diesel as fuel,” Therm. Sci., vol. 24, no. 1A, p. 13, 2020. doi: 10.2298/TSCI180325233B
[38] M. Khalaf, T. Xuan, W. A. Abdel-Fadeel, H. M. Mustafa, S. Abdelhady, and M. F. Esmail, “A comparative study of diesel engine fueled by Jatropha and castor biodiesel: Performance, emissions, and sustainability assessment,” Process Saf. Environ. Prot., vol. 188, pp. 453–466, 2024. doi: 10.1016/j.psep.2024.05.137.
[39] K. Alagu, B. Nagappan, J. Jayaraman, and A. Arul Gnana Dhas, “Impact of antioxidant additives on the performance and emission characteristics of CI engine fuelled with B20 blend of rice bran biodiesel,” Environ. Sci. Pollut. Res., vol. 25, pp. 17634–17644, 2018. doi: 10.1007/s11356-018-1934-1.
[40] R. Meherzi, C. Boubahri, D. O. Lendoye, A. Elleuch, and J. Bessrour, “Numerical simulation of the effect of adding oxygenated fuel (ethanol) to commercial gasoline on engine performance and NOx emissions,” Int. J. Low-Carbon Technol., vol. 20, pp. 1001–1011, 2025. doi: 10.1093/ijlct/ctae065
[41] A. Bhikuning, M. Hafnan, and J. D. I. Wijaya, “Pengaruh pencampuran minyak tanah dengan bahan bakar minyak diesel, biodiesel dan lainnya—Review,” J. Rekayasa Mesin, vol. 13, no. 3, pp. 717–730, 2022. doi: 10.21776/jrm.v13i3.1090

[42] P. Geng, X. Hu, and X. Lin, “Effects of oxygen enrichment and air humidification on the combustion and emissions of the biodiesel marine diesel engine,” J. Mar. Sci. Eng., vol. 13, no. 2, p. 271, 2025. doi: 10.3390/jmse13020271
[43] V. Sharma, A. K. Hossain, and G. Duraisamy, “Experimental investigation of neat biodiesels’ saturation level on combustion and emission characteristics in a CI engine,” Energies, vol. 14, no. 16, p. 5203, 2021. doi: 10.3390/en14165203
[44] F. A. Ghany, B. Wahono, A. Praptijanto, Y. Putrasari, A. Dimyani, A. Nur, M. Pratama, and M. K. A. Wardana, “Study on the effect of high-concentration oxygen enrichment on engine performance and exhaust emissions using diesel fuel and palm biodiesel substitute fuel,” Energies, vol. 17, no. 1, p. 244, 2024. doi: 10.3390/en17010244