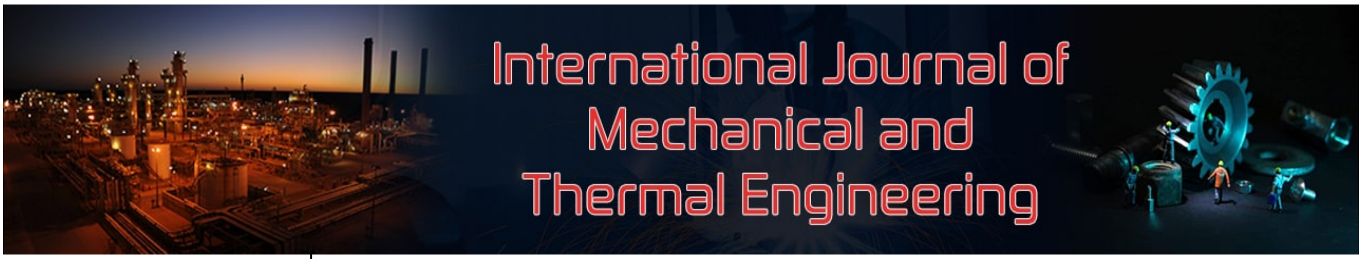

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Performance and methane emissions of diesel engine operating on fuel extracted from waste engine oil

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Abstract
This study investigates the effect of blending conventional diesel (D) with 10% of DWL extracted from waste engine oil via thermal distillation (90%D + 10%W) on engine performance and methane emissions under low-load conditions. Experiments were conducted on a Lombardini engine operating with compression ignition across loads (2, 4, 6 kg) and speeds (1550-2150 rpm). The results show that the 90%D + 10%W blend increased the BSFC with increasing loads and reduced the BTE with increasing loads compared to conventional diesel. This can be attributed to the lower cetane number, calorific value, and other physical properties of DWL. More importantly, methane emissions were significantly reduced under optimal conditions: by 14.28% (2 kg), 27.08% (4 kg), and 9.09% (6 kg) at 1850 rpm. This demonstrates the blend's ability to reduce methane, a potent greenhouse gas, despite some minor trade-offs in efficiency, offering a sustainable pathway for recycling waste engine oil.

Keywords: Methane emissions Ch_4, waste engine oil recycling, waste lubricating oil, performance and methane emissions, methane emissions reduction

Introduction

Many scientists and researchers are focusing on identifying alternative sources to fossil fuels due to concerns over the depletion of these finite resources and the urgent need to mitigate fuel consumption and global warming by reducing pollutant emissions from internal combustion engine exhausts [1, 2]. Waste lubricating oils in compression ignition engines have emerged as a promising alternative fuel, with numerous studies demonstrating their comparability to petroleum-based fuels [3]. Moreover, these oils are increasingly recognized as environmental pollutants, primarily due to improper disposal, which leads to soil and water contamination. To ensure their appropriate use, companies and industries have been advancing techniques for recycling and processing waste lubricating oils through various methods. This treatment allows for the extraction of fuel that is comparable to conventional diesel, although with lower efficiency relative to standard diesel fuel [4]. Such processes have the potential to minimize harmful emissions, including methane, a low-toxicity greenhouse gas that contributes to global warming. Consequently, using recovered materials from waste lubricating oils in internal combustion engines could significantly reduce both global warming and air pollution. Several studies have examined the blending of recovered lubricating oils and their conversion for use in compression ignition (CI) engines, particularly investigating the impact of engine load on engine performance and emissions. Arpa *et al.* (2010) [5] investigate the impact of Diesel-Like Fuel (DLF) produced from waste engine oil on engine performance. The DLF was produced using a pyrolytic distillation method, with 60% of lubricant oil converted into usable fuel. The effect of the load on engine performance showed a 0.69% increase in torque, brake mean effective pressure, and brake thermal efficiency, along with a 4.99% decrease in brake specific fuel consumption compared to diesel fuel. Zervas *et al.* (2010) [6] tested vehicles using diesel, gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG) across multiple emission standards (e.g., Euro 1-4). measured methane (CH_4) emissions from diesel passenger cars, averaging 5.9 mg/km (representing 26.67% of total hydrocarbons in exhaust). Where CH_4 is a potent greenhouse gas with a global warming potential of 20-40 times that of CO_2. Nayak *et al.* (2013) [7] investigated the use of biodiesel produced from waste cooking oil in diesel engines. The results showed that the B60 blend (60% biodiesel + 40% conventional diesel) delivered the best engine performance compared to pure biodiesel (B100). Regarding the effect of engine load on performance, the B60 blend achieved the highest brake thermal efficiency (~20-25% at full load), while pure biodiesel (B100) exhibited a higher BSFC by 10-15% compared to standard diesel, along with an increase in exhaust gas temperature by 12-15%, attributed to its higher oxygen content. Naima *et al*. (2013) [8] reviewed waste oils (engine, cooking, and plastic) as an alternative diesel fuel. Biodiesel from cooking oil (WCO) showed that at full load, torque and thermal efficiency increased by approximately 0.69%, while the BSFC of biodiesel decreased by 8.31%. Demirbas *et al*. (2015) [9] converted waste engine oil to diesel fuel using thermal distillation. To improve fuel properties, sodium carbonate (Na2CO3) was added at 2%, 6%, and 10% by weight. The additives increased the distillation temperature, indicating potential higher combustion efficiency and improved engine performance, and also helped reduce the sulfur content. Prabakaran *et al*. (2016) [10] explore the impact of blending recycled engine oil with diesel on engine performance. The recycled oil, treated with acetic acid and clay, was mixed with diesel in varying proportions (5%, 15%, and 20%). The results show that the blends increase BTE by 5%, 4%, and 2%, respectively, at full load, while BSFC decreases by 6%, 5%, and 2%. Omidvarborna *et al*. (2016) [11] investigated methane (CH_4) emissions from engine exhaust under low-temperature combustion.CH_4 is a potent greenhouse gas with 25 times the global warming potential of CO_2. The study tested three biodiesel feedstocks, SME, WCO, and their blends (B20/B50/B100) with ultra-low sulfur diesel (ULSD) in a laboratory combustion chamber. They found that CH_4 emissions increased with higher biodiesel blend ratios, peaking at 2.7 mol% for pure soybean biodiesel (SME), compared to 2.4% for waste cooking oil (WCO) and 2.3% for tallow oil (TO). Kamieniak *et al*. (2017) [12] conducted a study using Pd/Ni-hydroxyapatite catalysts to treat exhaust from engines operating on diesel and natural gas (methane-rich). Addressed methane abatement in simulated diesel-natural gas dual-fuel exhaust, achieving 88% CH_4 reduction via catalytic dry reforming. Wang *et al*. (2017) [13] used diesel-like fuel (DLF) derived from used lube oil (WLO) as a substitute for diesel. The results showed that the BSFC of DLF fuel was approximately 3% lower at 3000 rpm under light and medium loads compared to diesel. Qasim *et al*. (2017) [14] studied the effect of load on engine performance and emissions using biodiesel-like fuel (BLF) blends derived from a blend of waste canola oil and waste transformer oil. At maximum load, the BSFC increased with higher BLF concentrations in the blends, with BLF15, BLF20, and BLF25 being 2.48%, 4.74%, and 6.54% higher, respectively, compared to diesel, due to the lower calorific value of the blends. The BTE for all BLF blends decreased by 1.99% to 4.91%, with BLF25 showing a 6.42% decrease. Hussain *et al*. (2020) [15] used pyrolyzed waste engine oil (WEO) as an alternative fuel for diesel engines. Electrical pyrolysis oil (EPO) and microwave pyrolysis oil (MPO) were tested, with results showing that the BTE at full load was 26% for diesel, 25.95% for EPO, and 25% for MPO, slightly lower than diesel. Lee *et al*. (2021) [16] studied methane emissions in a natural-gas/diesel dual-fuel engine. Methane constituted 52-87% of total hydrocarbon (THC) emissions under conventional dual-fuel combustion, primarily due to unburned natural gas trapped in crevice volumes. Effendy *et al*. (2021) [17] conducted a study on waste-derived fuel (WDF) from used lubricating oil in an internal combustion engine. The study tested 100% waste-derived fuel (W100) and a 50% blend (W50), demonstrating a 3.22% increase in brake torque, a 2.89% increase in power, and an 8.31% reduction in BSFC compared to diesel. Emissions improved, with an 11.89% decrease in smoke opacity in W100 due to enhanced combustion resulting from the higher cetane number (48.1) and reduced viscosity**.** Tripathi *et al*. (2022) [18] conducted a review on engines that operate using methane port injection and/or direct injection (from natural gas, biogas, or hydrates) with pilot diesel fuel. They concluded that diesel engines operating on a methane-diesel dual-fuel system increase unburned methane (CH_4) emissions in the exhaust, contributing to total hydrocarbons (THC). The percentage rises with higher methane energy shares due to incomplete combustion. The study emphasizes that methane emissions are a drawback, contributing to the greenhouse effect.

With the continued depletion of global crude oil reserves, scientists and researchers are exploring alternative fuels, including the recycling of waste engine oil, which would otherwise be discarded and cause environmental harm. This approach aims to mitigate crude oil depletion and reduce the associated economic costs. While the effects of blending waste engine oil with conventional diesel fuel have not been extensively studied, ongoing research is focusing on the application of these blends in internal combustion engines. However, there remains a gap in the literature regarding the impact of these blends on engine performance and emissions, particularly methane emissions from engine exhaust, which is a significant concern in the context of global warming, especially under low-load conditions. Low-load conditions were specifically chosen for investigation due to the unique challenges they present in compression ignition engines, such as poor fuel utilization and their effect on methane emissions, which result in inefficient combustion. Furthermore, investigating low-load conditions offers valuable insights into internal combustion engine performance and the impact of various operating parameters on methane emissions and engine efficiency. To address this issue, the blending of engine lubricating oil (DWL), extracted from waste engine oil via thermal distillation, is proposed to produce a fuel with properties nearly identical to those of conventional diesel. By blending DWL with diesel fuel at a ratio of 10% DWL to 90% conventional diesel, a blend suitable for compression ignition engines can be produced, potentially reducing methane emissions. The primary objective of this study is to assess the effects of DWL, derived from waste engine oil, when blended with conventional diesel, on the performance of compression ignition engines and methane emissions under low-load conditions. Additionally, the study aims to evaluate whether this blend could serve as a viable alternative to conventional diesel, particularly in scenarios where fuel availability is a concern, while reducing environmental impacts and mitigating global warming.

It is noteworthy that no researchers have previously addressed the study of the effect of fuel extracted from waste engine oil on methane emissions. Due to the limited previous studies in this field, our research is the first to explore this topic.

2. Experimental Work

This study aimed to evaluate the impact of fuel extracted from waste engine oil (DWL) when blended with conventional diesel fuel in a 90% conventional diesel and

10% DWL volume ratio, on engine performance and emissions under low-load conditions, in addition to mitigating the environmental consequences of the improper disposal of waste engine oil. The waste engine oil was processed through a thermal distillation method. The samples were analyzed at the Oil and Gas Laboratory at North Refineries Company, located at the Baiji Refinery. The properties of the extracted fuel are presented in Table 1. The extracted fuel was then blended with conventional diesel in a 90% diesel and 10% DWL ratio (90% D + 10% W), as illustrated in Figure 1.

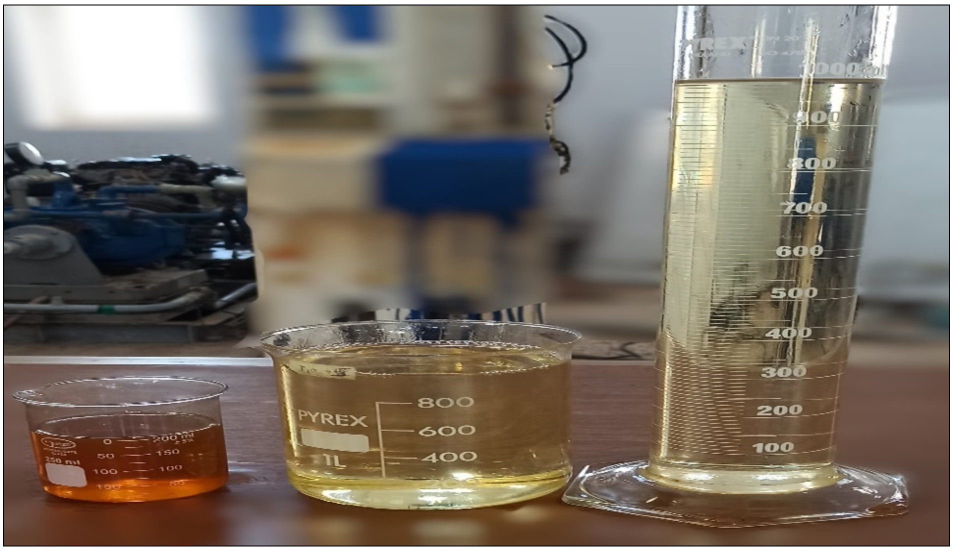

Fig 1: Blending Ratios for The Sample Used In The Test

Table 1: Properties of The Blends

No	SAMPLE	Density kg/m^3	LHV (J/kg)	Viscosity@15 °C/CST	CN.	Flash Point °C	API	Sulfur conc.
1	100% D	831.9	41891154.78	3.1726	53.229	73	*38.59*	1.0856
2	100%W	840.8	20139004.24	7.3066	36.422	86	*36.95*	0.6551
4	90%D 10%W	835.4	41779205.15	3.5571	48.002	80	*37.85*	1.0688

The performance and emissions of the engine were evaluated under varying load conditions of 2, 4, and 6 kg, and at engine speeds of 1550, 1700, 1850, 2000, and 2150 rpm. The study examined several critical performance parameters, including brake power, specific fuel consumption under braking conditions, and brake thermal efficiency. The experiments utilized a Lombardini compression-ignition engine, a two-cylinder, four-stroke configuration. The engine's maximum power output is 11.5 hp at 3600 rpm, with a stroke length of 72 mm and a cylinder diameter of 62 mm. The compression ratio is 22.8:1, and the combustion chamber volume is 505 mm³, as shown in Figure 2. The engine's cooling system employs water as the working fluid. The engine is connected to a brake power measurement device, specifically a hydraulic dynamometer, which records the engine's brake power. The load meter, model TM-50, allows the engine to be loaded with a maximum capacity of 50 horsepower at a speed of 1500 rpm. The system consists of several key components: a pressure gauge to monitor water pressure, a flow meter to measure the water intake, and load cells to record the weight in kilograms. A rotary speed meter is attached to the rotating shaft to measure the engine's rotational speed. The experimental setup is equipped with a measurement panel that includes various scales for data collection. Figures 2 and Diagram 1 illustrate all the devices and components used in the experiment.

Fig 2: The engine and devices used in the test.

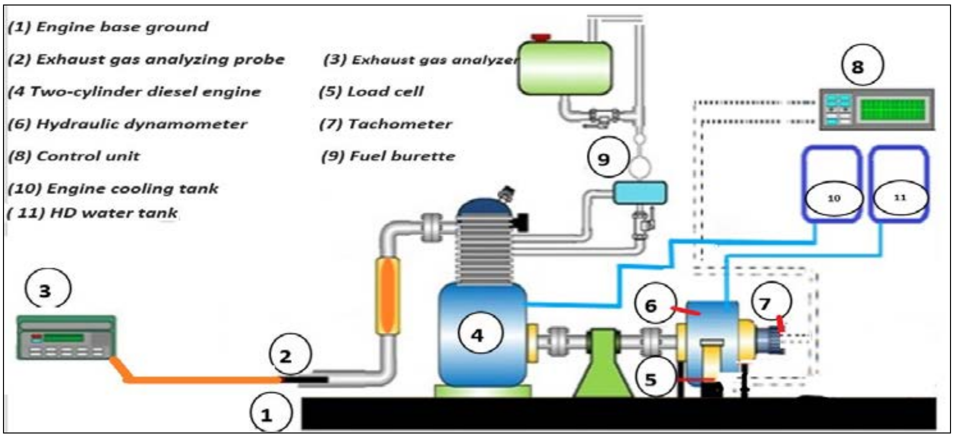

Diagram 1: Schematic diagram of all devices used in the test

The tests commenced by operating the engine on conventional diesel fuel to establish baseline performance data. Subsequently, the engine was tested using extended fuel blends with conventional diesel. The fuel blend used in these tests consisted of 90% diesel and 10% DWL. During these experiments, critical data were recorded, including engine speed, fuel consumption, pressure differences in the air stream, engine load, and exhaust emissions. This data provides insights into the performance of the extended fuel blends in comparison to conventional diesel.

The measurement panel is equipped with digital displays that provide essential information, including fuel consumption in cubic milliliters per second, load weight in kilograms, temperature in degrees Celsius, pressure differences in the manometer connected to the air intake flow meter in millimeters, and engine speed in revolutions per minute. An automotive exhaust gas analyzer (HPC501) was employed to measure the levels of various emissions, with a particular focus on methane (CH_4) emissions in this study. This device facilitates the evaluation of the engine's fuel combustion efficiency and its contribution to air pollution, as depicted in Figure 3.

Fig 3: Emission analyzer device

The obtained data were used to calculate the test engine's performance parameters, including brake power, brake-specific fuel consumption, and brake thermal efficiency. Calculating engine performance coefficients requires the application of mathematical equations.

The fuel mass flow value ($\dot{m}_{fuel}$) was found through the fuel volumetric flow ($\dot{\forall}_{fuel}$) and fuel density (ρ_{fuel}) According to the following equation [19, 20] and [21]

$$\dot{m}_{fuel} = \rho_{fuel} \times \dot{\forall}_{fuel} \quad (1)$$

The brake power is determined by measuring the braking torque (τ) with the crankshaft's force and rotational speed (N) gauges. Therefore, the value of the braking power is calculated using the following equation. [19, 20] and [21].

$$\text{BP} = \frac{2\pi}{60} N \times \tau \quad (2)$$

Where the engine torque was calculated from the following equation:

$$\tau = F \times b \quad (3)$$

The force was calculated from the following equation:

$$\text{F} = \text{M} \times \text{g} \quad (4)$$

Where b = 0.242 m represents the balance arm of the load scale.

The brake-specific fuel consumption rate (BSFC) indicates the amount of fuel an engine consumes to produce power. It is calculated by dividing the fuel flowing into the engine by the brake power (BP). The following equation was used [19, 20] and [21].

$$BSFC = \frac{\dot{m}_{fuel}}{BP} \quad (5)$$

The thermal energy supplied to the test engine comes from the heat content of the fuel introduced into the combustion chamber and is calculated using the following equation [19, 20] and [21].

$$\dot{Q}_{in} = \dot{m}_f \times LHV \quad (6)$$

The braking thermal efficiency is the ratio of the braking power in the engine crankshaft to the power resulting from fuel combustion and is calculated using the following equation [19, 20] and [21].

$$\eta_{thb} = \frac{BP}{Q_{in} * \eta_c} \quad (7)$$

Whereas the value of combustion efficiency (η_c) It was considered equal to 97%.

3. Results and discussion

3.1 Brake power (BP)

Engine brake power is the effective engine power output. Figure 4 show how brake power is related to rotational speed at 100% diesel fuel and all test blend. From the figure, one can see that power is increased with an increase in engine speed. In addition, the figure indicates that power increases with constant speed against rising load at 50% and 66% rates at 1850 rpm when compared with a 2 kg load to another load, arriving at a maximum value of 3205 watts with a 6 kg load for all blends. This is because an increase in load leads to more torque, thus contributing to more braking power, which boosts combustion and produces more power. Moreover, one can see that the break power is the same for all test blends at a particular speed and constant load since the calculation of break power is mainly a function of both speed and torque, which is a factor of the load. These findings are consistent with those of previous studies [22] and [23].

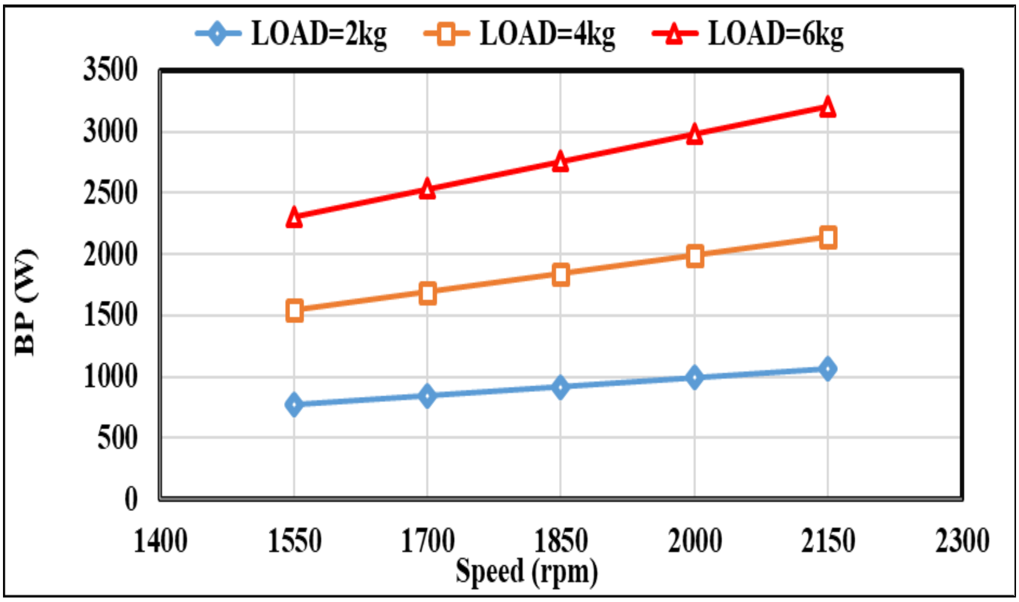

Fig 4: Brake Power (BP) With Rotational Speed for Diesel D100% And 10% DWL Blends.

3.2 Brake specific fuel consumption (BSFC)

Figure 5 show the BSFC trend at various loads (2, 4, and 6 kg) at a speed of 1850 rpm, with various types of fuel: (D100%) and (D90%-DWL10%). It can be seen that BSFC decreases progressively with a rise in load for all types of fuel. Although this reduction in BSFC might seem desirable at first glance, a more precise interpretation of the data depends on the context of engine operation. At elevated loads, the engine delivers more power, which reduces the comparative fuel consumption per unit of power produced (i.e., lower BSFC). However, this does not mean that the engine is using less fuel by absolute measure. To the contrary, the amount of fuel consumed increases with the load due to the higher energy requirement [24]. However, the fuel is being utilized more efficiently, increasing the output power. Comparing the fuel blends, the D90%-DWL10% blend achieves the highest BSFC for all load conditions, with the lowest BSFC for conventional diesel (D100%). This pattern primarily results from the lower calorific value and cetane number of DWL compared to conventional diesel, such that a larger amount of fuel needs to be burned to generate the same output power, leading to an increase in fuel consumption. Furthermore, the physical properties of DWL, including high viscosity, density, flash point, ignition delay, and low cetane number, hurt the combustion process. These properties can lead to incomplete combustion, higher levels of unburned fuel, and reduced thermal efficiency [25]. Collectively, these factors account for the apparent rise in fuel consumption with an increased ratio of DWL blend. Thus, BSFC has an inverse relationship with the calorific value and density of the fuel; with a reduction in the calorific value and density of the fuel, BSFC increases. However, the trend between BSFC and engine load is not straightforward. Although specific fuel consumption falls with rising load, fuel consumption increases as the engine works harder to satisfy the increased load requirements [26] and [27].

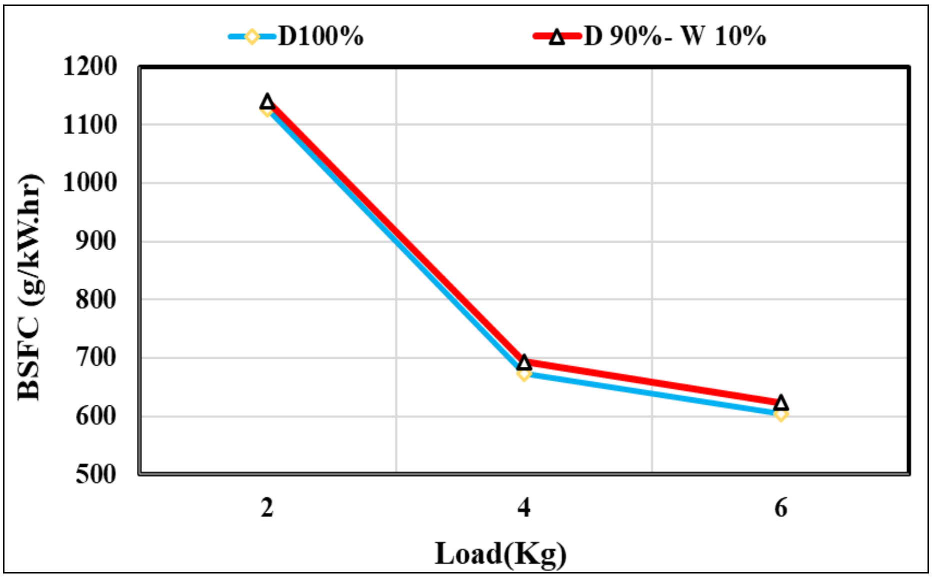

Fig 5: BSFC Variation with Loads at A Rotational Speed Of 1850 RPM.

3.3 Brake thermal efficiency (BTE)

Figure 6 illustrates the variation in BTE with engine load, ranging from 2 to 6 kg, at 1850 rpm, using conventional diesel fuel (100% D) and a 10% DWL blend. The figure demonstrates that BTE improves as engine load increases, irrespective of fuel type. This trend aligns with typical engine performance characteristics, as higher loads generally enhance combustion efficiency by increasing in-cylinder temperature and pressure. Among the tested fuels, 100% D demonstrates the highest thermal efficiency across all load conditions. Conversely, BTE progressively decreases with a 10% DWL blend. This decline in thermal efficiency can be attributed to several factors. DWL generally exhibits poorer combustion properties compared to conventional diesel, including a lower cetane number, inferior ignition quality, higher viscosity and density, the presence of heavy non-combustible materials, and an elevated flash point [25]. These drawbacks may contribute to incomplete combustion, preventing the complete conversion of the fuel's chemical energy into mechanical work. Additionally, heavier hydrocarbons or residual impurities in the DWL may interfere with air-fuel mixing and compromise combustion dynamics within the engine cylinder [28]. All of these factors contribute to the interrelationship between BTE and BSFC. When BTE decreases due to incomplete combustion or increased energy losses, greater fuel consumption is required to achieve the same output, as observed with blends containing 10% DWL [29].

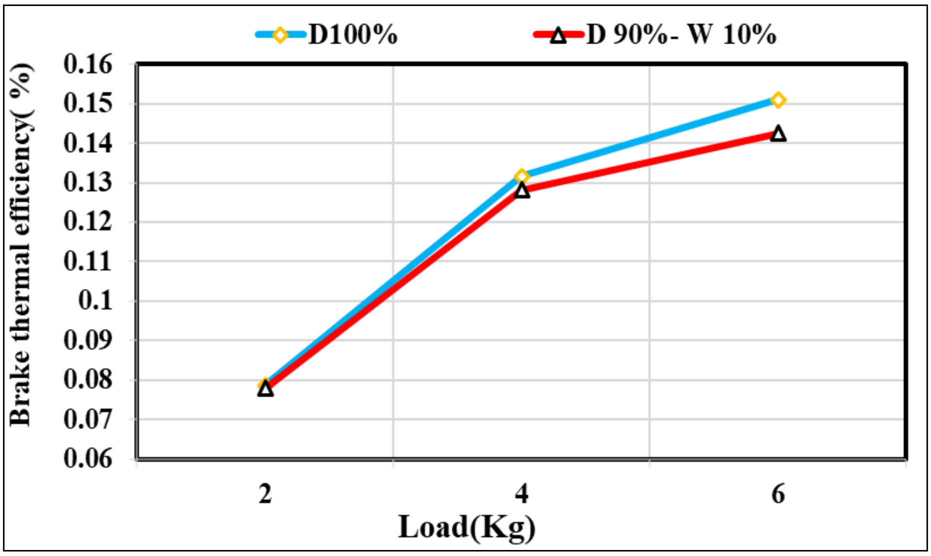

Fig 6: Brake Thermal Efficiency with Load At Speed 1850 rpm.

3.4 Methane gas emissions (CH_4)

Figures 7, 8, and 9 illustrate the analysis of CH_4 emission behavior from an engine operating on conventional diesel fuel and its blend with 10% (DWL) under three load conditions (2, 4, and 6 kg) and engine speeds ranging from 1550 to 2150 rpm. This study aims to assess the impact of incorporating DWL into fuel blend on environmental emissions, particularly methane emissions, a potent greenhouse gas [30]. Upon examining the figures, it is evident that methane emissions are relatively high at low speeds and across all loads, before decreasing at a specific speed of 1850 rpm. The most significant reduction occurs at a 4 kg load, which is attributed to the engine reaching its optimal operating point. At this load and speed, emissions decrease due to elevated temperatures, which promote complete combustion. Additionally, the improvement in the air-to-fuel ratio reduces fuel consumption, enabling the engine to operate efficiently under optimal temperature and pressure conditions [31]. As speed increases, methane emissions rise due to higher fuel demand, increasing methane emissions .The scientific mechanisms behind methane formation are primarily linked to incomplete combustion [32]. This occurs when oxygen does not fully react with the fuel's hydrocarbons to convert them into carbon dioxide, leading to the formation of unburned hydrocarbon gases such as methane. Several factors can contribute to this process, including low temperature in the combustion chamber or insufficient oxygen during combustion.

As shown in Fig. 7, the D90-W10 fuel blend demonstrates a 14.28% reduction in methane emissions at a speed of 1850 rpm and a 2 kg load compared to conventional diesel. This change in emissions reflects the influence of DWL on the combustion process. DWL enhances combustion efficiency at a 2 kg load, leading to a reduction in methane emissions.

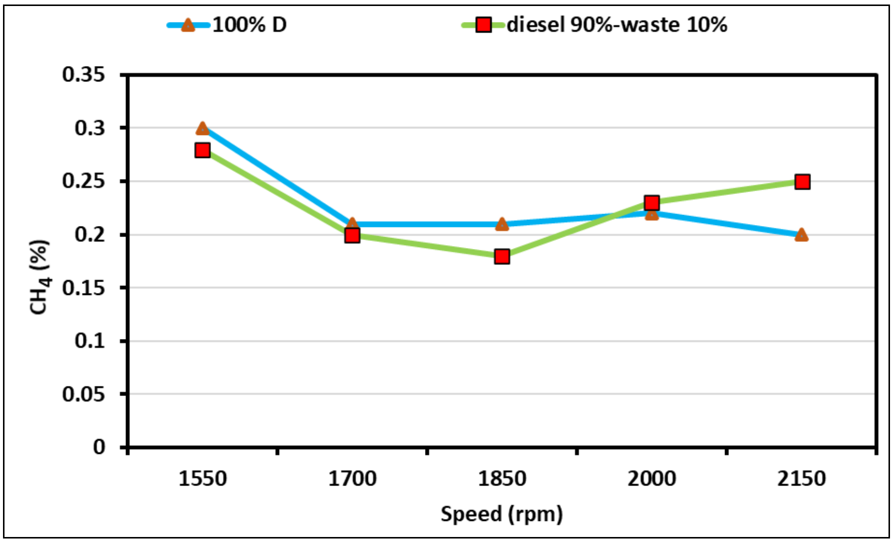

Fig 7: CH_4 emissions Versus Speed for Blends D100%, D90%+W10% At Load 2 Kg.

The load is increased to 4 kg at the same speed (1850 rpm), as shown in Fig. 8, the D90-W10 blend shows a more substantial reduction in methane emissions, reaching 27.08%. This suggests that the blend operates more efficiently at the higher load. As the load increases, the engine's demand rises, leading to higher fuel consumption and increased temperatures within the engine. Given that DWL contains components that may enhance combustion, it helps reduce methane emissions under these conditions. The engine operates more efficiently at medium loads, facilitating more complete combustion, which accounts for the significant decrease in methane emissions [31].

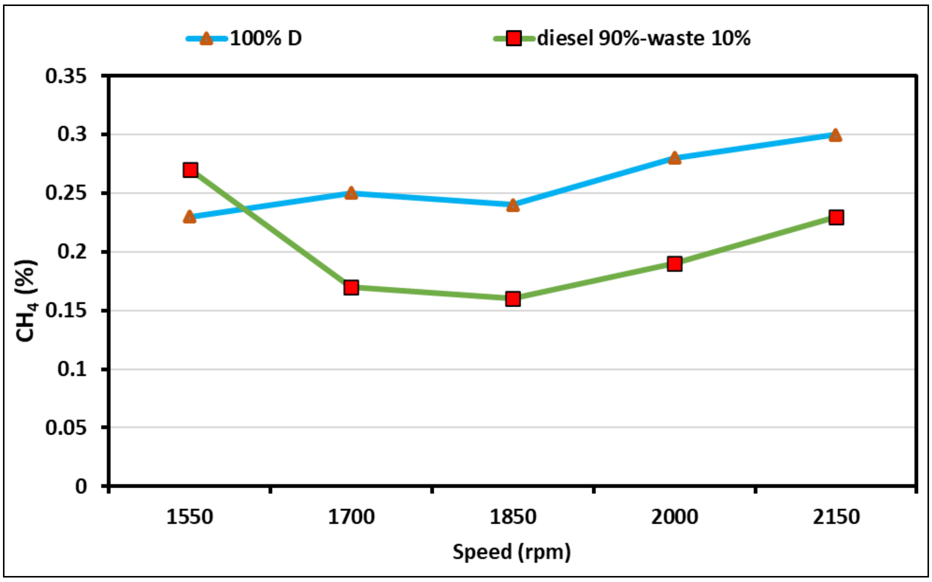

Fig 8: CH_4 emissions Versus Speed for Blends D100%, D90%+W10% At Load 4 Kg.

When the load is further increased to 6 kg, as shown in fig.9, the data reveal another reduction in methane emissions of 9.09% compared to conventional diesel at the same speed (1850 rpm). This reduction is smaller than the one observed at medium load, suggesting that the benefits of using DWL diminish as the load increases. Nevertheless, the decrease in methane emissions persists, indicating that DWL continues to contribute to improved combustion even under high-load conditions, albeit the effect becomes less pronounced as the load increases [11].

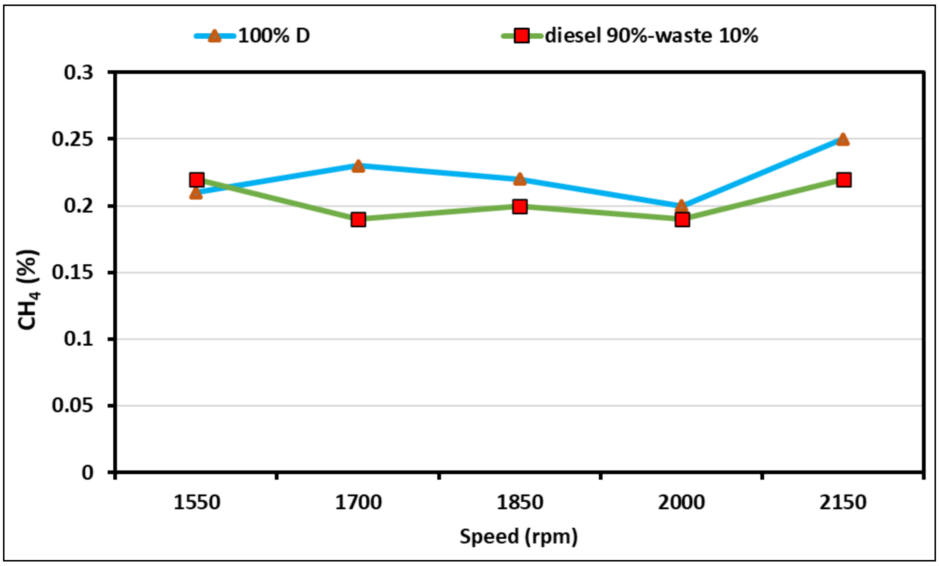

Fig 9: CH_4 emissions Versus Speed for Blends D100%, D90%+W10% At Load 6 Kg.

Thus, incorporating DWL into diesel generally results in reduced methane emissions, particularly under medium-speed and medium-load engine conditions. However, the effects of this addition vary depending on speed and load, with the benefits being more significant at lower to medium loads. The addition of DWL can enhance combustion, leading to lower methane emissions, although the effect is not always consistent across all loads and speeds. This variability may be attributed to the chemical and physical properties of the DWL, including temperature, pressure, viscosity, density, cetane number, and volatility, which influence the fuel combustion process in the engine and thereby mitigate methane formation [33] and [11].

Conclusions

1. Blending traditional diesel with 10% waste-derived fuel (90%D + 10%W) resulted in an increase in specific fuel consumption (BSFC) with higher loads, 2,4, and 6 kg. This increase is attributed to DWL's physical properties, such as its lower calorific value, higher viscosity, reduced cetane number, and higher flash point, which hinder effective combustion, particularly under loads.
2. A reduction in brake thermal efficiency (BTE) across the tested load range (2-6 kg) at 1850 rpm. This indicates that blending DWL with conventional diesel reduces the efficiency of converting thermal energy into mechanical power, especially at higher loads. The decrease is primarily due to the physical properties of the extracted fuel.
3. The blend significantly reduced methane emissions, a potent greenhouse gas, with a reduction of 14.28% (at 2 kg load), 27.08% (at 4 kg load), and 9.09% (at 6 kg load) at 1850 rpm. The maximum reduction in emissions occurred at the medium load (4 kg), indicating load-dependent combustion efficiency.
4. Despite the environmental benefits of reduced methane emissions, the addition of DWL to diesel results in a slight decrease in engine performance, especially at higher loads. The findings suggest that DWL can serve as a viable alternative fuel in certain cases. Still, its impact on engine efficiency and performance should be carefully considered under various operational conditions.
5. Despite the minor losses in efficiency, the 90%D + 10% DWL blend demonstrated a significant reduction in methane emissions at lower loads, offering a viable route for recycling waste engine oils while addressing greenhouse gas emissions issues in diesel engines.

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