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Assessment of Waste Cooking Oil Biodiesel as a Sustainable Fuel: Combustion and Performance Evaluation in a CI Engine

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Abstract

This study presents a comprehensive evaluation of waste cooking oil biodiesel blends (10%, 20%, and 25% by volume) in a single-cylinder, water-cooled diesel engine operating at constant 1500 rpm under varying load conditions. FTIR spectroscopy revealed characteristic biodiesel signatures, including strong ester carbonyl absorption at 1740 cm^{-1} and weaker hydrocarbon peaks (2800-3000 cm^{-1}) as compared to diesel. The biodiesel, synthesized through optimized transesterification (0.85% KOH catalyst, 6:1 methanol-to-oil ratio, 60°C reaction temperature, 600 rpm agitation speed, and 1-hour duration), exhibited key fuel properties including a calorific value of 38.45 MJ/kg and viscosity of 4.5 cSt. So, pure biodiesel is not recommended for this engine without modifications. Performance analysis revealed that while the 25% blend achieved 12.57% higher indicated power at 4 kW brake power compared to diesel, it suffered a 9.60% reduction in mechanical efficiency and a 19.61% decrease in brake thermal efficiency. The specific fuel consumption increased progressively with blend ratio, reaching 36.94% higher values for the 25% blend relative to diesel. Combustion characterization demonstrated significant differences, with peak cylinder pressure increasing by 5.77% (72.4 bar vs. 68.5 bar for diesel) and ignition delay shortening by 2.1 crank angle degrees for the 25% blend at full load conditions. The cumulative heat release rose by 5.93%, while net heat release decreased by 12.40% due to elevated exhaust gas temperatures that were 42.29% higher than diesel. Notably, the 20% blend emerged as the optimal compromise, delivering a 3.62% increase in peak cylinder pressure (63.2 bar) with only a 7.01% mechanical efficiency penalty. The smoke emissions from every fuel blend tested fell below the maximum level permitted by the ISO 11614 standard, confirming their environmental safety. These findings provide critical insights into the trade-offs between enhanced combustion characteristics and reduced thermal efficiency when utilizing WCO biodiesel blends in conventional diesel engines

Keywords: Waste Cooking Oil**,** Biodiesel, Diesel engine, Combustion characteristics, Engine performance

1. Introduction

As the demand and cost of traditional crude fuel increases, researchers are focusing on finding alternative sources of fuel that offer similar performance characteristics while producing fewer emissions. These alternative fuels can be derived from synthetic sources such as waste plastic and tires, which are by-products of petroleum distillation. Another alternative is biodiesel, which is obtained from both edible and non-edible crops and animal fat. Biodiesel has advantages and disadvantages compared to conventional diesel. Although it is carbon-free and produces lower CO, HC, and CO2 emissions, it has a lower calorific value and higher viscosity, which limits its use to blending with diesel up to 20%.

Biodiesel is a promising alternative to petroleum diesel, which is facing a significant hurdle due to higher feedstock costs (Semakula and Inambao, 2021). Refined vegetable oil is the major feedstock for industry standard, which can account for a staggering 80-90% of total biodiesel production expenses (Tabatabaei et al., 2019). Waste cooking oil (WCO) emerges as a potential replacement for refined vegetable oil.

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Economically, WCO is significantly cheaper than its refined vegetable oils and has a benefit from an environmental perspective. WCO reuse presents a sustainable solution. Improper disposal of used cooking oil can pollute water sources, but conversion into biodiesel eliminates this risk. Additionally, WCO biodiesel is a renewable resource, further promoting environmental responsibility. In addition, WCO avoids the competition for land use associated with traditional vegetable oils. Unlike these feedstocks, WCO doesn't compromise food security as it's derived from a waste product – used cooking oil (Manikandan et al., 2023). When considering the cost of production, biodiesel made from waste cooking oil can be more economical compared to petroleum diesel. However, to achieve a cost level that matches that of petroleum diesel, it's important to lower the cost of waste cooking oil so that large quantities can be produced affordably (Gopan et al., 2021).

Reusing cooking oil for frying is a common practice, driven by cost savings. However, this method comes with potential downsides for human health (Ganesan et al., 2018). Repeated exposure to high temperatures during frying causes chemical changes in the oil, potentially leading to the formation of harmful compounds and a change in surface tension and color while an increase in viscosity and specific heat(Nayak et al., 2016). While the exact health effects of consuming these altered oils are not fully understood, further research is warranted (Monika et al., 2023).

Instead of discarding this degraded oil, scientists have found ways to repurpose it as energy. Several studies have explored various techniques for converting waste cooking oil (WCO) into usable energy and fuels. These methods include hydrotreating (Bezergianni et al., 2010), gasification (Tamošiūnas et al., 2019), pyrolysis (Lam et al., 2016). However, these methods often require high energy inputs or produce lower-quality outputs. Among these, transesterification (Cordero-Ravelo and Schallenberg-Rodriguez, 2018) stands out as a cost-effective, high yield and environmentally friendly approach for transforming WCO into biodiesel, a renewable energy source (da Silva et al., 2022; Nabgan et al., 2022). Transesterification is a catalyst-driven chemical reaction between WCO and alcohol, which yields biodiesel as the main product alongside glycerol, a valuable byproduct with diverse applications in industries like personal care, pharmaceuticals, cosmetics, and food (Aghbashlo et al., 2018b, 2018a). The recovery and the quality of biodiesel through transesterification depends on the nature and the amount of catalyst and alcohol, along with reaction time, reaction temperature, and reactor type (Aghbashlo et al., 2018a; Gaur et al., 2021; Mohadesi et al., 2020; Zik et al., 2020). **

The chemical composition and thermo-physical properties of biodiesel vary significantly depending on the feedstock source, as different raw materials produce distinct methyl ester profiles. These variations directly influence key fuel characteristics, ultimately affecting engine performance, combustion behavior, and emission outputs (Adhikesavan et al., 2022). Multiple independent studies have systematically evaluated the performance characteristics of waste cooking oil (WCO) biodiesel in compression ignition engines. Research by Wcisło et al. (Wcisło et al., 2024) demonstrated that while prolonged frying increases biodiesel viscosity due to polar compound accumulation, other critical fuel properties including flash point and density remain largely unaffected. Their engine tests revealed comparable thermal efficiency between WCO and virgin oil biodiesel, with some studies noting marginally higher calorific values in waste-derived fuels (Adhikesavan et al., 2022; Wcisło et al., 2024).

The collective findings from several research groups (Rokhade et al., 2023; Srithejas et al., n.d.) indicate that WCO20 blends offer an optimal compromise, reducing carbon monoxide emissions by 4-12% and hydrocarbon emissions by 15-20% compared to petrodiesel. This emission improvement comes with a consistent but manageable 5-9% increase in NOx output across studies, attributable to biodiesel's oxygen content promoting more complete combustion. Muralidharan and Vasudevan (Muralidharan and Vasudevan, 2011) tested 20-80% waste cooking oil biodiesel blends in a variable compression ratio (18:1–22:1) engine at 1500 rpm. The 40% blend at 21:1 compression ratio achieved optimal efficiency (highest BTE, lowest SFC) but slightly increased NOx and HC emissions. Higher biodiesel blends also showed greater combustion pressure and longer ignition delay compared to diesel. Can (Can, 2014) found that 5% and 10% biodiesel fuel addition resulted in slightly increment on break specific fuel consumption (up to 4%) and reduction on break thermal efficiency (up to 2.8%).

Combustion analysis reveals important nuances in engine behavior. As demonstrated by Meng et al. (Meng et al., 2023), the higher cetane number of WCO biodiesel leads to shorter ignition delays but longer combustion duration, particularly noticeable in common-rail injection systems. While in another research, An et al. (An et al., 2013) tested waste cooking oil biodiesel in a common-rail diesel engine under varying injection pressures (80-160 MPa) and timings (0°-25° BTDC). They found slightly lower peak pressure (CPM) and heat release rate (HRR_{max}) with longer ignition delay (ID) in comparison to diesel, but improved smoke, CO, and HC emissions at higher injection pressures—though NO_x increased. The viscosity challenges at low engine loads identified by multiple researchers (Adhikesavan et al., 2022; Int ; Tran et al., 2021) suggest potential optimization opportunities through fuel system modifications or additive treatments.

While numerous studies have investigated biodiesel production from waste cooking oil (WCO), most have focused on single-use or moderately degraded oils with relatively low viscosity, and standard blend ratios such as B5, WCO10, and WCO20. These studies often overlook the real-world scenario of using severely degraded, multiple-times-used WCO, which is common in developing regions and typically exhibits high viscosity levels. Additionally, prior research has mainly emphasized regulated gaseous emissions (CO, HC, NOx), with limited attention to practical emission indicators like smoke opacity. In this study, biodiesel blends of 10%, 20%, and 25% were prepared from WCO with a viscosity of approximately 4.5 cSt, and tested for their effects on engine performance, combustion characteristics, and opacity-based emissions. The inclusion of higher blend ratios and the use of low-quality, heavily used WCO as feedstock provide new insights into the viability of such biodiesel in real-world engine applications. This work fills a critical gap by demonstrating how degraded WCO affects engine behavior, especially in terms of combustion and visible emissions, offering valuable data for regions with limited fuel refinement and emission control infrastructure.

2. Materials and Methods

The investigation was conducted in two phases. The first step was the production and fuel characterization of biodiesel, which was conducted in the bio-energy laboratory of Nepal Academy of Science and Technology (NAST), and engine testing, which was conducted at the Automobile Research Laboratory of Thapathali Campus.

2.1 Biodiesel Production

The stepwise production of biodiesel from waste cooking oil as shown in Figure 1 involves the following steps.

2.2 Sample Collection

Waste cooking was collected from various locally available restaurants of Kathmandu and Lalitpur.

a. Filtration

The collected waste cooking oil contains some minute particles of food, so it needs to be filtered to remove the remains of the food particles.

b. *FFA treatment*

Free fatty acid treatment is vital in determining the number of steps required for biodiesel production. When the FFA value is lower than 2%, single-step transesterification is performed. When the FFA value is greater than 2%, at first, acid treatment is conducted, which is later followed by transesterification. Acid treatment is acid-catalysed esterification, while the transesterification is base-catalysed. In this study, the FFA was found to be 1.93%, indicating that single-step transesterification is sufficient.

c. *Transesterification*

The optimum condition for the biodiesel production from a single-step transesterification is 0.85 % KOH by weight, 6:1 molar ratio of methanol to oil, agitation speed of 600 rpm, and reaction time of 1 hour.

d. *Purification*

The product of transesterification was placed in a separating funnel. The lower layer is of glycerol, and the upper layer is of biodiesel. The obtained biodiesel contains traces of methanol, so it needs to be washed several times. Hot distilled water is used to wash the biodiesel until the remaining water shows a neutral p^H.

e. *Drying*

Once the purification stage was completed, the biodiesel is kept in a hot air oven maintained at 110 °C for a duration of 6-8 hrs to make it free of moisture.

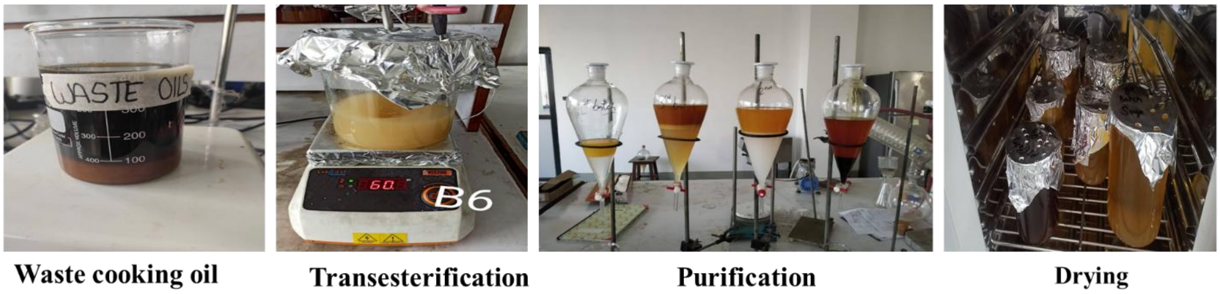

Figure 1. Stepwise biodiesel production from waste cooking oil (WCO).

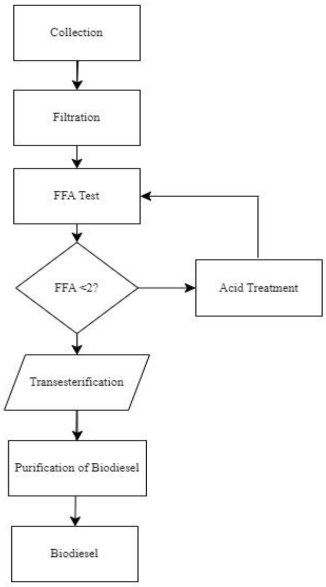

Figure 2. Layout of Biodiesel Production

2.3 Biodiesel Blend Preparation

A total of three blends of WCO biodiesel were prepared by mixing methyl ester (the final product of transesterification) in volumetric ratios of 10%, 20%, and 25% with diesel in proportions of 90%, 80%, and 75%, respectively. After blending, the mixture was well shaken for about 5 minutes to ensure proper mixing.

2.4 Engine Specification

Figure 3. Engine Test Setup

Table 1. Engine Configuration

Engine Type	Four-stroke, single-cylinder, water-cooled, naturally aspirated multifuel VCR test engine
Number of cylinders	1
Volume capacity	661 cc
Power	3.5 kW
Speed	1500 rpm
Compression Ratio	17.5:1

2.5 Engine Operating Conditions

Table 2. Engine working conditions

Parameter	Value
Compression Ratio	17.5
Injection Pressure	220
Nozzle hole	3
Start of Injection	-23

2.6 Technical Details of the Opacimeter

The Opacimeter model RTM 430 operates with power supplied via the Emissions System Analysis (ESA), Bosch Emissions Analysis (BEA), or Emissions Analysis Tester (EAM). It features a measuring chamber length of 432 mm and is designed to function effectively within a relative ambient air humidity of less than 90% without thawing. The device is suitable for application in temperature ranges between +2 °C and +40 °C, with a maximum exhaust-gas temperature at the device input of 200 °C. The Opacimeter has a protection class of IP 33 and its dimensions measure 594 mm in width, 203 mm in height, and 151 mm in depth. It weighs approximately 8 kg and produces noise emissions below 70 dB (A). Additionally, this product complies with electromagnetic compatibility standards as a Class A device according to EN 5502.

3. Results and Conclusion

3.1 Biodiesel Production

The optimum conditions for achieving a biodiesel yield of 88.65% were determined to be a methanol-to-oil molar ratio of 6:1, a KOH catalyst concentration of 1 wt.% of the oil, a reaction time of 60 minutes, and an agitation speed of 500 rpm.

3.2 Fuel Property

Table 3. Physicochemical Properties of diesel and biodiesel

Property	Diesel	Raw WCO	10WCO	20WCO	25WCO	Test Method
Density@15 °C	835	920.14	839.6	843.9	844.6	ASTM D 4052
Kinematic Viscosity@40 °C, cSt	2.42	6.5	2.77	2.87	2.95	ASTM D 445
Flash Point (Minimum), °C	42	-	45^0C	46^0C	48^0C	IS:1448
Calorific Value (kJ/kg)	42954.95	28450.92	42809.46	41663.96	40234.54	Bomb Calorimeter

Distillation,95%(v/v), Recovery, °C, Max	360	-	312	355	333	ASTM D 86/P 18/IP 123

3.3 Fourier Transform Infrared (FTIR) Spectroscopy Test:

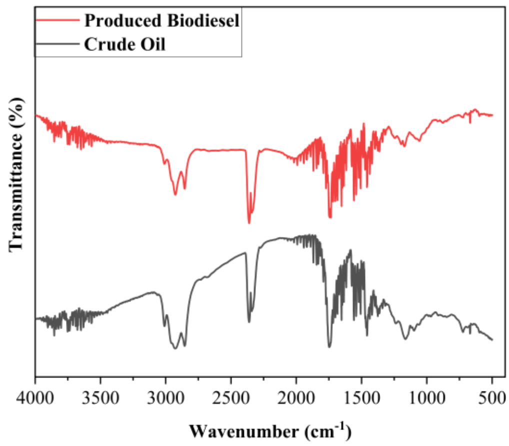

Figure **4.** Comparative study of the FTIR spectra of raw waste oils and their corresponding biodiesel products

FTIR analysis of waste cooking oils and biodiesel is illustrated in Figure 4. The transesterification reaction involves replacing the glycerol-backbone in the triglyceride with methanol, forming the methyl ester (biodiesel) and glycerol. This graph clearly illustrates the disappearance of functional groups related to glycerol and the appearance of a new functional group related to the methyl ester.

The successful formation of biodiesel can be confirmed through distinct changes observed in the FTIR spectra. The most crucial evidence is the appearance of a new, sharp, medium-intensity peak in the biodiesel spectrum (red) within the fingerprint region between 1430 and 1440 cm^{-1}, which corresponds to the O– CH3 bending vibration of the methyl ester (FAME) group. This indicates that the methyl group from methanol has successfully attached to the fatty acid chain, confirming the transesterification reaction. In contrast, the characteristic peaks of the crude oil (black) spectrum between 1000 and 1200 cm-1, particularly around 1190 cm-1 and 1035 cm-1 attributed to the C–O stretching vibrations of the glycerol backbone in triglycerides—are reduced or shifted in the biodiesel spectrum, signifying the consumption of triglycerides. Additionally, the absence of a broad O–H stretching band in the 3200–3500 cm-1 region in the biodiesel spectrum suggests effective removal of glycerol and water during purification, as crude oil or unpurified biodiesel typically exhibit this feature. Both spectra consistently display strong absorbance around 1740–1750 cm-1, corresponding to the C=O carbonyl stretch of ester groups, and peaks between 2800–3000 cm-1 representing C–H stretching vibrations of long fatty acid chains, which remain unchanged through the reaction. Overall, the emergence of the O–CH3 peak and the diminished O–H band provide clear, visual, and scientific evidence of successful biodiesel synthesis and purification.

3.4 Performance Characteristics

The relation of indicated power with brake power for various blends of biodiesel is illustrated in the Figure 3. With the rise of brake power, the indicated power goes on increasing. It was found that blends of biodiesel have higher indicated power as compared to diesel. As the blending ratio goes up, the calorific value of biodiesel blends declines, causing fuel consumption to increase, which is the primary cause of this trend. On comparing the change in indicated power for the range of brake power from 1 kW to 4 kW, it was found that IP increases by 7.23%, 8.99%, and 12.57% for 10WCO, 20WCO, and 25WCO respectively.

Theoretically specific fuel consumption is the ratio of fuel consumption per unit power per unit time. Specific fuel consumption has a direct link with calorific value. The higher the calorific value, the lower the specific fuel consumption (SFC). As shown in Figure 4, the specific fuel consumption of biodiesel blends increases with the blending ratio across different brake power levels. On increasing the blending ratio from 10WCO, 20WCO, and 25WCO, the SFC increases by 32.24%, 33.22%, and 36.94% respectively.

Mechanical efficiency shows the effectiveness in terms of brake power and indicated power. Mechanical efficiency is the ratio of Brake power to Indicated power. The test was performed on a constant BP diesel engine. Irrespective of the blends, for the same Load, the same indicated power was attained in the research engine. Diesel offered a lower indicated power, so it has a higher mechanical efficiency than the blends of biodiesel. As the proportion of biodiesel in the blend rises, mechanical efficiency tends to decrease. Mechanical efficiency drops by 3.91%, 7.01%, and 9.60% on average with blending ratios of 10WCO, 20WCO, and 25WCO, respectively. The relation between mechanical efficiency and Brake power for various blending ratios is shown in Figure 5.

Biodiesel offered a higher Exhaust gas (EGT) temperature as compared to the conventional diesel. This is attributed to the oxygen content in biodiesel and its lower calorific value compared to diesel. As shown in Figure 6, EGT rises with increasing brake power across various biodiesel blends, with higher blending ratios leading to greater EGT. For the blending ratios from 10WCO, 20WCO, and 25WCO, the EGT increases by 39.24%, 41.35%, and 42.29% respectively. Figure 6 illustrates the relationship between EGT and engine load for different biodiesel blends.

Brake thermal efficiency is the measure of the engine's ability to convert fuel energy into usable work. It has been found that with the rise of the blending ratio, the brake thermal efficiency decreases, due to the lower calorific value of the blends of biodiesel. On an average with the rise of the blending ratio from 10WCO, 20WCO, and 25WCO, the brake thermal efficiency decreases by 15.11%, 16.68%, and 19.61% respectively. The correlation between brake thermal efficiency and brake power for various biodiesel blends is presented in Figure 7.

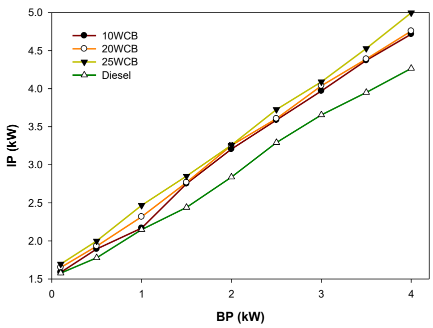

Figure 5. Relation of IP and BP

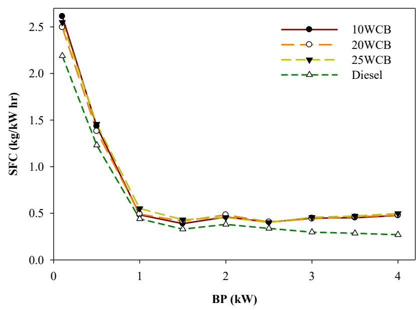

Figure 6. Relation of SFC with BP

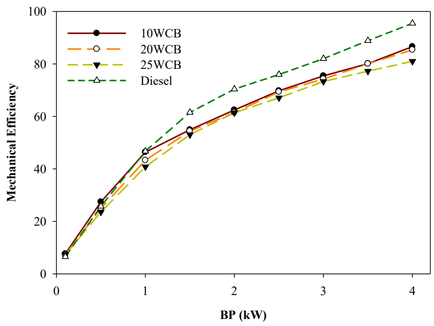

Figure 7. Relation of Mechanical Efficiency and BP

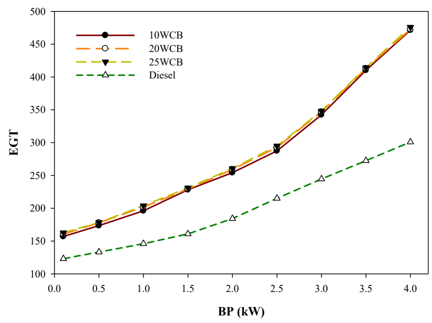

Figure 8. Relation of EGT and BP

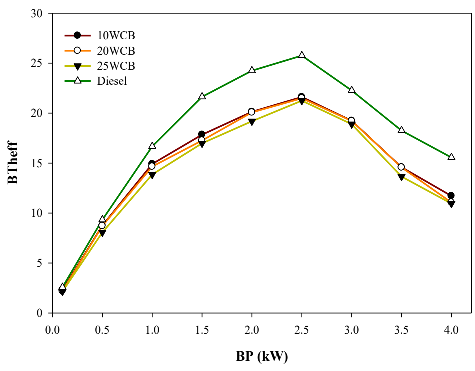

Figure 9. Relation of BTE and BP

3.5 Combustion Characteristics

The maximum cylinder pressure refers to the highest pressure generated by the combustion of fuel within the combustion chamber. Property of the fuel, such as calorific value, viscosity, and, has a straightforward consequence on the CPM of the engine.

Figure 8 shows that biodiesel blends exhibit a higher CPM compared to diesel, with CPM increasing progressively as the blending ratio rises. This is because biodiesel has a lower calorific value than diesel. So higher the fuel consumption of the fuel is desired in the cylinder, this can be observed in Figure 4. In addition to the higher fuel consumption, biodiesel has a lower ignition delay. Compared to diesel, biodiesel possesses a superior cetane index. An increase in the blending ratio leads to a higher cetane number. These blends of biodiesel demonstrate reduced ignition delay. The rise in cylinder pressure is attributed to reduced ignition delay and elevated fuel consumption. On an average with the rise of the blending ratio, it was found that CPM increases by 2.57%, 3.62%, and 5.77% respectively for the blends of 10WCO, 20WCO, and 25WCO respectively. The relation between CPM and Brake Power is shown in Figure 8.

The elevated cylinder pressure results in a higher cumulative heat release rate for biodiesel blends compared to diesel. Cumulative heat release (CHR) is the total amount of heat released by the burning of the fuel. This is the exothermic heat that is liberated by the burning of fuel. Higher fuel consumption and lower calorific value attributes for higher cumulative heat release in the combustion chamber. For 10WCO, 20WCO, and 25WCO, it was found that CHR increases by 1.98%, 2.13%, and 5.93% respectively. The relation between CHR and BP for various blends of biodiesel is presented in Figure 11. The useful heat release is the net heat release (NHR). As the brake power of the research engine is kept constant, excess heat is produced in the combustion chamber when biodiesel blends are used, resulting in losses. As a result, the mean gas temperature is elevated in the case of biodiesel blends. NHR for the blends of biodiesel for 10WCO, 20WCO, and 25WCO decreases by 7.50%, 9.83%, and 12.40% respectively, and this relation is shown in Figure 9.

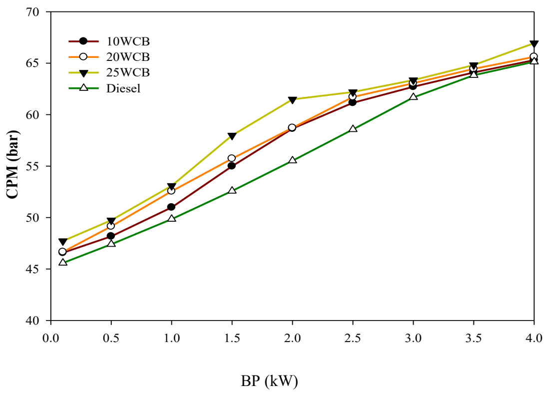

Figure 10. Relation of CPM and BP

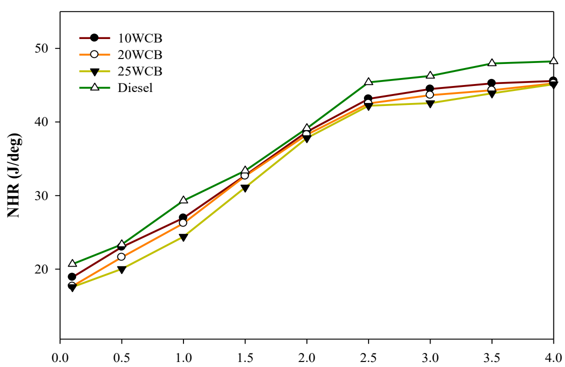

Figure 11. Relation of NHR and BP

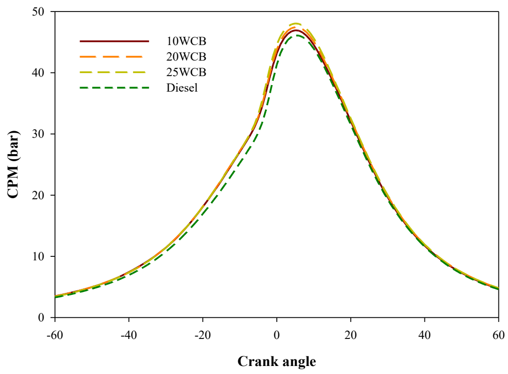

Figure 12. Relation of CPM vs Crank angle

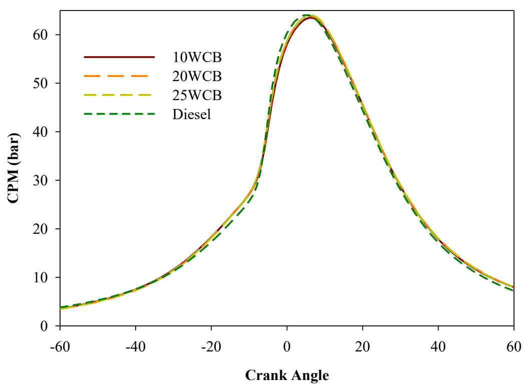

Figure 13. Relation of CPM vs Crank angle

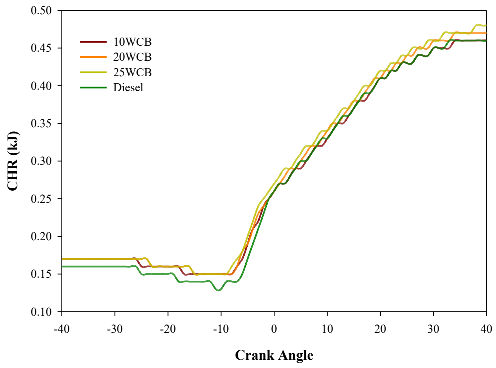

Figure 14. Relation of CHR vs Crank angle

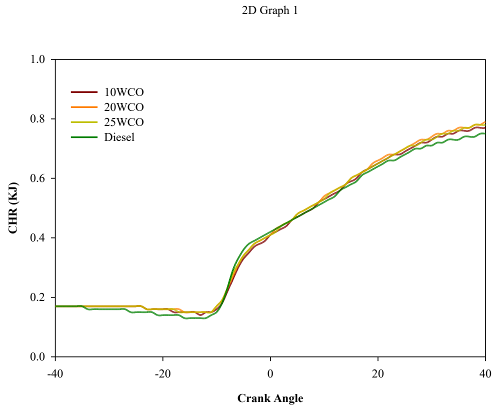

Figure 15. Relation of CHR vs Crank angle

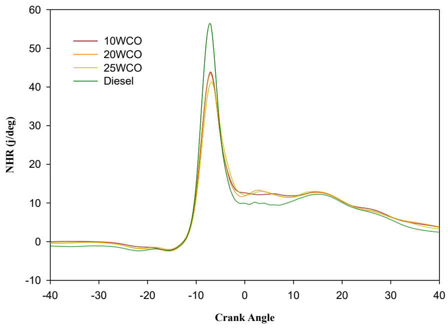

Figure 16. Relation of NHR vs Crank angle

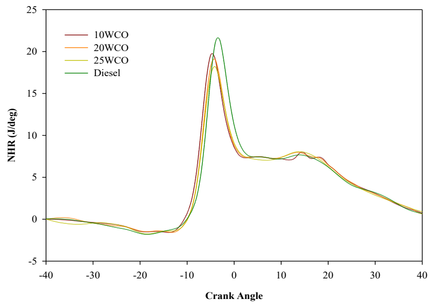

Figure 17. Relation of NHR vs Crank angle

3.6 Emission Characteristics

This investigation focused solely on smoke opacity due to the unavailability of an emission analyzer. Nevertheless, findings from Ozsezen et al. (Ozsezen et al., 2009) indicate that opacity measurements can reliably reflect emission behaviour: biodiesel, including that produced from waste cooking oil (WCO), generally reduces carbon monoxide, unburned hydrocarbons, and smoke emissions. A typical trade-off is a slight increase in nitrogen oxides, which is attributed to the higher oxygen content in biodiesel that promotes more complete combustion. According to ISO 11614, opacimeters are used to measure smoke opacity, with a maximum allowable value of 2.44 m-1 for diesel fuel. In this study, the measured opacity values for diesel, 10WCO, 20WCO, and 25WCO blends were 2.15, 1.71, 1.4, and 1.47 m^{-1}, respectively, as shown in Figure 18. The results demonstrate that increasing the biodiesel content in the fuel reduces smoke opacity, likely due to the oxygen-rich nature of biodiesel improving combustion efficiency. This aligns with the conclusions of Ozsezen et al., confirming that opacity meter data can serve as a reasonable indicator of emission characteristics.

The slight increase in opacity from 1.40 (20 WCO) to 1.47 (25 WCO) likely results from competing factors in fuel combustion. While biodiesel's oxygen content generally improves combustion, the higher viscosity of the 20WCO blend may begin to impair optimal fuel atomization. This can create localized rich combustion zones where incomplete burning occurs, generating slightly more particulate matter. The balance between improved oxygen content and compromised spray characteristics appears most favorable at the 20WCO blend ratio for this engine configuration.

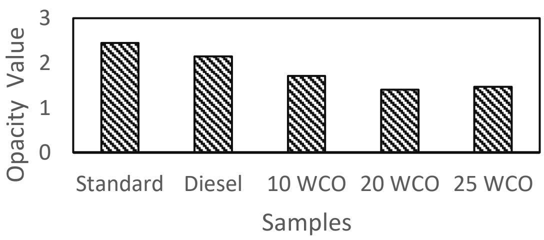

Figure 18. Opacity result of biodiesel blend & diesel

4 Conclusions

This study investigates the performance and combustion characteristics of biodiesel derived from waste cooking oil (WCO) in comparison to conventional diesel. The impact of different blend ratios (10WCO, 20WCO, and 25WCO) and engine load on engine behaviour and emissions was analyzed, including an opacity test to assess emission characteristics. The findings reveal that increasing the WCO concentration enhances certain combustion parameters, with peak cylinder pressure rising by 2.57%, 3.62%, and 5.77% for the respective blends, alongside increased cumulative heat release (1.98%, 2.13%, and 5.93%). These improvements suggest more vigorous combustion at higher WCO ratios. Furthermore, indicated power saw notable gains of 7.23%, 8.99%, and 12.57%, demonstrating the potential for higher mechanical output. However, the brake thermal efficiency decreased by 15.11%, 16.68%, and 19.61%, indicating reduced fuel economy. Elevated EGT rising by 39.24%, 41.35%, and 42.29%—point to greater heat losses, which could affect engine longevity. Despite these trade-offs, all tested blends conform to standard biodiesel properties, affirming their feasibility as alternative fuels. The study underscores that while WCO biodiesel blends improve combustion efficiency and power output, their adverse effects on thermal efficiency and exhaust temperatures necessitate further optimization to balance performance and sustainability in diesel engines.

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Declaration of interests

The authors state that they have no financial interests or personal connections that might have affected the outcomes of the work described in this manuscript.

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