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On the Influence of Engine Compression Ratio on Diesel Engine Performance and Emission Fueled with Biodiesel Extracted from Waste Cooking Oil

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Abstract: Despite the extensive research on biodiesels, further investigation is warranted on the impact of compression ratios on emissions and engine performance. This study addresses this gap by evaluating the effects of increasing the engine's compression ratio on engine performance metrics—brake-specific fuel consumption (BSFC), power, torque, and exhaust gas temperature—and emissions—unburnt hydrocarbons (HCs), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and oxygen (O_2)—when fueled with a 20% blend of waste cooking oil biodiesel (WCB20) and petroleum diesel (PD) under various operating conditions. The viscosity of the prepared fuels was measured at 25 °C and 40 °C. Experiments were conducted on a single-cylinder diesel engine under wide-open throttle conditions at three different speeds (1400 rpm, 2000 rpm, and 2600 rpm) and two compression ratios (16:1 and 18:1). The results revealed that at a lower compression ratio, both WCB20 and petroleum diesel exhibited reduced BSFC compared to higher compression ratios. However, increasing the compression ratio from 16:1 to 18:1 significantly decreased HC emissions but increased CO_2 and NO_x emissions. Engine power increased with engine speed for both fuels and compression ratios, with WCB20 initially producing less power than diesel but surpassing it at higher compression ratios. WCB20 demonstrated improved combustion quality with lower unburnt hydrocarbons and carbon monoxide emissions due to its higher oxygen content, promoting complete combustion. This study provides critical insights into optimizing engine performance and emission characteristics by manipulating compression ratios and utilizing biodiesel blends, paving the way for more efficient and environmentally friendly diesel engine operations.

Keywords: biodiesel; waste cooking oil; compression ratio; emission; performance

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1. Introduction

In recent years, there has been a significant increase in the employment of waste cooling oil in various aspects of academic or industrial settings. On the other hand, utilizing waste cooking oils in useful applications supports the principles of environmental sustainability, mitigates the accumulation of trash in landfills, and provides economically viable alternatives across multiple sectors [1,2]. Considering the global efforts to transition towards more sustainable energy sources, the utilization of waste cooling oil emerges as a crucial component of the overall solution. Furthermore, the conversion of waste cooking oil into biodiesel has experienced substantial growth. The global availability of used cooking oil (UCO) as a feedstock for biodiesel production is significant. According to estimates, the world generates approximately 41–67 million tons of UCO annually [3]. This substantial amount of UCO presents as a valuable resource for biodiesel production, considering that it can be collected from households, restaurants, and the food industry. The conversion efficiency of UCO to biodiesel varies based on factors like the quality of the oil and the technology used [4]. The global UCO supply has the potential to produce around 5 million tons of biodiesel annually [5]. This could significantly reduce the dependence on fossil fuels and lower greenhouse gas emissions. Additionally, utilizing UCO for biodiesel production promotes waste management and environmental sustainability. By diverting UCO from landfills and waterways, this practice helps mitigate environmental pollution and supports a circular economy model [6]. Overall, the widespread collection and processing of UCO into biodiesel not only offers a renewable energy source but also provides economic and environmental benefits. It is an essential component of the global transition towards sustainable energy systems [5,7]. Researchers have refined processes like transesterification, which chemically transforms the triglycerides present in the oil into biodiesel, making it a viable and economically attractive alternative to traditional fossil fuels [8,9]. In addition to its environmental benefits, the transesterification approach has economic advantages. Waste cooking oil is abundantly available, often at a low cost or even for free, making it an accessible resource for biodiesel production [10–12]. This not only reduces the demand for vegetable oils but also helps curb the environmental impact of oil extraction and transportation.

Despite the fact that there are numerous published works on the usage of biodiesel and its impact on engine performance and emission, the need for further understanding is continuing, as reported recently [13–15]. In the recent literature [16], there is limited work on the influence of the compression ratio on diesel engine performance and emission when running on biodiesel, especially biodiesel produced from waste cooking oil. Furthermore, investigating the combustion characteristics and emissions of biodiesel blends under varying compression ratios is an area of interest. It is well known that a high compression ratio would improve the thermal efficiency of diesel engines, which in turn increases the power output and torque [17,18], i.e., it is advantageous in applications where power and torque are critical, such as heavy-duty trucks and industrial machinery. On the other hand, the influence of the compression ratio on emissions is a more complex subject. A high compression ratio would raise combustion temperatures and then increase the emissions of nitrogen oxides (NO_x) [19–21]. In other words, for a newly developed fuel, it is essential to investigate the influence of the compression ratio on the engine performance and emission. Accordingly, further understanding of the influence of the compression ratio on engine performance and emission with the usage of biodiesel made of waste cooking oil motivates the current study.

In this work, conventional engine diesel performance and emission were evaluated while it was running with pure diesel or diesel blended with 20% biodiesel produced from waste cooking oil. The blending ratio was selected based on the recommendation given in the literature [22,23].

2. Materials and Methods

2.1. Fuel Blend Preparation

The waste cooking oil was converted to biodiesel using the transesterification method, as described in Al-lwayzy and Yusaf [24]. The procedure started by cleaning 1 L of WCO from impurities using microfilter bags and then heating to a temperature of 70 °C for 10 min to remove any water and to speed up the reaction. A magnetic stirrer was used to mix the oil with a mixture of methanol and sodium hydroxide (NaOH). In total, 250 mL of methanol and sodium hydroxide were added to every liter of oil. The entire solution was kept in a separate funnel for almost 24 h, and a clear separation layer between the glycerol and the pure biodiesel was achieved. The biodiesel was then removed and washed with water, and water was removed using a centrifuge device to obtain pure biodiesel. The water dissolves and carries away the contaminants, which are then separated from the biodiesel. This process may be repeated several times with fresh water until the biodiesel is clear, indicating the removal of most impurities. To prepare WCB20, 200 mL of WCB100 was mixed with 800 mL of pure diesel. The viscosity and calorific values were measured for the fuel using a viscometer and bomb calorimeter. The properties of the fuels used in this work are given in Table 1.

Table 1. Fuel properties.

Properties	PD	CSO	ASTM Method	WCB20
Density kg/m^3 at 15 °C	838	850	D1298	840.4
Calorific value, MJ/kg	43.92	41.68	D5865	43.47
Cetan number	50	52	D613	50.4

2.2. Experimental Setup

The experiments were conducted in the engine laboratory of the University of Southern Queensland, utilizing the GUNT (11 kW) single-cylinder 4-stroke diesel engine CT300, water-cooled, Figure 1. The engine is a dual-fuel system with the feature of variable compression ratio capabilities (5:1 to 19:1). The experimental setup is equipped with a dynamometer, fuel consumption measurement system, gas analyzer, and heat exchange system. In addition, the setup is outfitted with essential sensors for capturing engine performance data, i.e., the sensor array encompasses an in-cylinder pressure transducer, crankshaft encoder is used for piston position measurement, and engine measures engine rotational speed. The setup is connected by a data acquisition system and dedicated software capable of recording, saving, and processing the data. This encompasses in-cylinder pressure, exhaust gas temperature, engine power, engine torque, fuel consumption, brake-specific fuel consumption, and thermal efficiency. The gas analyzer is integrated into the system to measure oxygen level, carbon dioxide (CO_2) concentrations, carbon monoxide (CO) level, nitrogen oxides (NO_x), unburnt hydrocarbons, and Lambda.

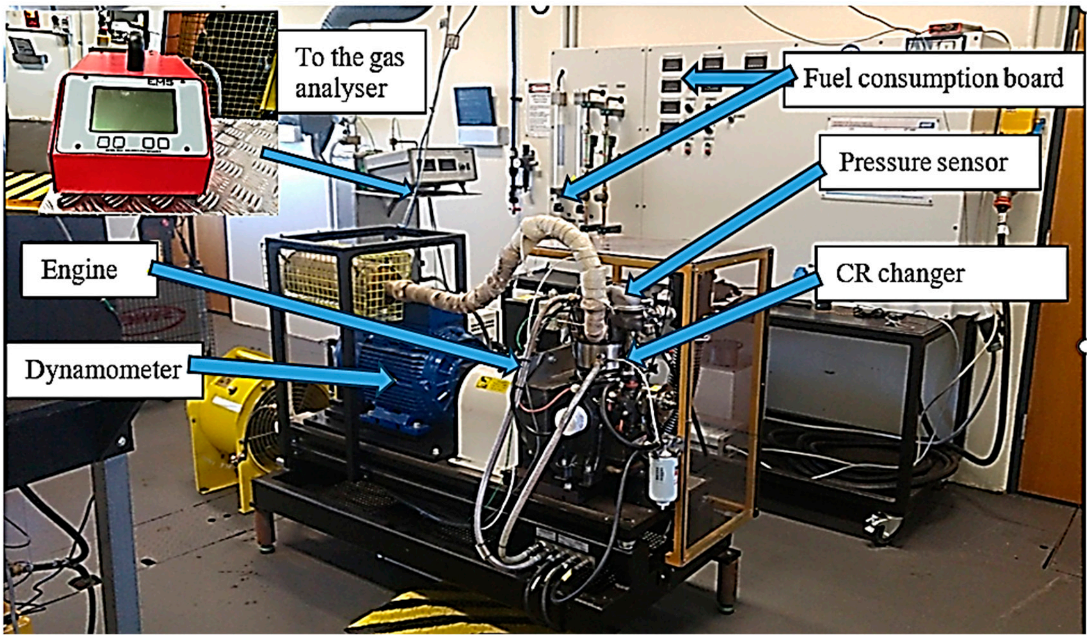

Figure 1. Engine setup.

2.3. Test Procedure

The experiments were carried out using two specific compression ratios: 16:1 and 18:1. These compression ratios were chosen after preliminary testing and by the recommendations of the engine manufacturer. This engine's maximum theoretical compression ratio is 19:1. During the preliminary testing phase, the engine exhibited knocking, and there was a high risk of engine damage when using an unknown fuel. As a result, selecting two compression ratios with a reasonable difference between them was advisable to obtain meaningful variations in the output parameters. Likewise, when it comes to fuel types like WCB100, the manufacturer discourages using B100 biodiesel due to its potential implications for the engine warranty. On the other hand, biodiesel B2 has received recommendations from numerous researchers as a promising renewable fuel alternative [24–26]. The engine speeds were set at 1400, 2000, and 2600 rpm. Fuel properties (calorific value, density, chemical composition, and specific gravity) and the engine's compression ratio were keyed in the operating system, i.e., provided as input variables to the computer software.

In addition, the experimental setup was linked to a weather station, enabling the acquisition of crucial environmental parameters, including ambient temperature and humidity. The initial testing phase involved using petroleum diesel (PD) fuel at the selected operating parameter. Once the engine reached a specified operating temperature, engine performance and emission parameters were recorded under these conditions. At the end of each experiment, the engine was stopped, the fuel system was cleaned, and filters were changed to run on waste cooking oil diesel WCB20 following similar steps to those described before. After the initial run, the engine was allowed to cool down, and the compression ratio was changed from 16:1 to 18:1. The entire procedure was then replicated with PD and WCB20 fuels. To ensure robustness and statistical reliability, the experiment was conducted three times, with the average results subsequently plotted in the Discussion section.

3. Results and Discussion

In this section, various engine performance parameters like the engine brake power (kW), torque (N.m), and brake-specific fuel consumption (g/kW.h), the engine emissions parameters of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), oxygen (O_2), and unburnt hydrocarbons (HCs), and the exhaust temperature of the fuel are presented for two different compression ratios: 16:1 and 18:1. The results are presented for two different types of fuels, petroleum diesel (PD) and petroleum diesel blended with 20% biodiesel produced from waste cooking oil (WCB 20%), at various engine speeds of 1400 rpm, 2000 rpm, and 2600 rpm at wide-open throttle and the maximum fuel line open.

The viscosity of the fuels was measured, and their comparison can be observed in Figure 2. This figure presents the viscosity of the waste cooking oil and waste cooking oil biodiesel after transesterifications at different fuel temperatures of 25 °C and 40 °C compared with PD. The waste cooking oil viscosity dropped from 160 cP to 58.5 cP when the temperature increased from 25 °C to 40 °C. The viscosity of a substance will decrease as the temperature increases [27,28]. This is because when particles move at a higher speed, their interactions become shorter, resulting in reduced internal friction or stress [29–31]. As a result, the viscosity decreases. It can also be seen that the viscosity of biodiesel produced from waste cooking oil (WCB100) is reasonably close to that of petroleum diesel. The WCB20 viscosity is similar to that of PD at both tested temperatures, with a 2.67% difference at 25 °C and 1.46% at 40 °C.

3.1. Performance Analysis

3.1.1. Brake-Specific Fuel Consumption (BSFC)

Figure 3 displays the BSFC vs. engine speeds for both the PD and WCB20 fuels at different compression ratios (16:1 and 18:1). The BSFC for the diesel is relatively higher than that for WCB20 for both compression ratios. This is aligned with previous research results [32–34] showing that WCB has increased thermal efficiency, which means less BSFC. The BSFC break-specific fuel consumption is a parameter that describes the fuel consumption required to produce a specific quantity of power. The lower the brake's fuel consumption value, the better the performance and thermal efficiency. At both compression ratios of 16:1 and 18:1, the BSFC for petroleum diesel is 5.9% higher than that for the WCB20 fuels at 1400 rpm and 2600 rpm; the difference was insignificant at the engine speed of 2000 rpm. The phenomenon where the BSFC curve exhibits a minimum at a specific engine speed, such as around 2000 rpm, is an intriguing aspect of engine performance dynamics [35]. This occurrence can be attributed to several interrelated factors that enhance engine efficiency and optimize fuel combustion processes at this particular speed [36]. The maximum difference between the tested fuels is 7.05% at 2600 rpm. Increasing the compression ratio from 16:1 to 18:1 reduces the BSFC significantly for both fuels, which means less fuel is required to produce the same amount of power. The gap between petroleum diesel and WCB20 increased with the increase in CR, indicating that WCB20 had a higher response than diesel to the change in compression ratios. This is due to the higher cetane number, which allows WCB20 to achieve higher thermal efficiency with high compression ratios [37,38].

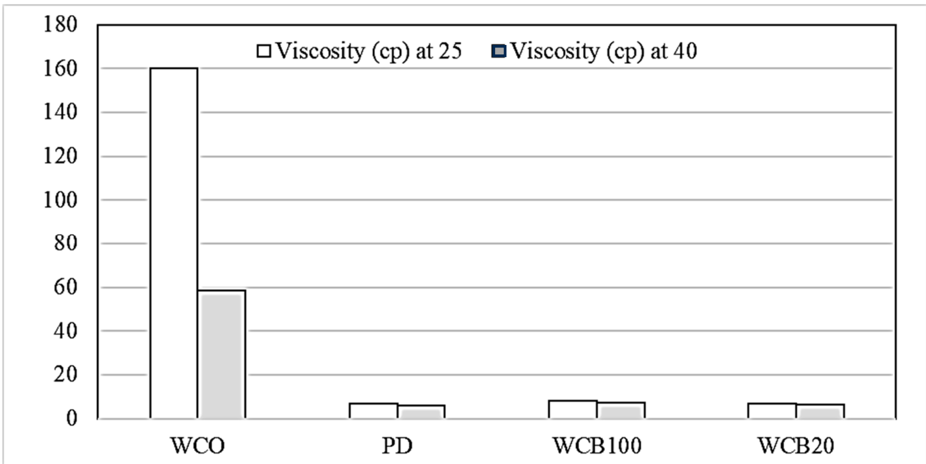

Figure 2. The viscosity of the fuels at 25 °C and 40 °C.

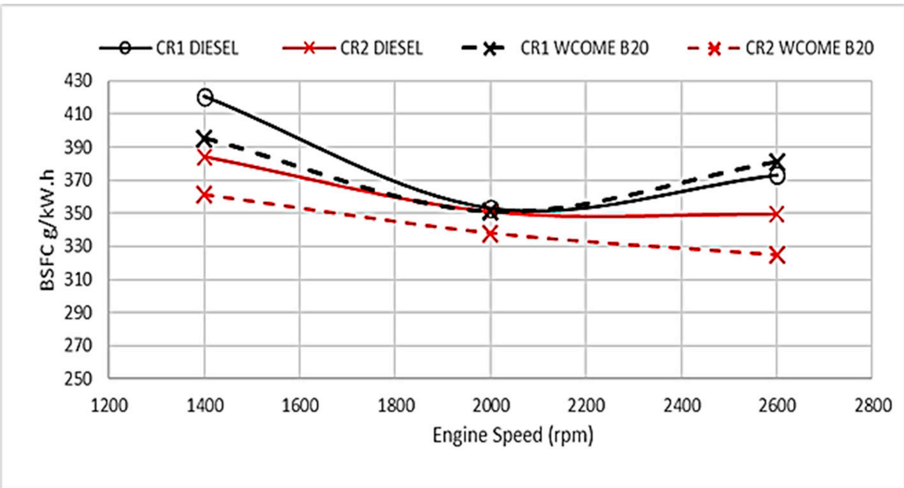

Figure 3. BSFC (g/kW.h) vs. the engine speed (rpm) at 16:1 and 18:1 CR.

3.1.2. Power

Figure 4 shows the relationship between the engine brake power and the engine speeds at two different compression ratios. It can be observed that the power increases as the engine speed increases for both fuels and both compression ratios, 16:1 and 18:1. It is proven that biodiesel, which has a lower calorific value than petroleum diesel, produces less brake power. It clearly can be seen in Figure 4 that the power of WCB20 is less than that of diesel at all speeds. However, the difference is insignificant, and the maximum differences were found to be less than 2.66% at an engine speed of 1400 rpm at a compression ratio of 16:1. Power produced from WCB20 became higher than that produced from petroleum diesel when the compression ratio increased. This aligned with the hypothesis that increasing the compression ratio improves the power produced from fuel WCB20 due to the higher cetane number, which allows the biodiesel to go to higher compression ratios.

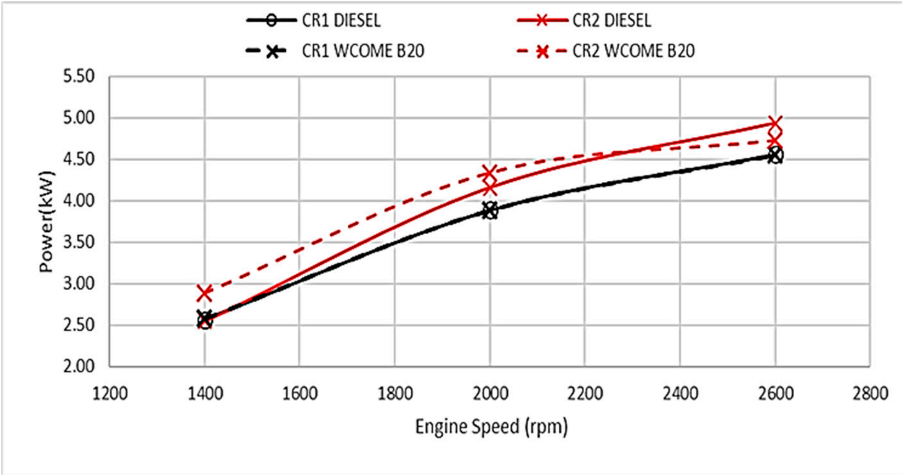

Figure 4. Power vs. the engine speed (rpm) at 16:1 and 18:1 CR.

It can be seen from the figure that the power produced from diesel fuel becomes 2.49% less than that produced from a blend of WCB20 at an engine speed of 1400 rpm and 3.95% less than that produced at an engine speed of 2000 rpm. The petroleum diesel still produces 4.3% higher power than WCB20 at an engine speed of 2600 rpm for a compression ratio of 18:1. This could be due to the higher engine speed (low load) applied to the engine, which allows the engine to have higher rpm with petroleum diesel than with WCB20 due to higher viscosity and reduces the fuel flow rate [39].

3.1.3. Torque

The variation in torque is shown in Figure 5. The engine torque follows the same pattern of power; however, the maximum engine torque can be found for both fuels at 2000 rpm. Figure 5 shows that PD gives higher torque than WCB20 at all speeds for the same compression ratio. Increasing the compression ratio from 16:1 to 18:1 dramatically improved the torque produced by the engine using WCB20. WCB20 produces a maximum torque of 19.6 (N.m) at 18:1, higher than the maximum torque produced with PD of 18.5 (N.m) in normal operating conditions of 16:1. This is aligned with the hypothesis that the engine parameters, such as the compression ratio, can overcome the issue of lower engine brake power with biodiesels due to the lower heating value. This is due to the higher cetane number, higher density, and more oxygen in the structure of WCB20 [34] along with the increasing CR.

The maximum difference between torque produced when PD fuel and WCB20 were used was significant when 16:1 was used. On the other hand, there was an insignificant improvement in the power produced by WCB20 at 1400 rpm when a CR of 18:1 was used. The power produced by WCB20 was less than that produced by PD, by 4.16%, at 2000 rpm.

3.1.4. Torque

The exhaust gas temperature versus the engine speed at 16:1 and 18:1 CR is given in Figure 6. It can be observed that the exhaust gas temperature for a blend of WCB20 and PD fuel increased as the engine speed increased. The exhaust gas temperature for the PD and WCB20 is similar at all the engine speeds at the compression ratio of 16:1.

At a compression ratio of 18:1, the exhaust temperature of the blend of WCB20 is 2.87% higher than that of PD at an engine speed of 2000 rpm and 5.96% lower at a speed of 2600 rpm.

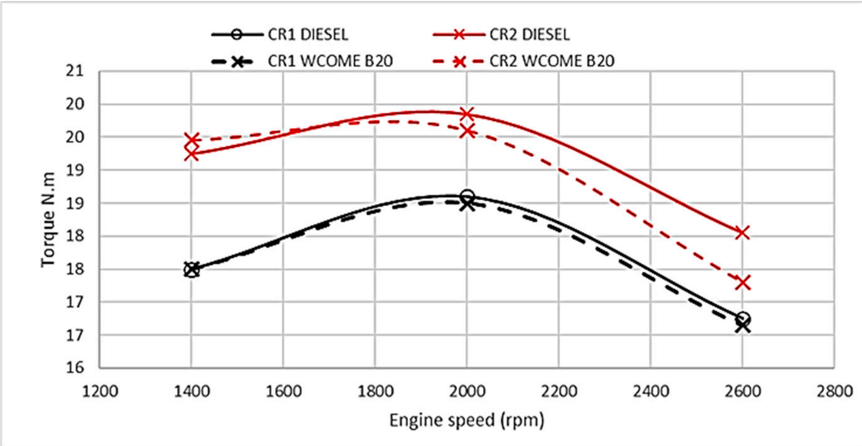

Figure 5. Engine torque vs. the engine speed (rpm) at 16:1 and 18:1 CR.

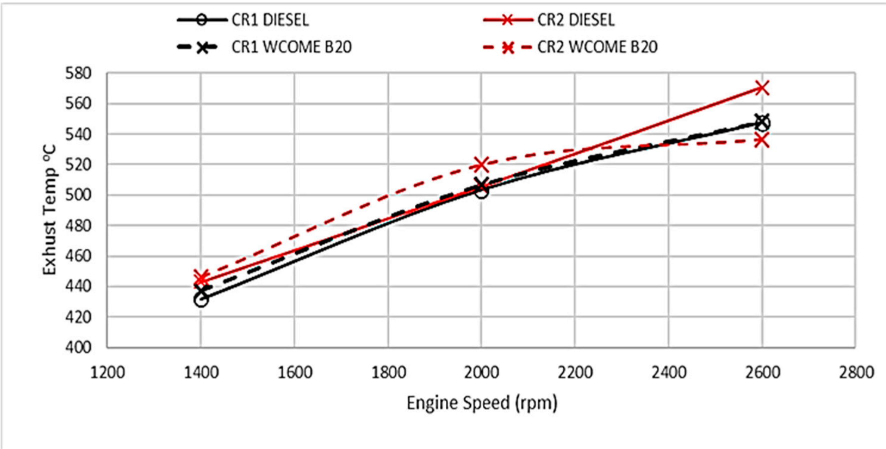

Figure 6. Engine exhaust gas temp. vs. the engine speed (rpm) at 16:1 and 18:1 CR.

3.2. Emission Characteristics

3.2.1. Unburnt Hydrocarbons Emission

The results for unburnt hydrocarbon emission according to the engine speed at 16:1 and 18:1 CR are given in Figure 7. The maximum unburnt hydrocarbon emission for the PD is 9.14% higher than that of a blend of WCB20 and relatively similar at the other engine speed for a compression ratio of 16:1. It has been reported that the HC amount was found to be lower than that from PD [32,33]. This can be attributed to the high concentration of oxygen in biodiesel compared to diesel, which results in more complete combustion.

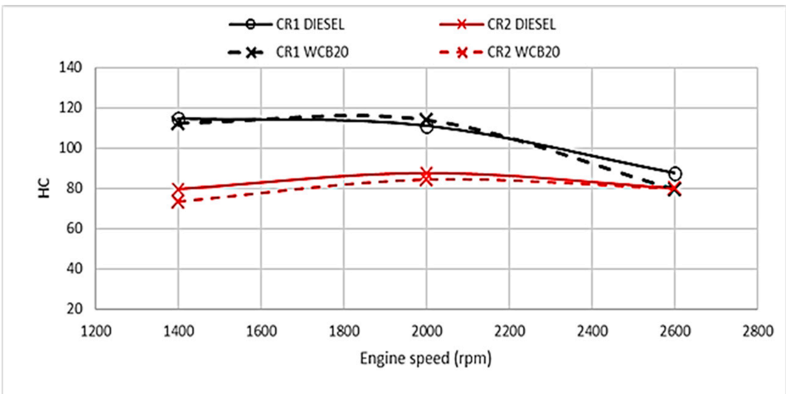

Figure 7. Unburnt hydrocarbon (HC) emission vs. the engine speed (rpm) at 16:1 and 18:1 CR.

At a compression ratio of 18:1, the unburnt hydrocarbon emission for WCB20 is 7.55% less than that for PD at an engine speed of 1400 rpm, 3.4% less than that at an engine speed of 2000 rpm, and relatively similar at 2600 rpm for a compression ratio of 18:1. The values show that the unburnt hydrocarbon emissions were reduced by increasing the CR of the engine. This indicates that the emission is cleaner, and better combustion quality occurs with a higher CR.

3.2.2. Carbon Dioxide Emission

The results for carbon dioxide emission (CO_2) according to the engine speed are given in Figure 8. The CO_2 emission for both diesel fuel and WCB20 increases with increasing engine speed. The figure shows that increasing the CR increases the CO_2 emission. Increased CO_2 indicates complete combustion as the number of carbon atoms that react with oxygen increases. The difference between PD and WCB20 in CO_2 emission is insignificant and less than 1.01% in most cases. These findings agree with Gaur and Goyal [34], showing that biodiesel blends have more oxygen than diesel, which leads to higher CO_2 emissions in biodiesel blends.

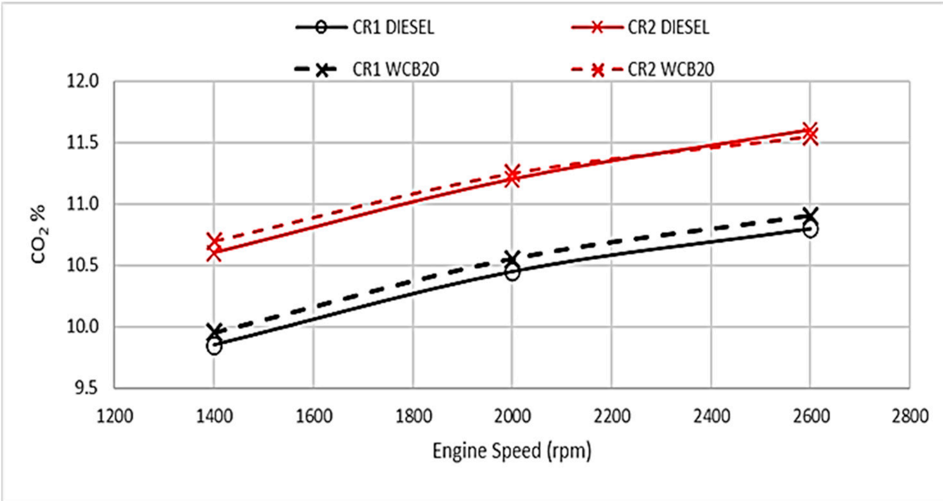

Figure 8. CO_2 emission vs. the engine speed (rpm) at 16:1 and 18:1 CR.

3.2.3. Carbon Monoxide (CO) Emission

Figure 9 depicts the mean results for carbon monoxide emission (CO). The lower the CO emission, the better the combustion. Carbon monoxide is produced during the intermediate combustion of hydrocarbons. Its formation depends upon the concentration of oxygen, the air–fuel equivalence ratio, the type of fuel, the start of injection timing, the injection pressure, and the speed. The phenomenon where the CO emission curve reaches a maximum at a specific engine speed, such as around 2000 rpm, can be explained by several interrelated factors related to the combustion process and engine operation [40]. Carbon monoxide is a byproduct of incomplete combustion, where not all the carbon in the fuel is converted into carbon dioxide (CO_2) [41]. The maximum CO emissions at around 2000 rpm are primarily due to suboptimal combustion conditions, including a rich air–fuel mixture, inadequate combustion temperatures, poor air–fuel mixing, and potentially less effective catalytic conversion [42]. The carbon monoxide emission produced from WCB20 is 16% lower than that produced from PD at an engine speed of 1400 rpm, 3.5% higher at an engine speed of 2000 rpm, and 4.11% lower at an engine speed of 2600 rpm for a compression ratio of 16:1. Changing the compression ratio has improved the overall CO emission at all engine speeds and with both fuels. WCB20 has responded to the change in CR more positively than PD and dropped to a significantly lower emission than that for PD at a CR of 18:1. The carbon monoxide emission for WCB20 is slightly more than 10% lower than that for PD at engine speeds of 1400 rpm and 2000 rpm, and 15.3% lower than that for PD at the engine speed of 2600 rpm. This is due to the high content of oxygen in biodiesel, which causes more complete combustion, and less carbon monoxide emission is produced in a blend of WCB20. Carbon monoxide is an extremely deadly gas, and reducing it is an achievement. Previous research reported the same finding, where the CO level dropped significantly when WCB20 was used compared to PD [32,33].

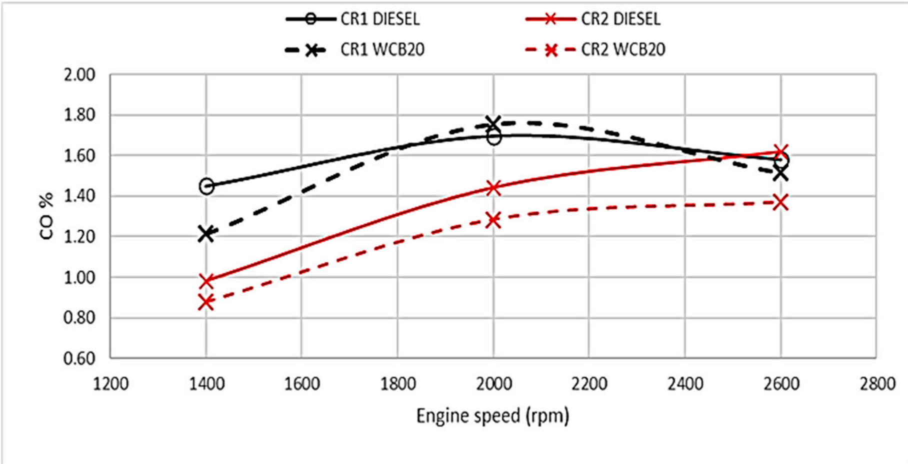

Figure 9. CO emission vs. the engine speed (rpm) at 16:1 and 18:1 CR.

3.2.4. Nitrogen Oxide Emission

Nitrogen oxides (NO_x) are the outcome of oxygen and nitrogen reactions at high combustion temperatures. They are considered harmful to the environment. The formation of NO_x depends upon the oxygen concentration, combustion flame temperature, and reaction. Figure 10 depicts the variation in nitrogen oxides versus the engine speed for different compression ratios. This figure shows that there is no significant difference in the NO_x emission between WCB20 and PD for a compression ratio of 16:1. This is not the case for a compression ratio of 18:1. The NO_x emission for WCB20 is noticeably higher than that of PD, by 19.4%, 13.5%, and 18.58% at the engine speeds of 1400 rpm, 2000 rpm, and 2600 rpm, respectively, for a compression ratio of 18:1. This high emission of nitrogen oxides in the blend of WCB20 is due to the presence of a high concentration of oxygen in biodiesel and the higher temperature of the combustion. This finding aligned with the findings that a higher CR increased combustion temperatures and then increased the emissions of nitrogen oxides (NO_x) [43,44].

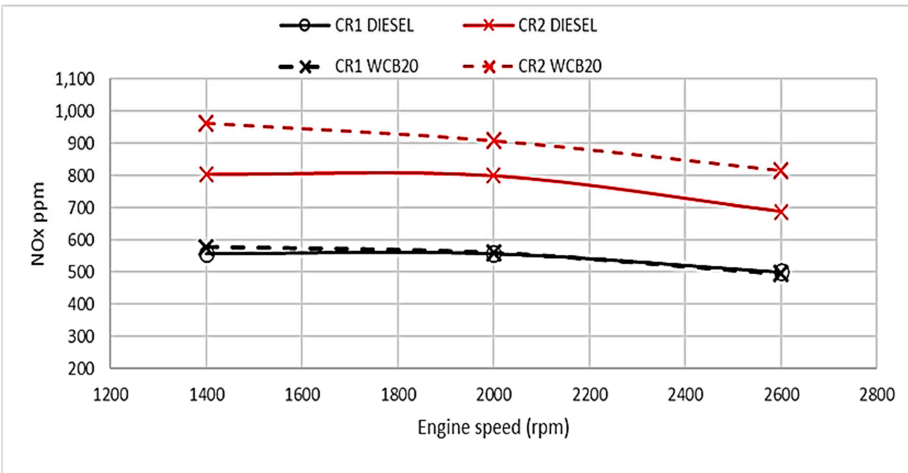

Figure 10. Nitrogen oxide (NO_x) emission vs. the engine speed (rpm) at 16:1 and 18:1 CR.

3.2.5. Oxygen Emission

The variation in oxygen emission is shown in Figure 11. The oxygen emission for the blend of WCB20 is higher than that of petroleum diesel in terms of the speed and compression ratios. Increasing the compression ratio from 16:1 to 18:1 has dropped the oxygen level in the exhaust gas emission. This finding is aligned with the finding of this work of higher power and torque, which is explained by the fact that more oxygen was used to react with carbon and achieve complete combustion [34,45]. This is also aligned with the finding that CO_2 gas levels were higher and there was less CO.

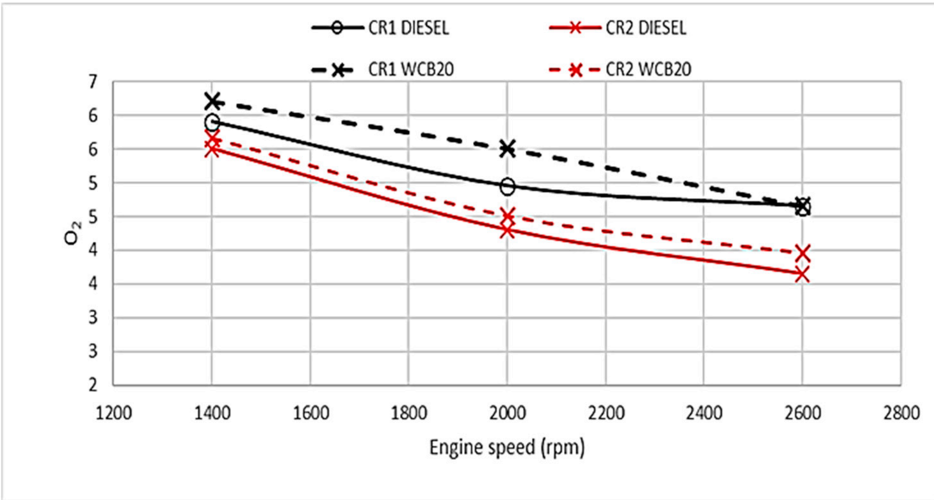

Figure 11. Oxygen gas vs. the engine speed (rpm) at 16:1 and 18:1 CR.

The maximum difference was seen at the 2000 rpm engine speed, when the oxygen level was 11.1% higher than that of petroleum diesel at 16:1 CR. The oxygen emission for WCB20 is 8.22% higher than that for diesel fuel at an engine speed of 2600 rpm, for a compression ratio of 18:1.

4. Conclusions

In summary, this study sought to explore the impact of varying compression ratios on the performance and emissions of WCB20 as a viable alternative to traditional diesel fuel in internal combustion engines. The investigation focused on two specific compression ratios, 16:1 and 18:1, and yielded several noteworthy findings.

The study revealed that increasing the compression ratio from 16:1 to 18:1 significantly enhanced the engine brake power, torque, and BSFC when the engine was fueled with WCB20 compared to PD. This highlights the potential for higher compression ratios to optimize the engine performance when operating on biodiesel blends like WCB20.

Emissions data were improved when WCB20 was used in comparison to conventional diesel fuel. The combustion of WCB20 resulted in reduced levels of unburnt hydrocarbons (HCs), signifying cleaner and more efficient combustion processes. Regarding the carbon monoxide (CO) emissions, WCB20 also outperformed diesel, with the advantage being more pronounced at the higher compression ratio of 18:1. This decrease in CO emissions is an improvement from an environmental standpoint. However, it is essential to address the observation that nitrogen oxide (NO_x) emissions increased when utilizing WCB20, particularly at the 18:1 compression ratio.

On average, the production cost for 1 L of WCB20 is estimated to be between 0.50 and 0.70 USD, depending on factors like the scale of production, regional economic conditions, and technological efficiencies. The price of 1 L of PD typically fluctuates between 0.80 and 1.00 USD, and is largely influenced by global crude oil prices and regional taxation policies. In contrast, WCB20's lower production costs make it an economically viable alternative, particularly when considering potential subsidies or incentives for renewable energy sources.

In conclusion, this study underscores the potential of WCB20, derived from waste cooking oil, to enhance engine performance and reduce specific harmful emissions, mainly when applied at higher compression ratios. Nevertheless, further investigation of other engine parameter adjustments, such as fine-tuning the ignition duration and timing, is needed to mitigate the rise in NO_x and CO_2 emissions. Further research and development are necessary to optimize the production processes, enhance the fuel properties, and expand the feedstock base. The technology roadmap should include advancements in biodiesel refining technologies, exploration of other waste and non-food feedstocks, and improvements in engine designs to maximize the efficiency of biodiesel use. A realistic timeline would involve incremental developments over the next decade, with specific milestones of improved production efficiencies and expanded market adoption.

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Nomenclature

The following abbreviations have been used throughout the text and bibliography:

WCO	waste cooking oil
WCB20	waste cooking oil biodiesel 20%
BSFC	brake-specific fuel consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
HC	hydrocarbon
BP	brake power
PD	petroleum diesel
CSO	Cotton Seed Oil
UCO	used cooking oil
CO_2	carbon dioxide

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