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Evaluating Engine Performance, Emissions, Noise, and Vibration: A Comparative Study of Diesel and Biodiesel Fuel Mixture

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Abstract

This study investigates the performance, emissions, noise, and vibration characteristics of a single-cylinder, air-cooled, four-stroke diesel engine running on pure diesel (D100) and biodiesel blends (B10: 90% diesel, 10% biodiesel; B20: 80% diesel, 20% biodiesel) at 1800 rpm, where the engine delivers maximum torque. Key metrics such as torque, power, brake specific fuel consumption (BSFC), exhaust gas temperature, noise, vibration, and emissions (CO, CO_2, HC, O_2, NO_x, and smoke opacity) were analyzed. The findings indicate that B10 enhances torque, power output, and overall fuel efficiency, especially at low to medium loads, with a significant 17.54% reduction in BSFC compared to D100 at 40% engine load. Vibration levels generally increased with biodiesel addition, while B10 and B20 both reduced smoke opacity, with B20 having a more substantial effect. HC emissions decreased at idle with B10 but increased at higher loads, suggesting more complete combustion with potential thermal stress on engine components. Noise and vibration results were mixed; B20 reduced noise at higher loads but increased vibration. At 100% load, B20 decreased noise by 1.42% compared to D100. Despite benefits such as improved torque and reduced particulate emissions, biodiesel blends, particularly B20, led to increased NO_x and CO_2 emissions, emphasizing the need for further optimization of blend formulations and emission control strategies. This study provides valuable insights into the trade-offs and potential of biodiesel blends as sustainable diesel alternatives.

Keywords: Biodiesel, Diesel Engine, Engine Noise, Engine Vibration

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1. Introduction

The primary objective of this study is to evaluate and compare the performance, emissions, noise, and vibration characteristics of a diesel engine when fueled with pure diesel and biodiesel fuel blends. The use of biodiesel blends will result in comparable or slightly lower engine performance (torque and power) compared to diesel, with an expected increase in BSFC due to the lower energy content of biodiesel. Biodiesel blends will result in lower CO, HC, and soot emissions compared to pure diesel fuel, but may increase NO_x emissions. Engines fueled with biodiesel blends will exhibit lower noise levels and higher vibration levels than those fueled with conventional diesel fuel, especially at higher engine loads.

Nowadays, the demand for alternative renewable fuels for internal combustion engines has increased due to the depletion of fossil fuels and air pollution. Biodiesel fuel obtained from various sources such as animal fats and edible and non-edible oils is a potential alternative to diesel fuel [1–4]. The search for sustainable and environmentally friendly energy sources has led to increased interest in alternative fuels for internal combustion engines. In this context, biodiesel derived from renewable resources such as vegetable oils or animal fats has emerged as a promising candidate due to its potential to reduce the environmental impact of transportation systems. Biodiesel is known for its lower greenhouse gas emissions and reduced dependence on fossil fuels compared to traditional diesel fuel [5–11].

However, widespread adoption of biodiesel faces several challenges, including its compatibility with existing engine technologies, performance characteristics, and potential trade-offs in engine efficiency and emissions [12–14]. Consequently, there is a critical need to comprehensively evaluate the impact of biodiesel-diesel fuel blends on engine performance, emissions, and noise and vibration characteristics [15–17].

Susilo et al. studied the effect of diesel-essential oil fuel blends on engine performance, noise and vibration. They found that fuel consumption, emissions, noise and vibration varied with different blend ratios (B10 and B20) and engine speeds. Specifically, at lower engine speeds, the B10 blend exhibited higher fuel consumption and lower noise and vibration, while the B20 blend led to lower emissions [18]. Prabakaran [19]conducted a study titled Experimental Investigation of Use of Biobutanol and Improved Waste Engine Oil Fuel in Compression Ignition Engine for Performance. This study reported that a mixture of 50% improved waste engine oil and 50% butanol in compression ignition engines can provide similar performance to diesel at rated power, but may cause slightly higher carbon monoxide and hydrocarbon emissions. Saravanan et al. [20] investigated the use of BL20 blend, a blend of rapeseed and Mahua biodiesel in a variable compression ratio diesel engine. Their study found that the BL20 blend offered

performance and emission characteristics close to diesel, with slightly lower brake thermal efficiency and reduced CO, HC and smoke emissions. However, NO_x emissions were marginally higher. The results suggest that BL20 can serve as a viable alternative to diesel without requiring engine modifications. Polat studied the effect of adding Al_2O_3 nanoparticles to a diesel-biodiesel blend and the results showed that BTE increased by 4.51% compared to the diesel-biodiesel blend. Additionally, the author showed that various emissions, including HC, CO and NO_x emissions, decreased with the exhaust gas temperature by adding 1 g Al_2O_3 to the fuel mixture [21]. Yang and colleagues experimentally examined the effect of adding 10% butanol to diesel waste cooking oil biodiesel mixtures ranging from 10% to 40%. Authors reported that the addition of butanol reduced specific fuel consumption (BSFC) and CO emissions [22].

When the studies are examined, it can be seen that the use of biodiesel in diesel engines has been extensively researched in order to address environmental concerns and reduce dependence on fossil fuels. One critical aspect of this research is understanding how biodiesel affects engine vibration and noise, which are important factors affecting engine performance, human comfort and occupational safety. Biodiesel blends from various sources, such as linseed oil, pine oil, soap nut oil, sunflower, canola, corn, Niger seed oil, mustard oil, and Moringa oleifera oil, have been shown to generally reduce engine vibration and noise compared to conventional diesel [15,23–30]. S. Jaikumar et al. reported that linseed oil biodiesel blends significantly reduced vibration and noise intensity in VCR diesel engines, while better results were achieved at higher compression ratios and loads [23]. V. Venkatesan et al. reported that pine oil-soap nut oil biodiesel blends (P75SNB25) reduced vibration at peak performance in agricultural tractor engines, while both blends reduced noise by 2.34% compared to diesel operation [24].

Uludamar, E. et al. reported that fueling an unmodified compression ignition engine with sunflower, canola and corn biodiesel mixtures and the addition of hydrogen gas reduced vibration acceleration and exhaust emissions depending on engine speed [15]. Jaikumar, S. et al. reported that Niger seed oil methyl ester (NSOME) blends and hydrogen-enriched biodiesel reduced vibration and noise levels in CI engines, while higher hydrogen flow rates reduced vibration and noise levels [26]. Uludamar, E. et al. reported that engine noise and vibration decreased as the biodiesel ratio increased, the use of pure biodiesel reached the maximum level, and linear and nonlinear regression models could accurately predict this relationship [28]. Tüccar, G. reported that diesel engines running on mustard oil biodiesel and hydrogen gas significantly reduce engine vibration and noise levels, while NO_x emissions increase due to increased combustion temperature [29]. Jaikumar, S. et al. According to the results of their experiments with Moringa oleifera oil biodiesel mixtures, they reported that the BD20D80 fuel mixture significantly reduced the vibration and noise intensity in diesel engines and was a fuel suitable for use in compression ignition engines without the need for modification [30]. Sanatha, K. et al. According to the experimental results conducted with ZnO nanoparticle baheda oil biodiesel mixture (BOME20), they reported that vibration and noise in diesel engines with variable compression ratios were significantly reduced, and the lowest RMS (root mean square) speed and noise were reached at a compression ratio of 16.5 [31].

This research aims to address this gap by conducting a comparative study on engine performance, emissions, noise and vibration of diesel and biodiesel fuel blends. The study covers key factors affecting engine operation and environmental impact, including fuel efficiency, power output, nitrogen oxide (NO_x), particulate matter (PM), carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and noise and vibration levels. will focus on evaluating the parameters.

This research aims to provide valuable information about the feasibility and potential benefits of using biodiesel as an alternative fuel in internal combustion engines by systematically examining the performance of diesel and biodiesel blends under various operating conditions. The findings of this study are expected to contribute to ongoing efforts aimed at promoting sustainable transportation solutions and reducing the environmental footprint of the automotive industry.

This study presents a comprehensive assessment of engine performance, emissions, noise, and vibration characteristics using diesel and biodiesel blends (B10 and B20) in a single-cylinder, air-cooled, four-stroke diesel engine. The novelty of this study lies in its holistic approach to evaluate multiple performance metrics across a wide range of engine loads, particularly at 1800 rpm, the speed at which the engine delivers its maximum torque. Unlike previous studies that usually focus on isolated performance aspects or a limited engine load range, this study provides a detailed comparative analysis of how biodiesel blends affect various engine parameters, including noise and vibration, which are less reported in biodiesel research.

The biodiesel used in this study was produced from waste vegetable oils using conventional methods, highlighting the potential for sustainable fuel alternatives. The main steps involved in the study were; waste vegetable oils were converted to biodiesel using a conventional transesterification process, a single-cylinder, air-cooled, four-stroke diesel engine was used for testing. The engine was operated at a constant speed of 1800 rpm at six different engine loads (0%, 20%, 40%, 60%, 80% and 100%), performance metrics such as torque, power, brake specific fuel consumption (BSFC), exhaust gas temperature, noise, vibration and emissions (CO, CO_2, HC, O_2, NO_x and smoke opacity) were measured for pure diesel, B10 and B20 fuel blends, the collected data were analyzed to compare the effects of different fuel blends on engine performance and emissions with a focus on identifying changes associated with the use of biodiesel. The findings of the study contribute to the existing knowledge by providing insights into the potential of biodiesel blends in reducing particulate emissions and noise, as well as highlighting challenges such as increased NO_x and CO_2 emissions. This research highlights the importance of considering multiple performance parameters when evaluating alternative fuels and provides a basis for further optimizing biodiesel formulations to balance performance and environmental impact.

2. Material and Methods

The experiments of this study were carried out in Sakarya University of Applied Sciences, Arifiye Vocational School, Engine Test and Simulation Laboratory. The experimental setup includes a test engine, electric dynamometer, exhaust gas analyzer, digital scale for mass fuel measurement, k-type thermocouple for exhaust temperature measurement, noise measurement device, vibration measurement device, data acquisition panel and software. The tests were carried out at the maximum torque speed of 1800 rpm. This particular engine speed is important because it represents the optimum operating condition where the engine is most efficient and performs best. Testing at maximum torque is important because it allows for a comprehensive evaluation of the engine's performance, emissions, noise, and vibration characteristics under the most severe operating conditions. Experiments were also conducted at this speed at various engine loads (0%, 20%, 40%, 60%, 80%, and 100%). These load conditions were selected to simulate different real-world operating scenarios ranging from idle (0% load) to full load (100% load). Evaluating the engine across this load spectrum provides a holistic understanding of how biodiesel blends affect engine behavior under different mechanical stress levels. This approach allows the study to cover the full range of engine operational characteristics, allowing for a robust comparison between diesel and biodiesel fuel blends in various practical applications. The schematic view of the experimental setup is given in Figure 1.

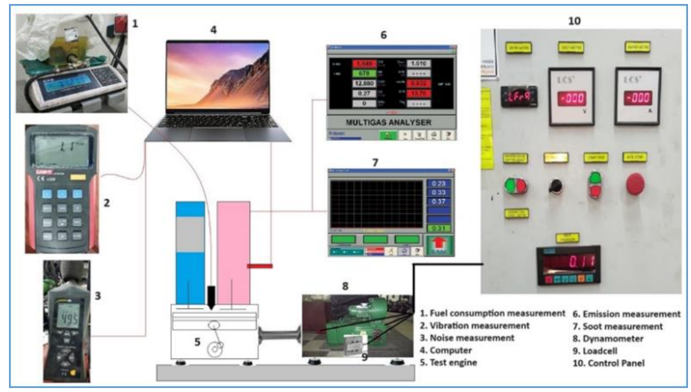

Fig. 1. Experimental setup

Antor 3LD510 brand single-cylinder, air-cooled, direct injection diesel engine was used as the experimental engine. The technical specifications of the test engine are given in Table 1.

Table 1. Test engine technical properties

Test Engine	**Antor 3LD510**
Number of cylinders	1
Stroke x Diameter [mm]	90 x 85
Total cylinder volume [cm^3]	510
Compression ratio	17.5/1
Engine power [HP]	12
Maximum torque [Nm @1800 rpm]	32.85

The test engine was braked by a KEMSAN brand 15 kW DC electric dynamometer. The experiments were carried out at 0%, 20%, 40%, 60%, 80% and 100% engine loads. BILSA brand exhaust emission device was used for exhaust gas analysis. The technical specifications of the exhaust gas analyser are given in Table 2. For vibration measurement, UNI-T UT315A brand vibration measuring device was used. Technical specifications of the device are given in the Table 3. Noise measurement PCE 322A brand noise measuring device was used. Technical specifications of the noise measuring device are given in the Table 4.

Table 2. Exhaust gas analyser technical properties

Parameters	Measurement Limit	Sensitivity
CO	0-10%	0.01%
CO_2	0-20%	0.01%
HC	0-10000	1 PPM
O_2	0-25%	0.01%
CO Corr	0-10%	0.00%
NO_x	0-5000	1 PPM
Lambda	0-2000	0.001
Opacity	0-100%	0.10%
Working Ambient Temperature	5°C…..+45 °C	0.01%

Table 3. Vibration measurement device technical data

Vibration Measurement Device	UNI-T UT315A
Acceleration measurement	0.1 ~ 199.9 m/s^2 (peak value)
Velocity measurement	0.01 ~ 19.9 cm/s (true RMS)
Displacement measurement	0.001 ~ 1.999 mm (peak to peak value)
Measurement error	±5%+2dgts
Frequency range (acceleration)	10 Hz ~ 10 kHz
Frequency range (velocity)	10 Hz ~ 1 kHz
Frequency range (displacement)	10 Hz ~ 500 Hz
LCD display	2000-count display
Refresh cycle	1 s
Data storage	1999 sets
Power supply	9V 6F22

Table 4. Sound level meter technical data

Sound Level Meter	PCE 322A
Noise levels	30 ... 130 dB
Dynamic range	50 dB
Display	4-digit LCD
Resolution	0.1 dB
Accuracy ±1.4 dB	±1.4 dB
Sampling rate	2 x per second
Frequency	31.5 Hz ... 8 kHz
Storage capacity	32,700 readings
Microphone type	Electret condenser
Functions	MIN, MAX, HOLD, ALARM

The fuels used in the experiments were obtained by volumetric mixing of standard diesel and produced biodiesel. A graphical abstract of the study is given in Figure 2. In addition, the properties of the fuels used in the experiments are shown in Table 5.

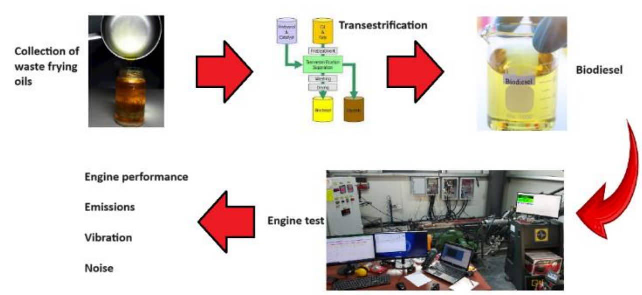

Fig. 2. Graphical abstract

Table 5. Properties of test fuels

Properties	Unit	Diesel	B10	B20
Density at 15°C	kg/m^3	829.48	834.952	840.424
Viscosity at 40 °C	mm^2/s	3.00	3.129	3.258
Flash point	°C	75.00	84.85	94.7
Cetane number	-	51.00	51.16	51.32
Calorific Value	kcal/kg	42.60	42.57	42.54
Water content	%(m/m)	0.02	0.0229	0.0258

The biodiesel used in this study was produced from waste vegetable oils following a conventional transesterification process. The waste vegetable oils were collected from various sources, primarily restaurants and food processing plants, which contained used cooking oil. The waste vegetable oils were first collected and filtered to remove impurities such as food particles and water. This step is crucial to ensure the quality of the biodiesel and to prevent potential problems during the transesterification process. The filtered oil was then subjected to the transesterification process, where it was reacted with methanol in the presence of a catalyst, typically sodium hydroxide (NaOH) or potassium hydroxide (KOH) [32]. The reaction produces biodiesel (methyl esters) and glycerol as byproducts. The reaction conditions, such as temperature and reaction time, were carefully controlled to maximize the biodiesel yield. After the reaction, the mixture was allowed to settle, and the biodiesel was separated from the glycerol. The biodiesel layer was then washed with water to remove the remaining methanol, catalyst, and impurities. Finally, the purified biodiesel was dried to remove the remaining water. The biodiesel produced was subjected to quality control tests to ensure that it met the standards required for use in diesel engines. Key parameters such as density, viscosity, and cetane number were measured and found to be within the acceptable range specified by standards such as ASTM D6751 or EN 14214. This biodiesel was then used in the engine experiments discussed in this study. Using waste vegetable oils as feedstock not only provides an environmentally friendly alternative to fossil fuels, but also contributes to waste reduction and sustainability efforts.

3. Results

In this study, an experimental study was carried out for three different fuels in a single-cylinder diesel engine. As a result of the experimental study, torque, power, specific fuel consumption, noise, vibration and emission values were measured for no-load, 20%, 40%, 60%, 80% and 100% load conditions.

Figure 3 presents a comparative analysis of torque output for a diesel engine using pure diesel, B10 (90% diesel, 10% biodiesel), and B20 (80% diesel, 20% biodiesel) at various engine loads. The key findings are: At 20% load, B10 and B20 exhibit higher torque than diesel, with B10 showing a significant increase. At 40% and 60% loads, B10 slightly outperforms diesel, while B20 equals or exceeds diesel's torque output. At 80% load, B10 achieves the highest torque, followed closely by B20, both outperforming diesel. At 100% load, all three fuels provide the same torque, indicating that fuel type has little effect under maximum load. These results indicate that biodiesel blends, particularly B10, increase torque performance under most load conditions, particularly at low to moderate loads. B20 also shows potential, particularly at higher loads. The use of biodiesel blends can improve engine performance while offering environmental benefits such as reduced emissions. B10 stands out as the most suitable blend to balance improved torque and engine efficiency at various loads, while B20 shows promise, especially at medium to high loads, but with some considerations for economic and mechanical factors [33,34].

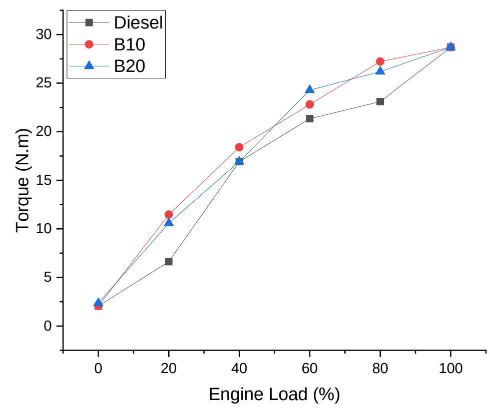

Fig. 3. Diesel biodiesel fuel mixture torque value changing with engine load

Figure 4 shows the variation in engine power versus engine load for diesel, B10, and B20 fuel blends. At 20% load, B10 significantly increases power to 2.16 kW compared to 1.25 kW for diesel, and shows superior performance at low loads. B20 also increases power to 2.00 kW, but not as significantly as B10. At 40% load, B10 produces 3.46 kW, slightly outperforming diesel and B20, which produce 3.19 kW. This trend continues at 60% load, where B20 reaches its peak power output of 4.57 kW, followed by B10 at 4.30 kW and diesel at 4.02 kW, indicating that a higher biodiesel content can improve medium-load performance. At 80% load, B10 again shows a significant power advantage at 5.13kW, while B20 is just behind at 4.93kW, both outperforming diesel at 4.35kW. However, at 100% load, all three fuels combine for a power output of 5.4kW, suggesting no significant effect of fuel type at maximum load. These results show that biodiesel blends, particularly B10, consistently increase engine power across a range of load conditions, offering both performance improvements and potential environmental benefits by reducing reliance on fossil fuels. B20 also shows promise, particularly at medium to high loads, but its advantages must be considered alongside economic and mechanical factors. Overall, B10 appears to provide the best balance between improved power and engine efficiency [20,35,36].

The differences in torque performance between diesel, B10 and B20 can be largely attributed to the oxygen content and combustion characteristics of biodiesel across various loads. Biodiesel contains more oxygen than diesel, which can improve combustion efficiency, particularly at low and moderate loads. Therefore, B10 and B20 generally outperform diesel in torque output at these loads. However, the balance between oxygen content and other fuel properties such as energy density and cetane number plays an important role. B10, with its lower biodiesel content, appears to provide better balance at certain loads, leading to higher torque output. In contrast, B20, while benefiting from more oxygen, may suffer from slightly lower energy content, which may offset the gains from improved combustion efficiency at some loads. At full load, the engine combustion process is likely optimized to the extent that the type of fuel blend has a minimal effect on torque, as shown by the equal torque outputs for all three fuels. In general, the selection of the biodiesel blend should take into account the specific load conditions; B10 may offer potentially better performance at low to medium loads, while B20 may be more beneficial at medium to high loads [37].

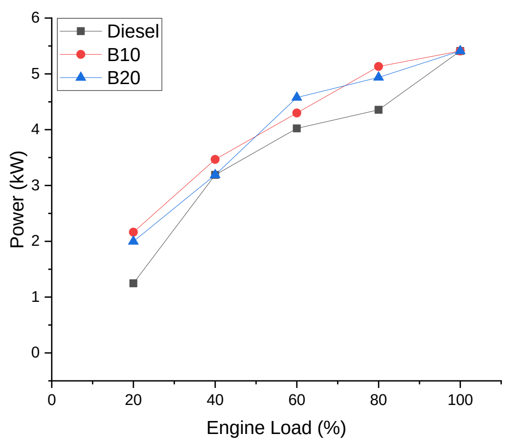

Fig. 4. Diesel biodiesel fuel mixture power changing with engine load

Figure 5 shows the variation of brake specific fuel consumption (BSFC) depending on engine load. At 20% load, diesel has the highest BSFC (413.4 g/kWh), while B10 shows better fuel efficiency by significantly reducing BSFC to 285.6 g/kWh. B20 also improves efficiency with a BSFC of 342.5 g/kWh, but is less efficient than B10. At 40% load, diesel has a BSFC of 308.5 g/kWh, while B10 and B20 achieve slightly better efficiencies at 279.1 g/kWh and 280.3 g/kWh, respectively. At 60% load, B10 continues to offer a slight fuel efficiency advantage (307.5 g/kWh) over diesel (351.3 g/kWh), while B20 performs comparable to diesel (319.6 g/kWh). At 80% load, B10 maintains better efficiency (307.5 g/kWh) than both diesel and B20. However, at 100% load, diesel demonstrates better fuel efficiency (303.9 g/kWh) compared to B10 (306.2 g/kWh) and B20 (320.6 g/kWh). In summary, B10 generally improves fuel efficiency under most load conditions, especially at low and medium loads. B20 also improves efficiency, but to a slightly lesser extent than B10. At full load, diesel maintains better efficiency, suggesting that biodiesel blends may have a marginal efficiency trade-off at maximum load. Overall, B10 appears to be the optimal blend for balancing engine performance with improved fuel efficiency at varying loads, with B20 showing promise, particularly at lower loads [38,39].

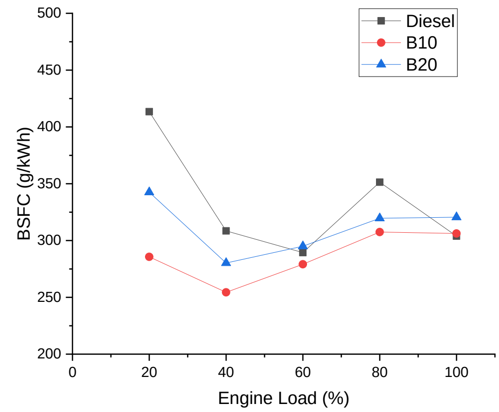

Fig. 5. Diesel biodiesel fuel mixture BSFC changing with engine load

Figure 6 shows the variation in exhaust gas temperature (EGT) with engine load for diesel, B10 and B20 fuels. Key observations are: At no load, the EGT of diesel is 138°C, with B10 and B20 being slightly higher at 142.5°C and 139.1°C, respectively. At 20% load, the EGT of diesel is 212°C, with B10 and B20 increasing this to approximately 230°C, indicating a marginal increase in EGT in the biodiesel blends. At 40% load, the EGT differences between the fuels are minimal, with diesel at 331.2°C and B10 and B20 showing slight changes. However, at 60% load, B20 results in a more significant increase in EGT (438.3°C) compared to diesel (402.7°C) and B10 (407.2°C). At 80% load, B10 and B20 significantly increase EGT to approximately 483°C compared to diesel's 448.5°C. At full load, B20 reaches its highest EGT of 498.6°C, while diesel and B10 show slightly lower values. In general, biodiesel blends, especially B20, tend to increase EGT, especially at medium to high loads. This increase in temperature may be due to the higher oxygen content in biodiesel, which may lead to more complete combustion. While this can improve combustion efficiency, it also requires careful consideration of engine thermal management and component durability [40,41].

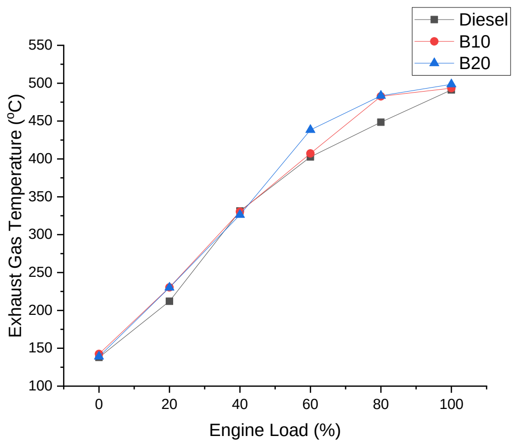

Fig. 6. Diesel biodiesel fuel mixture Exhaust Gas Temperature changing with engine load

Figure 7 shows the changes in noise levels with engine load for diesel, B10 and B20 fuels. At no load, the noise levels are similar for all fuels; diesel 95.3 dB, B10 slightly lower 94.7 dBA and B20 95.4 dBA. At 20% load, B10 slightly reduces noise compared to diesel, while B20 increases it to 97.7 dBA. At 40% load, both biodiesel blends slightly increase noise compared to diesel. However, at 60% load, B20 shows a reduction in noise (96.3 dBA) compared to diesel (97.1 dBA), while B10 remains similar to diesel. At 80% load, B20 reduces noise to 95.9 dB, while B10 slightly increases it. At full load, B20 provides the most significant noise reduction at 95.3 dB compared to diesel and B10, which show similar noise levels. Overall, B20 consistently reduces noise, especially at medium to high loads, making it a strong candidate for applications where noise reduction is critical. B10 shows mixed results, with a slight noise reduction at low loads but an increase at higher loads. These findings suggest that B20 is more effective at minimizing noise without compromising engine performance, especially in conditions where noise reduction is important [42,43].

The noise levels measured during the experiments were evaluated in the context of applicable standards and guidelines. Although no specific noise limit value is prescribed for small, single-cylinder diesel engines such as those used in this study, general industry practices and standards provide a useful reference. According to ISO 3744, the acceptable noise level for machinery and equipment is generally below 85 dB(A) to ensure compliance with workplace safety standards, depending on the environment and operating conditions. The noise levels measured in this study ranged from 94.7 dB(A) to 98.3 dB(A) across different engine loads and fuel mixtures, exceeding this threshold, indicating that additional noise control measures may be required in practical applications to ensure compliance with occupational safety regulations. A study by Qosim, N. (2022) reported that a diesel engine can produce a noise level of approximately 92.805 dBA at 1100 rpm in indoor conditions [44]. In the study conducted by Susilo, S.,et al. (2022), it was reported that noise levels can vary significantly with engine speed and can range from 105.7 dBA at 1300 rpm to 112.3 dBA at 1900 rpm [45]. In their study, Nurullah Gultekin et al. (2024) measured noise levels between 101 and 103.5 dBA in experiments conducted at 1850 rpm in a hydrogen-diesel dual fuel engine [46]. In the study published by Halil Erdi Gülcan et al. in 2023, it is seen that the engine noise was measured in the range of 101 to 103.5 dBA under similar operating conditions [47]. It shows that noise levels for comparable engines operating under similar conditions range from 90 dBA to 115 dBA and that biodiesel blends generally lead to marginally higher noise emissions due to the different combustion characteristics of biodiesel compared to pure diesel. Considering these references, the noise levels observed in this study are consistent with those reported in the literature, especially when biodiesel blends are used. However, in real-world applications, specific noise control strategies need to be employed to meet acceptable noise levels according to ISO and OSHA standards.

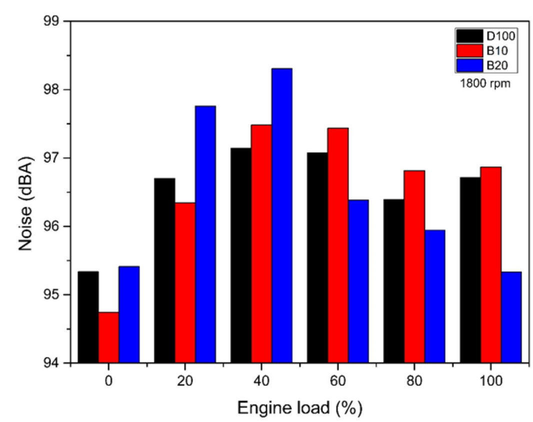

Fig. 7. Diesel biodiesel fuel mixture Noise value changing with engine load

Figure 8 shows the variation in vibration levels with engine load for diesel, B10 and B20 fuels. At no load, all fuels exhibit similar vibration levels; diesel 71.7 m/s², B10 slightly higher 75.2 m/s² and B20 74.4 m/s². At 20% load, both B10 and B20 show increased vibration, with B20 reaching 87.3 m/s², the highest among the fuels. At 40% load, B10 slightly reduces vibration to 86.1 m/s² compared to 87.4 m/s² for diesel, while B20 is close to diesel. At 60% load, both biodiesel blends slightly increase vibration levels; B10 85.1 m/s² and B20 86.3 m/s². At 80% load, B10 reduces vibration to 87.4 m/s², while B20 increases it to 91.7 m/s². At full load, B20 reduces vibration slightly to 95.6 m/s² compared to B10's 96.2 m/s², but both are higher than diesel's 93.8 m/s². In summary, biodiesel blends, particularly B10, can reduce vibration at moderate to high loads, making it a potential option for applications where vibration reduction is critical. However, B20 shows mixed effects, with increased vibration at low and moderate loads but slight reductions at higher loads. These findings suggest that B10 provides a better balance between vibration control and engine performance, while the effects of B20 should be carefully evaluated, particularly under changing load conditions [48,49].

The vibration levels measured during the experiments were analyzed in relation to applicable national and international standards. Vibration exposure limits are of critical importance in ensuring the operational safety and comfort of motor systems, especially for equipment that may be exposed to long-term use. According to ISO 10816, which provides guidelines for the assessment of machine vibration by taking measurements on non-rotating parts, vibration intensity levels for small, low-power machines should generally remain below 4.5 mm/s RMS for general mechanical condition monitoring. The vibration levels observed in this study and reported in m/s² correspond to vibration intensity levels higher than the generally acceptable limits specified by the ISO standard, especially under high load conditions.

It shows that the average vibration measurement in diesel engines varies depending on the operating conditions, fuel type and load, showing low vibrations of around 0.017 m/s² in optimized conditions, up to 3219 m/s² in overload conditions, and that the use of magnetized fuel or changes in coolant temperature can lead to a decrease or increase in vibrations respectively [50]. In their studies, Gültekin et al. and Gülcan et al. measured diesel engine vibration with similar characteristics in the range of 103-128 m/s² [46,47].

These studies have shown that biodiesel blends can affect vibration levels due to differences in fuel combustion characteristics, with B10 and B20 blends generally resulting in higher vibration levels compared to pure diesel. Considering these references, the vibration levels measured in this study are consistent with those reported in similar studies, especially when biodiesel blends are used. However, it is necessary to consider vibration reduction strategies in practical applications to ensure compliance with ISO standards, especially in environments where prolonged exposure to high vibration levels may pose a risk to equipment life and operator comfort.

Figure 9 shows the variation in CO emissions with engine load. At 0% load, B10 slightly reduces CO emissions (0.09%) compared to diesel (0.096%), while B20 increases to 0.115%. At 20% load, B10 continues to reduce emissions (0.033%), outperforming both diesel (0.044%) and B20 (0.042%). However, at 40% and 60% loads, both B10 and B20 increase CO emissions, with B20 showing a more pronounced effect (0.301% and 0.63%) compared to diesel (0.034% and 0.27%). At higher loads (80% and 100%), B10 maintains emissions similar to or slightly lower than diesel (1.316% vs. 1.32% at 80% and 2.179% vs. 2.24% at 100%), while B20 generally increases emissions (1.38% at 80% and 2.29% at 100%). In summary, B10 consistently demonstrates the potential to reduce CO emissions at low and high loads, while B20 tends to increase emissions, particularly at medium to high loads. These results suggest that B10 is a more effective blend for balancing reduced CO emissions with engine performance [51,52].

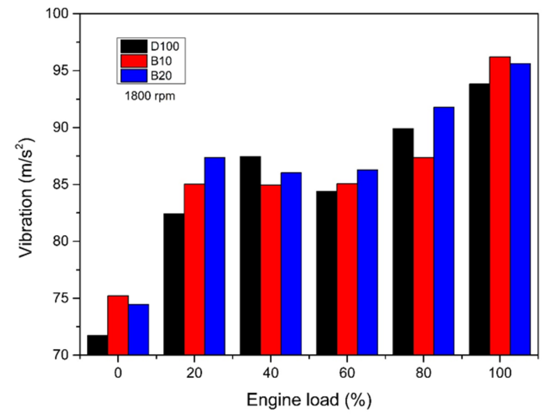

Fig. 8. Diesel biodiesel fuel mixture vibration value changing with engine load

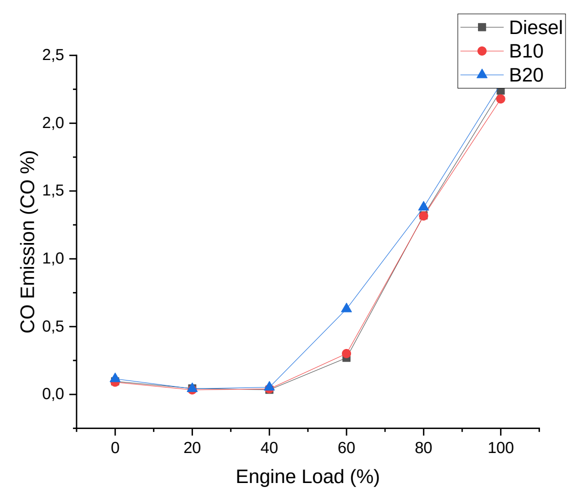

Fig. 9. Diesel biodiesel fuel mixture CO Emission value changing with engine load

Figure 10 shows the variation in CO_2 emissions with engine load. At all load conditions, both B10 and B20 biodiesel blends result in consistently higher CO_2 emissions compared to diesel. At 0% load, B10 and B20 increase CO_2 emissions from 2.138% (diesel) to 2.373% and 2.382%, respectively. This trend continues at 20% load, where CO_2 emissions increase more significantly with B10 (5.038%) and B20 (5.175%) compared to diesel (3.915%). Similar patterns are observed at medium and high loads; B10 and B20 show significant increases in CO_2 emissions, particularly at 60% load (9.91% and 10.78% vs. 9.14% for diesel) and 100% load (12.088% and 12.27% vs. 11.57% for diesel). These results suggest that biodiesel blends lead to more complete combustion and increased CO_2 production under all load conditions due to their higher oxygen and carbon content. While biodiesel blends offer environmental benefits such as reduced particulate matter, the consistent increase in CO_2 emissions suggests that they may not be ideal for applications prioritizing CO_2 reduction. B20, in particular, shows the highest increase in CO_2 emissions, highlighting the need for careful consideration when using higher biodiesel content [53,54].

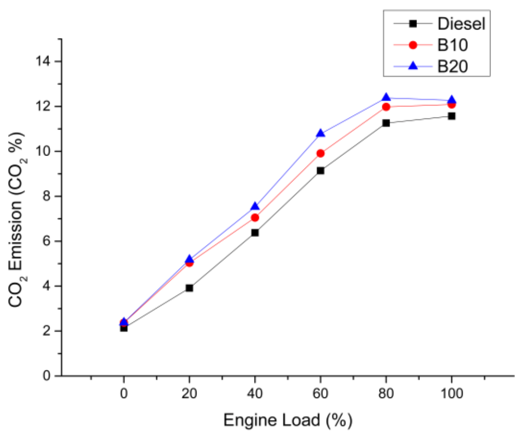

Fig. 10. Diesel biodiesel fuel mixture CO_2 Emission value changing with engine load

Figure 11 shows the variation in O_2 emissions with engine load for diesel, B10 and B20 fuels. At all load conditions, both biodiesel blends (B10 and B20) consistently reduce O_2 emissions compared to pure diesel. At 0% load, diesel shows an O_2 emission of 17.44%, while B10 and B20 reduce it to 13.23% and 13.22%, respectively. The pattern of lower O_2 emissions with biodiesel blends continues at 40% load (11.35% for diesel versus 10.66% for B10 and 10.1% for B20) and 60% load (7.29% for diesel versus 6.56% for B10 and 5.32% for B20). At higher loads, the trend continues and B10 and B20 show lower O_2 emissions than diesel. For example, at 80% load, diesel produces 3.31% emissions, while B10 and B20 reduce this to 2.67% and 2.23%. Even at 100% load, both blends maintain lower O2 emissions; B10 is 1.44% and B20 is 1.48%; for diesel, it is 1.96%. These results show that biodiesel blends, especially B20, increase combustion efficiency by reducing excess oxygen in the exhaust at various engine loads. B20 consistently provides the lowest O_2 emissions, making it the most suitable blend for improving combustion efficiency. B10 also effectively reduces O_2 emissions, especially at low and medium loads; however, its effect is slightly less pronounced at higher loads compared to B20 [55].

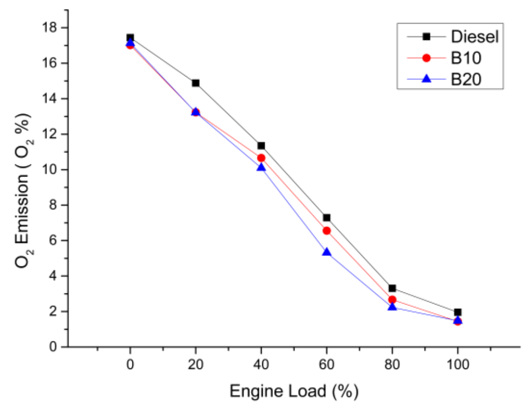

Fig. 11. Diesel biodiesel fuel mixture O_2 Emission value changing with engine load

Figure 12 shows the changes in HC emissions with engine load for diesel, B10 and B20 fuels. At 0% load, B10 reduces HC emissions from 18 ppm (diesel) to 14 ppm, indicating improved combustion efficiency, while B20 matches diesel at 18 ppm. At 20% load, HC emissions increase with biodiesel, particularly with B20 increasing to 32 ppm, indicating less efficient combustion. At 40% load, both blends increase HC emissions, with B20 reaching 42 ppm compared to 8 ppm for diesel. This trend continues at 60% load, where B20 emissions peak at 47 ppm. At higher loads, the effects of biodiesel change. At 80% load, B10 slightly increases HC emissions (22 ppm) compared to diesel (18 ppm), while B20 matches diesel. At 100% load, B20 slightly reduces HC emissions to 25 ppm compared with 26 ppm for diesel and 27 ppm for B10, indicating improved combustion efficiency at full load. In general, B10 reduces HC emissions at idle but tends to increase them at higher loads, whereas B20 shows higher emissions at low to medium loads but may reduce them at full load. This suggests that the effectiveness of biodiesel blends on HC emissions is engine load dependent, with B20 offering potential benefits at maximum load conditions.

The use of biodiesel in diesel engines has been widely studied due to its potential to reduce certain emissions and dependence on fossil fuels. However, it has been observed that biodiesel may lead to increased hydrocarbon (HC) emissions, especially at medium engine loads and maximum torque speeds. Biodiesel has higher oxygen content and different combustion characteristics compared to conventional diesel, which may lead to incomplete combustion and higher HC emissions at medium loads [56–59]. The ignition delay and combustion duration of biodiesel blends can vary significantly, especially at moderate loads. This variability can lead to incomplete combustion and increased HC emissions [58–60].

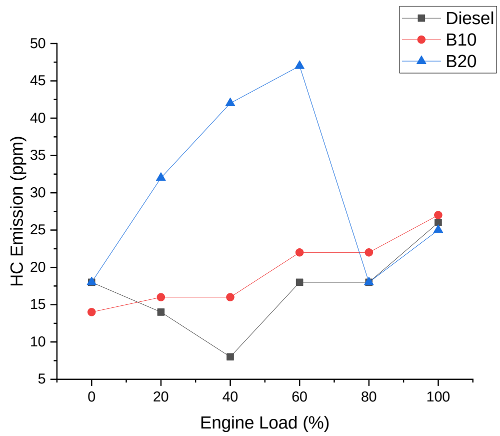

Fig. 12. Diesel biodiesel fuel mixture HC Emission value changing with engine load

Diesel-biodiesel fuel mixture NO_x Emission value changing with engine load can be seen in Figure 13. At 0% engine load, the NO_x emission for diesel is 136 ppm. B10 shows a higher NO_x emission of 197 ppm, and B20 exhibits an emission of 169 ppm. This indicates that both biodiesel blends increase NO_x emissions at idle conditions, with B10 having a more pronounced effect. At 20% engine load, diesel produces a NO_x emission of 588 ppm. B10 significantly increases the emission to 866 ppm, while B20 further increases it to 994 ppm. This suggests that both biodiesel blends tend to increase NO_x emissions under low load conditions, with B20 showing a greater increase. At 40% engine load, diesel has a NO_x emission of 1212 ppm. B10 increases the emission to 1318 ppm, and B20 further increases it to 1519 ppm. This indicates that both biodiesel blends consistently lead to higher NO_x emissions at mid-load conditions, with B20 showing the highest increase. When the engine load reaches 60%, diesel produces a NO_x emission of 1321 ppm. B10 shows a slightly higher emission of 1346 ppm, while B20 exhibits a similar emission level of 1350 ppm. This suggests that higher biodiesel content results in slightly higher NO_x emissions at mid-load conditions. At 80% engine load, diesel shows a NO_x emission of 1009 ppm. B10 has a higher emission of 1111 ppm, and B20 shows a slightly lower emission of 1070 ppm compared to B10. This indicates that B20, although still higher than diesel, leads to relatively lower NO_x emissions compared to B10 at higher loads. Finally, at 100% engine load, diesel has a NO_x emission of 827 ppm. B10 shows a higher emission of 959 ppm, while B20 exhibits the highest emission of 985 ppm. This indicates that under maximum load conditions, both biodiesel blends produce higher NO_x emissions compared to diesel, with B20 showing the greatest increase.

The discussion of these findings reveals several important trends and implications for engine NO_x emission performance using different fuel mixtures. Biodiesel blends, particularly B20, tend to increase NO_x emissions across most load conditions, suggesting that while biodiesel offers environmental benefits such as reduced particulate matter and lower sulfur content, it may also lead to higher NO_x emissions. This increase in NO_x emissions could be attributed to the higher oxygen content and combustion temperatures associated with biodiesel. Based on the data, neither B10 nor B20 is optimal for reducing NO_x emissions, as both blends consistently produce higher emissions compared to pure diesel. This indicates that while biodiesel blends may offer other environmental benefits, their impact on NO_x emissions needs to be carefully managed [61].

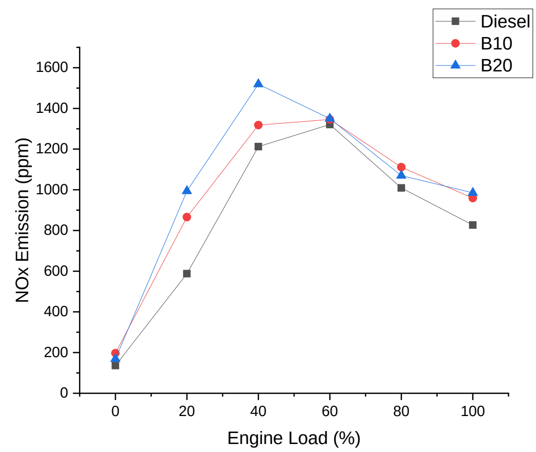

Fig. 13. Diesel biodiesel fuel mixture NOx Emission value changing with engine load

Diesel-biodiesel fuel mixture Smoke opacity value changing with engine load can be seen in Figure 14. At 0% engine load, the smoke opacity for diesel is 2%. Both B10 and B20 show a lower smoke opacity of 1%. This indicates that both biodiesel blends result in reduced smoke emissions at idle conditions. At 20% engine load, diesel produces a smoke opacity of 4%. B10 reduces the smoke opacity to 2.5%, and B20 further reduces it to 1.75%. This suggests that both biodiesel blends significantly reduce smoke emissions under low load conditions, with B20 having a more pronounced effect. At 40% engine load, diesel has a smoke opacity of 5%. B10 maintains the same smoke opacity of 4%, while B20 shows a much lower smoke opacity of 2.35%. This indicates that both biodiesel blends continue to reduce smoke emissions at mid-load conditions, with B20 showing a greater reduction. When the engine load reaches 60%, diesel produces a smoke opacity of 15.23%. B10 significantly reduces the smoke opacity to 6%, while B20 shows a moderate reduction to 9.43%. This suggests that higher biodiesel content results in lower smoke emissions at mid-load conditions. At 80% engine load, diesel shows a smoke opacity of 32.1%. B10 has a significantly lower smoke opacity of 23.04%, and B20 also shows a reduced smoke opacity of 28.93%. This indicates that both biodiesel blends lead to decreased smoke emissions at higher loads, with B10 having the most significant impact. Finally, at 100% engine load, diesel has a smoke opacity of 36%.

B10 shows a lower smoke opacity of 30.73%, while B20 exhibits a slightly higher opacity of 33.31% compared to B10 but still lower than diesel. This indicates that under maximum load conditions, both biodiesel blends continue to produce lower smoke emissions compared to diesel, with B10 showing the greatest reduction.

The discussion of these findings reveals several important trends and implications for engine smoke opacity performance using different fuel mixtures. Biodiesel blends, particularly B10, consistently reduce smoke emissions across all load conditions. The lower smoke opacity observed in B10 fuel compared to D100 and B20 at medium and high loads can be attributed to several factors related to the composition and combustion characteristics of biodiesel blends. Biodiesel contains natural oxygen within its molecular structure, which increases combustion efficiency. The oxygen present in B10 improves the oxidation process during combustion, allowing the fuel to burn more completely. This results in a reduction in the formation of soot and particulate matter, which are primary contributors to smoke opacity. B10, a lower biodiesel blend, provides a balance between the oxygen content provided by biodiesel and the combustion characteristics of conventional diesel. At medium and high loads, this balance can lead to an optimum fuel-air mixture that promotes better atomization and combustion, thereby reducing the formation of incomplete combustion products that contribute to smoke opacity. Biodiesel generally has a higher cetane number than conventional diesel fuel, resulting in shorter ignition delays and a more controlled combustion process. In B10, the presence of biodiesel can slightly increase the combustion temperature, which helps oxidize soot precursors and reduces smoke emissions. This effect can be more pronounced at medium and high loads, where combustion is more intense. Physical properties of biodiesel, such as higher viscosity and surface tension, can affect fuel atomization properties. In the case of B10, the lower biodiesel concentration allows fuel atomization and atomization to still be close to that of pure diesel, leading to better mixing and combustion, especially under higher load conditions. This can result in lower smoke opacity compared to B20, where the higher biodiesel content can negatively affect atomization properties. The lower aromatic content in biodiesel compared to conventional diesel results in lower soot formation during combustion. At medium and high loads, engines generally operate at higher thermal efficiency, where the benefits of oxygen content and improved combustion properties of B10 become more apparent. In summary, the lower smoke opacity of B10 fuel at medium and high loads is thought to be due to a combination of improved combustion due to oxygen content, optimized fuel-air mixture, favorable combustion temperatures, and reduced soot formation. These factors work together to provide more complete combustion and lower particulate emissions, making B10 an effective blend for reducing smoke opacity under these conditions. This indicates that incorporating biodiesel into diesel fuel can be beneficial for reducing particulate emissions and improving air quality without significantly compromising engine performance. Based on the data, B10 appears to be the optimal blend for achieving the lowest smoke opacity and enhancing combustion efficiency across various load conditions. B20 also shows promise, particularly at lower and mid-loads, but its impact on smoke opacity at high loads is slightly less pronounced compared to B10 [52].

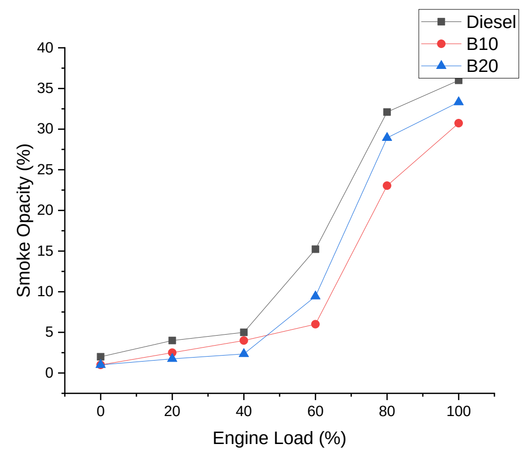

Fig. 14. Diesel biodiesel fuel mixture Smoke Opacity value changing with engine load

4. Conclusions

This study comprehensively analyzed the performance of a diesel engine using three different fuel types: pure diesel, B10 (a blend of 90% diesel and 10% biodiesel), and B20 (a blend of 80% diesel and 20% biodiesel). The engine's performance was evaluated across various metrics, including torque, power, brake specific fuel consumption (BSFC), exhaust gas temperature, noise, vibration, CO, CO_2, HC, O_2, NO_x emissions, and smoke opacity across different engine load percentages. The key findings and implications from these evaluations are summarized below:

•B10 consistently enhanced torque and power output compared to diesel, especially at low to mid-load conditions, indicating improved performance efficiency. B20 also showed improvements but to a lesser extent compared to B10, particularly at high load conditions.

•Both B10 and B20 generally showed lower BSFC values than diesel at lower loads, indicating better fuel efficiency. However, at higher loads, the BSFC for B10 and B20 was comparable to or slightly higher than diesel.

•Biodiesel blends, particularly B20, led to higher exhaust gas temperatures, suggesting more complete combustion but also indicating potential for higher thermal stress on engine components.

•B10 and B20 demonstrated mixed impacts on noise and vibration levels. While B20 tended to reduce noise at higher loads, it generally increased vibrations. Conversely, B10 showed slightly higher noise levels but could reduce vibrations at certain loads.

•B10 showed reduced CO emissions at most load conditions, whereas B20 had mixed results, reducing CO emissions at high loads but increasing them at low loads.

•B10 and B20 resulted in higher CO_2 emissions compared to diesel, indicating higher carbon content and more complete combustion.

•B10 effectively reduced HC emissions at idle but increased them at higher loads. B20 generally led to higher HC emissions at low to mid-loads but showed potential for reduction at higher loads.

•Biodiesel blends consistently reduced O_2 emissions, suggesting improved combustion efficiency.

•B10 and B20 resulted in higher NO_x emissions, with B20 showing the most significant increases. This is likely due to the higher oxygen content in biodiesel leading to increased combustion temperatures.

•B10 and B20 significantly reduced smoke opacity across all load conditions, with B10 showing the greatest reductions.

The findings suggest that incorporating biodiesel, particularly B10, can improve certain performance metrics such as torque, power, and smoke opacity, while also offering potential fuel efficiency benefits at lower loads. However, the increased NO_x and CO_2 emissions observed with biodiesel blends highlight a critical trade-off, emphasizing the need for strategies to mitigate these emissions. Additionally, the higher exhaust gas temperatures and mixed impacts on noise and vibration call for further investigation into the long-term effects on engine durability and performance. Future studies should focus on optimizing biodiesel blends to balance the benefits of reduced particulate emissions and improved combustion efficiency with the drawbacks of increased NO_x and CO_2 emissions. Long-term durability tests and advanced emission control technologies should also be explored to enhance the viability of biodiesel as a sustainable alternative to pure diesel.

In addition, the use of biodiesel blends can reduce dependence on pure fossil fuels and offer environmental benefits such as reduced emissions. Small improvements in power performance can also translate into improved fuel efficiency and operational cost savings. Based on the figures, B10 appears to be the optimal blend to provide a balance between improved power performance across a range of load conditions and maintenance of engine efficiency. B20 also shows promise, particularly at medium to high loads, but its benefits need to be weighed against potential economic and mechanical considerations. B10 in particular provides significant improvements in power performance across a range of engine loads. This makes them a viable alternative to pure diesel and offers both environmental and performance benefits.

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Nomenclature

Al_2O_3	:	Alumina
B10	:	%90 diesel + %10 biodiesel
B20	:	%80 diesel + %20 biodiesel
BL20	:	20% RM + 80% diesel
BSFC	:	Brake specific fuel consumption
BTE	:	Brake thermal efficiency
CO	:	Carbon monoxide
CO_2	:	Carbon dioxide
D100	:	Pure diesel
dBA	:	Decibel
EGT	:	Exhaust gas temperature
HC	:	Hydrocarbon
NO_x	:	Nitrogen oxide
O_2	:	Oxygen
PM	:	Particulate matter
RM	:	50% Rapeseed biofuel + 50% Mahua biofuel
rpm	:	Revolutions per minute

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Can Haşimoğlu: Conceptualization, Supervision, **Mahmut İnce** Conceptualization, **Samet Çelebi** Conceptualization, Writing-original draft, Validation, **Usame Demir**: Writing-original draft, Validation, Data curation, Formal analysis

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