

Article

The Impact of Utilizing Waste Sunflower Oil as a Biodiesel Blend on Four-Stroke Engine Performance and Emissions

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Abstract: The blending of biodiesel with petroleum diesel attracts much attention due to its high potential in reducing emissions. In this work, waste sunflower oil was converted to biodiesel by the trans-esterification method, and it was blended with petroleum diesel in three ratios (10, 30, and 50%). The impact of using these blended fuels in a four-stroke engine on engine performance and exhaust emissions at three engine loads (2, 4, and 6 N.m) was investigated and compared with the use of petroleum diesel and biodiesel. The engine performance was evaluated by determining the brake-specific fuel consumption (BSFC), engine effective power (Ne), brake-specific energy consumption (BSEC), brake thermal efficiency (BTE), and noise intensity. The evaluation of emissions from the engine exhaust was carried out by measuring the levels of carbon oxides (CO and CO₂), hydrocarbons (HC), nitrogen oxides (NO and NO₂), and particulate matter (PM). The results show that blending diesel with up to 30% biodiesel can reduce CO, HC, and PM emissions by $29.6 \pm 1\%$, $26.0 \pm 4\%$, and $31.0 \pm 3\%$, respectively. However, this decrease is associated with increasing CO₂ and NO_x emissions by $18.5 \pm 2.5\%$ and $29.0 \pm 6\%$, respectively. In addition, the engine showed acceptable performance when using up to 30% biodiesel, where the increase in fuel consumption was limited to $5.8 \pm 0.3\%$. In addition, the engine's effective power increased with the blending ratio of 10% by $2.0 \pm 0.6\%$, but then decreased with the blending ratio of 30% by only $2.0 \pm 0.6\%$. The noise intensity was also decreased by 2.4%, while BSEC and BTE were reduced by only $2.9 \pm 0.9\%$ and $3.5 \pm 1\%$, respectively. The results of this work provide deep insights regarding the utilization of waste sunflower oil as biodiesel to be blended with petroleum diesel, which is a considerable novel approach in the energy and environmental sectors.

Keywords: brake-specific fuel consumption; engine effective power; brake thermal efficiency; noise; brake-specific energy consumption



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1. Introduction

To meet different human needs, energy demand has increased, and thus, the demand for diesel fuel as a source of energy production has increased. The probability of fossil fuel depletion and increasing prices and emissions motivate manufacturers, governments, and researchers to find alternatives [1]. Thus, bio-diesel attracts much attention due to its high potential [2] and its attractive qualities in terms of high cetane number and oxygen content, which help to reduce engine knock and emissions, respectively [3]. However, the use of pure biodiesel is associated with some issues, such as increasing the deposit of carbon in the injector tip, increasing the amount of accumulation in the engine, and increasing the

wear in the cylinder liner [4]. Therefore, mixing biodiesel with ordinary fossil diesel has been suggested to minimize these negative effects.

In this research, the focus was on biodiesel production as a source of energy, as it is considered an alternative, renewable, and environmentally friendly fuel due to its lower generation rate of pollutants compared with petroleum diesel fuel [5]. Based on the literature, the heating value of biodiesel is about 11–15% lower than that of diesel [6,7]. In addition, the kinematic viscosity of biodiesel is within the acceptable range (1.9 to 6.0 mm²/s), and the flash point of all biodiesels is more than 150 °C [8,9], which makes it safer than petroleum-based diesel. Furthermore, it was found that mixing different percentages of bio-fuel with ordinary diesel fuel reduces exhaust gases such as carbon monoxide (CO) and particulate matters (PM) [10,11]. However, there is still uncertainty about the ability to reduce the emissions of carbon dioxide (CO₂) and nitrogen oxides (NO and NO₂) [4,12].

Pure biodiesel is referred to as B100, while its mixing by volume with petroleum diesel is referred to as B, and is represented by a biodiesel concentration ratio. Researchers found that the consumption of fuel increases by around 14% with the use of biodiesel [13], while the use of B30 obtained from waste vegetable oils in a single cylinder with a direct-injection diesel engine resulted in the lowering of thermal efficiency by 1–5% [14]. Rahman et al. reported that using B30 biodiesel has almost no significant impact on engine performance and emissions, but sacrificing a small amount of fuel can achieve slightly higher efficiency, a shorter ignition delay, and a lower rate of heat release [15]. The literature also showed great variation in carbon emissions based on the raw materials of biodiesel. For example, biodiesel generated from soy, corn, tallow, canola, and soybeans showed the highest carbon emissions, while waste cooking oil produced the lowest [16].

Biodiesel production can be carried out by different methods such as micro-emulsion, dilution (thinning), pyrolysis, and trans-esterification, and the latter is the most widely used [17]. In the trans-esterification method, biodiesel is formed through the reaction of an alcohol such as ethanol or methanol with oil (from vegetable or animal). The trans-esterification method has several advantages over other methods, such as low cost, high renewability, lower emissions, ease of production at an industrial scale, the high cetane number of the product, lighter reaction conditions, and characteristics close to those of standard diesel fuel. However, it has some disadvantages, such as the need for frequent and deep cleaning processes, unwanted side reactions, extensive separation, and large amounts of waste water [18,19].

This work aims to find an alternative fuel by utilizing waste sunflower oil to produce biodiesel fuel and mixing it with different percentages of ordinary diesel fuel and investigating the blended fuels' impacts on the performance of a four-stroke single-cylinder diesel engine and its emissions. We utilize waste sunflower oil is due to its availability in large amounts and the need to recycle it sustainably. The results of this work provide deep insights regarding the application of utilizing waste sunflower oil as biodiesel to be blended with petroleum diesel. Several advantages can be achieved by using this method, such as reducing the emission of pollutants from fuel combustion, avoiding the discharge of waste oil to the environment, producing biodiesel renewably, and reducing the noise level of diesel engines. Providing deep insights to achieve these targets is of considerable value in the energy and environmental sectors.

2. Research Materials and Methods

2.1. Biodiesel Production

Biodiesel was prepared from waste sunflower oil collected from restaurants and food factories in Baghdad city (Iraq) after a filtration step. A titration step was performed to identify the amount of catalyst required to neutralize the fatty acids in the waste sunflower oil. The titration was performed by dissolving one gram of potassium hydroxide (KOH, AUS CHEM SOURCE, 90%) in one liter of deionized water. Then, one milliliter of waste sunflower oil was dissolved into ten milliliters of isopropyl alcohol (CORECHEM 99.0%).

The pH was set to 8.5 ± 0.5 by adding sodium hydroxide (NaOH, 0.1 N) using an eyedropper with phenolphthalein as an indicator. The quantity of KOH that was added until the color of the oil changed to pink was recorded.

The waste sunflower oil was placed in a mixer basin and methanol (ACS grade > 99.8%) was added to it, while KOH was added as a catalyst with the help of magnetic stirring operating at a speed of 550 rpm to ensure a homogeneous reaction. The mixer was operated for five hours at 60 °C, which is below the boiling temperature of alcohol. Then, the materials were transferred to another closed basin and left for (24) h to precipitate the glycerin at the bottom of the basin. After the esterification process, the water was removed and the materials were heated to 60 °C. When the biodiesel was ready for use, it was mixed in the desired ratio with petroleum diesel fuel, which was obtained from the Al-Dorra refinery station (Baghdad, Iraq). The experimental procedure included using five fuel types, including non-blending diesel (D), B10, B30, B50, and B100. The properties of both the petroleum and biofuels are listed in Table 1, with the measurements taken at the Al-Dorra refinery laboratory.

Table 1. Characterization of all used fuel.

Type of Fuel	Fuel's Density (kg/m ³)	Fuel's Kinematic Viscosity (cSt) at 40	Calorific Value (CV) (KJ/Kg)	Cetane Number	LHV (MJ/kg)	Latent Heat of Vaporization (kJ/kg)
Diesel	839.00 ± 1.00	2.449	43,464.71	55.95	42.5	249.1 ± 1.00
B10	840.44 ± 1.00	2.70	43,034.21	56.35	42.0	250.5 ± 1.00
B30	851.61 ± 1.00	3.11	42,173.45	57.20	41.0	251.5 ± 1.00
B50	862.5 ± 1.00	3.51	41,312.60	58.05	40.5	252.5 ± 1.00
B100	884.00 ± 1.00	4.490	39,160.50	60.10	37.5	254.0 ± 1.00

2.2. Engine Tests

The aim of the second stage of this research was to conduct tests to evaluate the engine's performance and determine the proportion of emissions of burning gases. These tests were carried out in an internal combustion laboratory (TD 212, manufactured by AVL in Graz, Austria) in the Department of Power/Automotive Mechanics at Kut Technical Institute using a four-stroke single-cylinder diesel tester (Figure 1a) with pneumatic cooling. Its maximum power and torque are 3.5 Kw and 16 at 3600 rpm, respectively. The diameter of the engine cylinder is 69 mm, with a connected rod length of 104 mm and an engine capacity of 232 cm³. To evaluate the engine's efficiency, the engine was connected to a hydraulic dynamometer to set the required load on the engine. Furthermore, the engine was linked to the unit of measurement, where all test measurements from the engine were recorded (Figure 1b).

The work procedure and engine specifications are presented in detail in previous works [20]. Briefly, the procedure started with evacuating and refilling the engine fuel tank based on the required fuel type. A torque value of 2, 4, or 6 N.m was applied to the engine, keeping the engine speed constant at 2000 rpm for all tests. A warm-up period of 15 min was applied before loading the desired torque with a dynamometer control. Each experiment was triplicated, and the average values are presented in this work with their standard deviation.

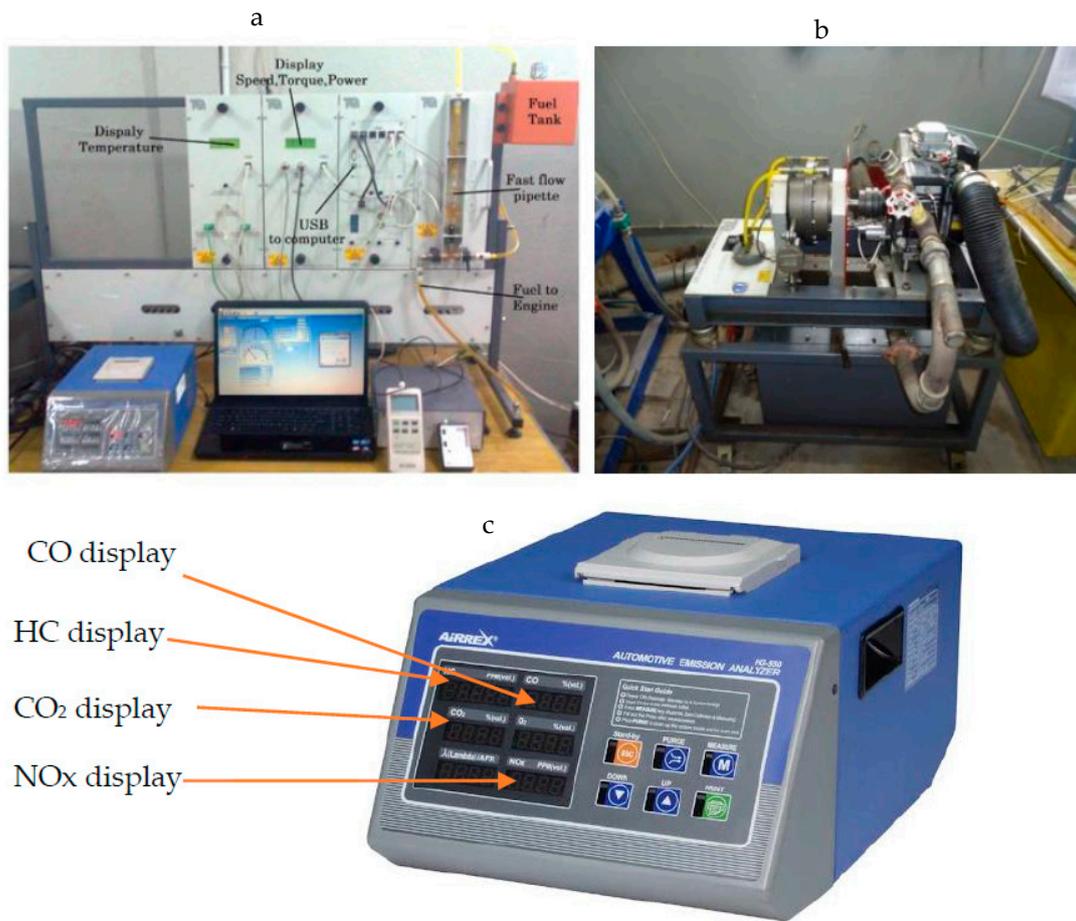


Figure 1. (a) Diesel engine, (b) measurement unit, and (c) emission analyzer.

2.3. Tested Parameters

The evaluation of performance was carried out by identifying several parameters, including BSFC (kg/kW.h), Ne (kW), BSEC (MJ/kW.h), BTE, and noise intensity. Equations (1)–(5), respectively, were used to calculate these parameters [21–24]:

$$BSFC = m^{\circ}f / B.P \quad (1)$$

$$Ne = MF / BSFC \quad (2)$$

$$BSEC = BSFC \times LHV \quad (3)$$

$$B.P = 2 \times \pi NT / 60,000 \quad (4)$$

$$\eta_{bth} = B.P \times 3600 / m^{\circ}f \times CV \quad (5)$$

where $m^{\circ}f$, B.P, MF, LHV, T, N, and CV are the fuel consumption rate (g/s), power produced (W), fuel mass flow rate, lower heating value (MJ/kg), engine brake load (N.m), speed (rpm), and heat value of the fuel kJ/kg.

2.4. Emission and Noise Tests

An emission test was conducted to calculate the gaseous percentages and PM emitted from the engine exhaust using an AIRREX HG-540 (AIRREX Co., Ltd., Seoul, Republic of Korea) gas analyzer (Figure 1c), which measures CO, CO₂, HC, and NO_x gases with accuracy and repeatability better than 0.10 m+. To measure the volume of the emission, the analyzer was connected to the testing engine exhaust by a line with a gas meter. To capture PM, a fiberglass filter (Grade 934-AH, Whatman, Maidstone, UK) was used, and the PM weight was measured by calculating the increase in the filter weight after each

experiment. The testing experiment was duplicated, and the average value is considered here. An Onossokki LA-7700 (Vantaa, Finland) sound pressure level meter (measurement frequency range: 10 Hz to 20 kHz and measurement level range: 20 to 128 dB) was used to measure the engine noise in decibels (dB). The noise level was measured for the five fuel types at the three load values at a constant speed. The measurement was conducted by setting up a microphone 1 m away from the four directions of the engine (front, left, right, and back).

3. Results and Discussion

3.1. Engine Performance

In this work, the method of blending diesel with bio-diesel manufactured from waste oil was used in different mixing ratios (10, 30, and 50%) in a four-stroke engine to compare their impacts on engine performance and emissions with those of petroleum diesel and pure biodiesel. Figure 2a shows the impact of blending petroleum diesel with the prepared biodiesel on the BSFC value, and indexes fuel efficiency by presenting the fuel-consumption rate per produced power. These experiments show that the BSFC values of B10 at various torque values are adjacent to that of petroleum diesel, while raising the mixing ratio resulted in higher BSFC values, which means a reduction in the overall engine efficiency with an increasing blending ratio.

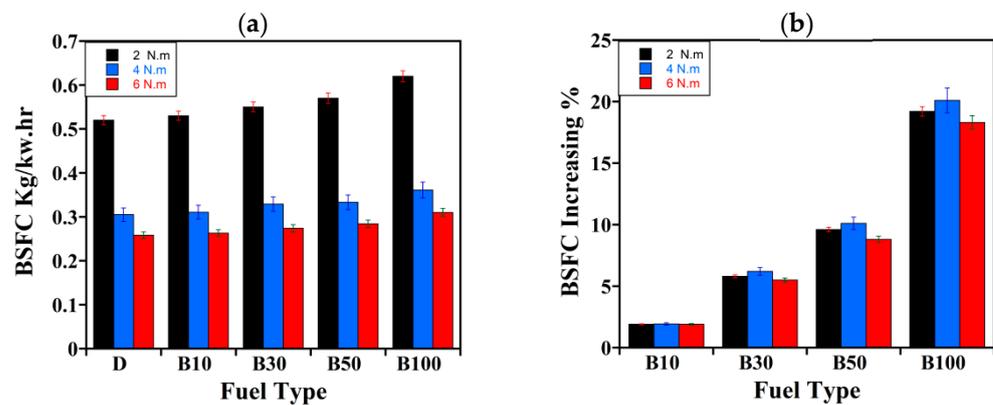


Figure 2. (a) The effect of increasing the mixing ratio of fuel at constant engine speed (2000 rpm) and various torques on BSFC (kg/kW.hr) and (b) increasing the % of BSFC.

Specifically, load values of 2.0 N.m, D, B10, B30, B50, and B100 result in BSFC values of 0.52, 0.53, 0.55, 0.57, and 0.62 (kg/kW.hr), respectively. Biodiesel has a lower heating value than petroleum diesel, and thus, blending fuel has a lower heating value than petroleum diesel, which causes higher fuel consumption to achieve the same engine power [4]. As shown in Figure 2b, the rises in the BSFC values with increasing biodiesel percentage are 1.9%, 5.8%, 9.6%, and 19.2%, respectively. This means that using B10 and B30 results in increasing fuel consumption by only 1.9% and 5.8%, respectively, while using B100 increases BSFC by 19.2% at the lowest load value (2.0 N.m).

At the highest torque value (6.0 N.m), there is a notable reduction in the BSFC values of all types of fuels compared to that at 2 N.m. Specifically, the BSFC values of D, B10, B30, B50, and B100 are 0.258, 0.263, 0.274, 0.284, and 0.310 (kg/kW.hr), respectively. This reduction in BSFC values is attributed to increasing the load value, which results in reduced fuel consumption, as indicated by the BSFC values, due to the increased chance for fuel to complete ignition. The rises in the BSFC values with rising biodiesel percentage at the highest torque value (6.0 N.m) are 1.9%, 6.2%, 10.1%, and 20.1%, respectively. This indicates that the loss in fuel consumption is very close at different load values. To confirm this conclusion, the BSFC value was also investigated at a torque value equal to 4 N.m. The BSFC values of D, B10, B30, B50 and B100 are 0.305, 0.311, 0.322, 0.333, and

0.361 (kg/kW.hr), respectively. The increases in the BSFC values are 1.9%, 5.5%, 8.8%, and 18.3%, respectively, which are so close to those of the other torque values.

Figure 3 shows that the effective power (N_e) of B10 is slightly higher than that of petroleum diesel, but the further increase in the blending ratio decreases the effective power. Specifically, the effective power values of D, B10, B30, B50, and B100 are 3.85, 3.9, 3.8, 3.7, and 3.5 (kW) at a torque value of 2 N.m. A similar trend is observed with higher torque values. Specifically, the effective power values of D, B10, B30, B50, and B100 at a torque value of 4 N.m are 6.55, 6.65, 6.50, 6.40, and 6.05 (kW), while the values are 7.75, 7.95, 7.55, 7.40, and 7.05 (kW), respectively, at a torque value of 6 N.m.

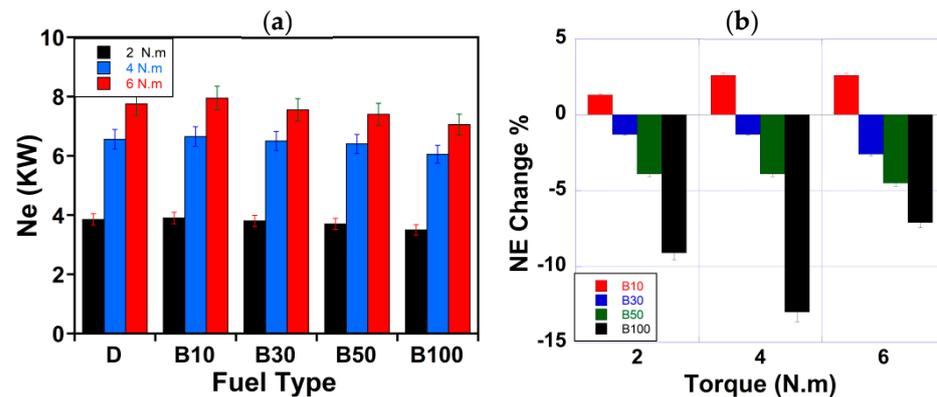


Figure 3. (a) The effect of increasing the mixing ratio of fuel at constant engine speed (2000 rpm) and different torques on engine effective power (N_e) and (b) the change %.

To make the results more understandable, Figure 3b shows the change percentage in the N_e values at different torque values for the blended fuel relative to diesel fuel. The engine's effective power increases when using B10 by $2.0 \pm 0.6\%$, but then decreases with B30 by the same percentage. The higher effective power of B10 is probably due to the higher oxygen content of the biodiesel, which improves combustion. The further increase in the biodiesel ratio results in a reduction in the effective power due to the lower calorific value and higher viscosity of biodiesel compared with that of petroleum diesel fuel. Increasing the fuel viscosity lowers the fuel flow rate and combustion efficiency, which results in power loss due to poorer fuel flow rate (MF in Equation (2)) and fuel atomization [25]. More in-depth, biodiesel has a higher boiling point, density, surface tension, viscosity, and latent heat of vaporization but lower vapor pressure compared with petroleum diesel. This resulted in higher spray penetration length and, thus, poorer atomization, and this is the reason for the lower N_e values at the higher torque values [26]. For this reason, an increase in the effective power is observed only in B10, and this increase is attributed to the impact of increasing the oxygen content, which has more influence than the viscosity impact. However, the further increase in the biodiesel ratio (B30, B50, and B100) leads to a decrease in the effective power due to the greater influence of viscosity compared to oxygen content.

Figure 4a shows the impact of blending biodiesel with diesel on the BSEC values. There is a notable decrease in BSEC values with rising torque values for all fuel types, while a slight increase can be observed upon raising the blending percentage. This behavior is somewhat expected due to the close connection between BSEC and BSFC values, where Equation (3) is used to determine the BSEC values based on the BSFC and LHV values. The LHV values of diesel and blended fuel are close; thus, the BSEC values are controlled considerably by the BSFC values. Biodiesel has a lower heating value than petroleum diesel, and this necessitates increasing fuel consumption to achieve the same engine efficiency [27]. As shown in Figure 4b, the loss of BSEC for blending fuel at different loads is in the range of 0.4% to 6.1%. These results indicate that the reduced percentage resulting from blending, especially with a ratio up to 30%, is within the acceptable range considering the advantages of blending, such as the reduction in the exhaust gases.

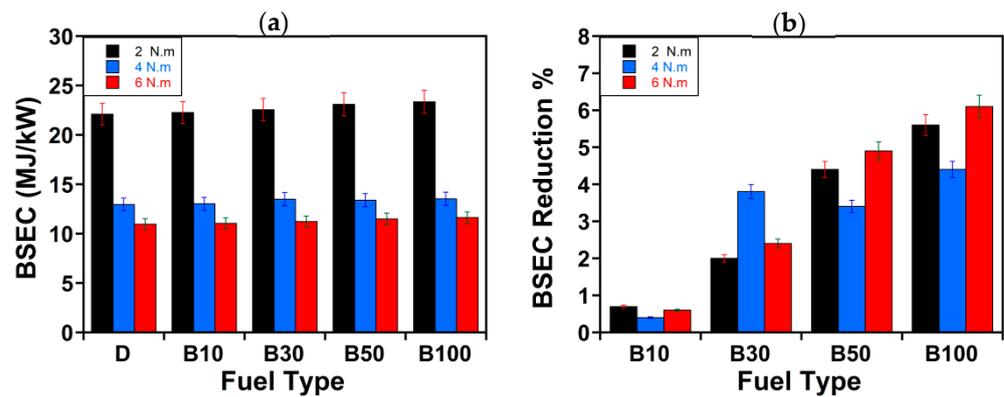


Figure 4. (a) The impact of increasing the blending ratio of fuel at a constant engine speed (2000 rpm) and various torques on BSEC MJ/kW.h and (b) the BSEC reduction percentage.

The impact of blending fuel on brake thermal efficiency at various loads is shown in Figure 5, which shows variations in the BTE values with increasing load and blending ratio. BTE is a helpful parameter to assess the efficiency of converting the energy in the fuel to mechanical output. BTE is calculated by dividing the brake power of the engine by the amount of energy supplied to the engine. The lost energy is evacuated by the engine in different forms, such as friction losses or heat transfer, through the engine cylinder and exhaust gases [28].

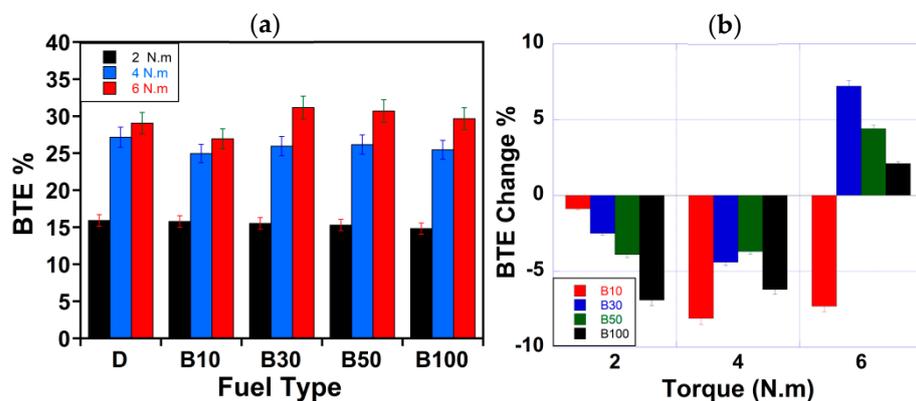


Figure 5. (a) The effect of increasing the mixing ratio of fuel at a constant speed (2000 rpm) and different torques on the brake thermal efficiency and (b) the BTE change %.

Generally, increasing the load increases the efficiency of all fuel types. This is probably due to decreasing fuel consumption at higher loads. B10 shows a reduction in efficiency compared with petroleum diesel, especially at high load values. A possible reason is the impact of lowering the calorific heat of fuel when combined with increased fuel viscosity as well. B30 shows another slight reduction in efficiency for the lowest load value. On the other hand, at the other load values, B30 shows better efficiency than B10, and a similar trend can be observed with B50. The variation in the BTE values indicates that there is more than one parameter effect on BTE. At lower loads, the impact of increasing the fuel viscosity would have more influence than the other parameters, resulting in an inferior combustion process and reduced BTE. On the other hand, blended fuels have lower heating values compared to petroleum diesel, which lowers the heat transfer losses and enhances BTE at higher load values [29,30]. B100 shows lower efficiency than diesel except at the highest load. At the highest torque value, B100 shows slightly higher BTE than diesel. The increased efficiency observed at higher load values in general, and especially with blended fuel, is probably due to the higher fuel injection pressure, which minimizes the impact of increasing viscosity with increasing biodiesel ratio [28]. In addition, higher oxygen content

of biodiesel fuel results in better combustion, and hence, a higher BTE value is gained. However, these results indicate that no general relationship can be deduced between BTE and the blending ratio, and several parameters may impact the correlation. Similar results that indicate a variation in BTE values with blending ratios and torque values are also reported in the literature [31].

Figure 6 shows the effect of mixing fuel on the engine noise level and the change percentage. Generally, raising the torque value increases the noise level, but increasing the blending ratio slightly decreases the noise level. This reduction in noise intensity is due to the positive influence of blending on the noise level in the injection pump and injector. Specifically, blending biodiesel with diesel resulted in a cooling impact on the cylinder charge due to the lower heating value of biodiesel and its higher oxygen content. This resulted in a reduction in the peak cylinder temperature, and this would reduce the machine knocking [32,33]. On the other hand, blending fuels show shorter ignition delay than that of petroleum diesel due to the higher cetane number of biodiesel fuel [4]. Shorter ignition delays were clearly observed at the higher blending ratio (50%) as well as with B100.

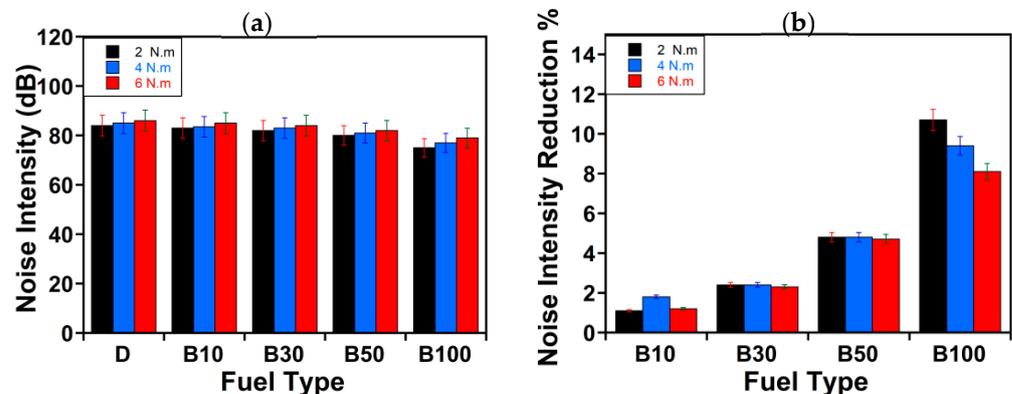


Figure 6. (a) The impact of increasing biodiesel ratio on the engine’s noise intensity (dB) and (b) reduction %.

3.2. Exhaust Gas Emissions

Figure 7 presents the results of the exhaust gases of the five types of fuel. In general, increasing the engine load resulted in an increase in the emissions for all types of fuel, which is probably due to several factors. The first of them is decreased combustion time, which resulted in increased HC and PM emissions. The second reason could be the increase in the temperature with increasing load, which resulted in a reduction in the partial combustion of the fuel resulting in CO emission. The third reason could be the increase in complete combustion, which resulted in increased CO₂ as well as NO emissions [33]. Thus, a reduction in emission upon increasing the applied load is only observed with CO due to the increasing temperature, which promotes full combustion, resulting in CO₂ formation and limiting the partial combustion that forms CO.

From Figure 7, a remarkable reduction in CO, HC, and PM can be noticed upon increasing the blending ratio. On the other hand, nitrogen oxide (NO and NO₂) and CO₂ emissions increase with increasing biodiesel ratio. As shown in Figure 8, the reduction percentages of CO with B10, B30, B50, and B100 at different torque values are 9.7 ± 1 , 29.6 ± 1 , 49 ± 2 , and 90.6 ± 1 , respectively. The chemical and physical properties of the fuel are crucial in CO emission, where the lack of oxygen is the main reason for increasing CO emission because it leads to partial combustion. Thus, increasing the biodiesel blending ratio resulted in a reduction in CO emissions due to the high oxygen content of biodiesel [34]. Similarly, the HC reductions that resulted from using B10, B30, B50, and B100 at various torque values are 10.6 ± 0.6 , 26.0 ± 4 , 48.0 ± 3 , and 88.0 ± 3 , respectively.

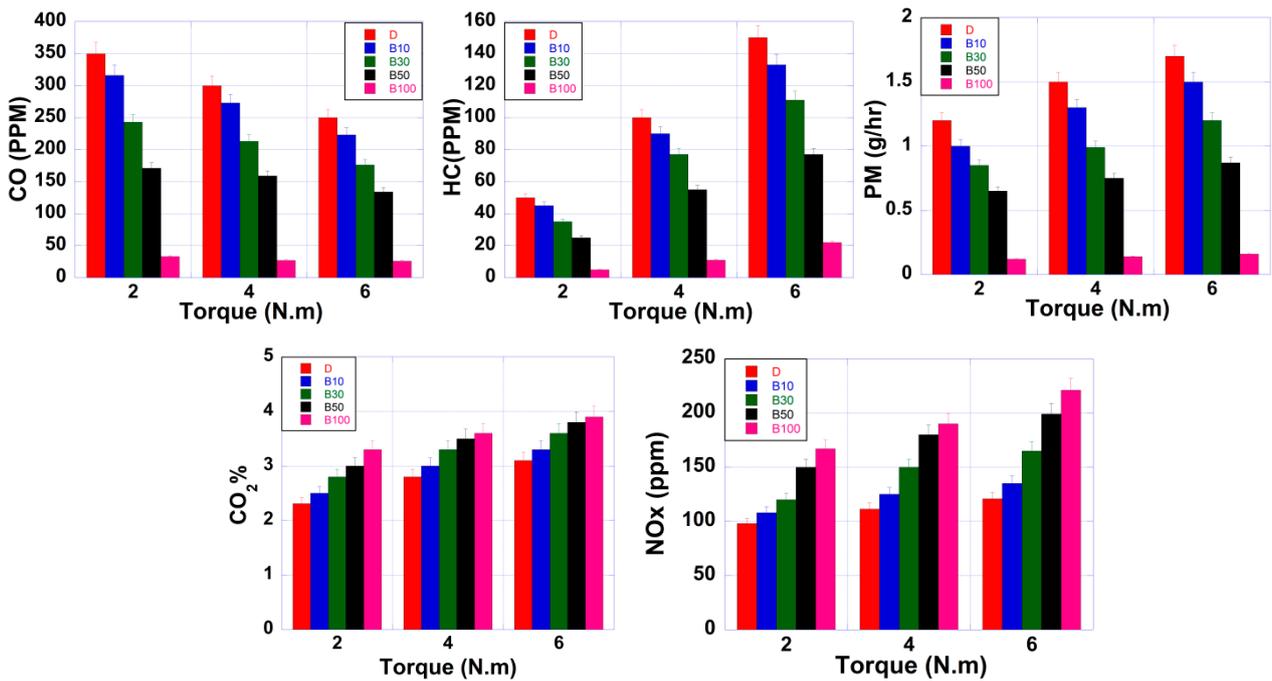


Figure 7. The impact of increasing the biodiesel ratio on the engine exhaust gas at different torque values and a constant engine speed (2000 rpm).

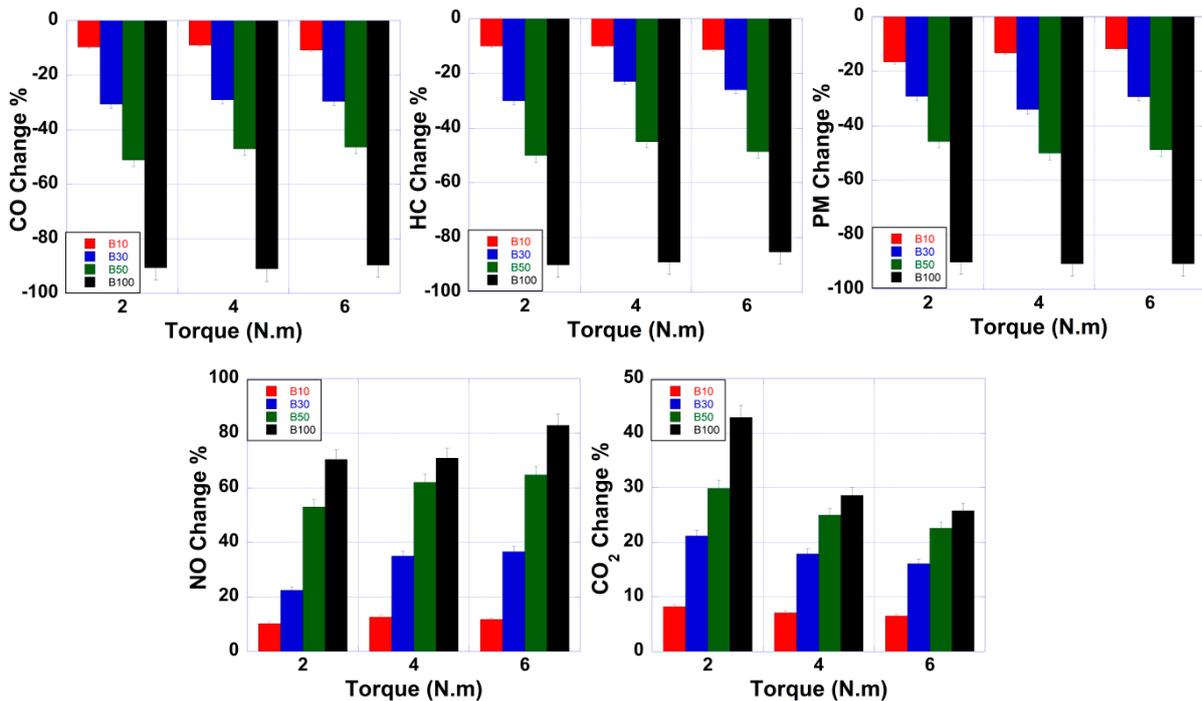
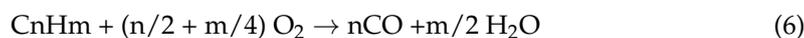


Figure 8. The change % of the engine exhaust gases at different torque values and biodiesel ratios and a constant engine speed (2000 rpm).

The incomplete combustion of fuel results in the emission of CO, which is an intermediate species with a slow rate of oxidation compared to other hydrocarbons [35]. For this reason, CO can be formed even with enough oxygen. Hydroxyl (OH) radicals play an essential role in the oxidation of CO, which is a highly exothermic reaction [36]. OH radicals are produced from the chain-branching reactions involved in the oxidation reaction. CO emission results from either the under-mixing or over-mixing of air with

fuel [37]. Under-mixing results from a low combustion temperature, which limits the oxidation of CO even in the presence of enough oxygen molecules. Over-mixing results from lean combustion associated with the ignition delay period. Using a numerical method, a two-step mechanism was suggested for the oxidation of different hydrocarbon fuels. The first step shows the oxidation of fuel, which results in the formation of CO (Equation (6)), while the second step is CO oxidation (Equation (7)) [38].



HC emission occurs due to the poor involvement of fuel in combustion and evaporation [39]. Thus, a high reduction in HC emissions occurs due to better combustion of fuel resulting from the higher oxygen content of biodiesel [40], which is also the reason behind the reduction in PM emissions. In addition, HC consists of unburned fuels, which result from insufficient temperature at the cylinder wall. At the wall, the combustion temperature is notably lower than that at the center of the cylinder. HC results from different species, including aromatics, alkenes, and alkanes [41–43].

The PM reductions that resulted from using B10, B30, B50, and B100 at various torque values are 13.6 ± 3 , 31.0 ± 3 , 48.0 ± 3 , and 90.3 ± 0.3 , respectively. Due to the higher availability of oxygen in biodiesel compared to diesel fuel, the oxygen content of PM resulting from biofuel combustion would be higher and it would have a higher oxidation rate [44]. The other factor responsible for the higher oxidation state of biodiesel is the higher temperature. A. S. (Ed) Cheng et al. found, from their numerical modeling of oxygenation in diesel and biodiesel, some evidence about the importance of the nature of the reaction products in PM formation [45]. Specifically, the variation in the pyrolysis of the fuel components, such as n-heptane, oxygenated DMM, and ethanol, leads to the next steps, which are the formation of an aromatic ring, the growth of PAH, and the inception of PM particles. The significant impact of providing more oxygen by adding biodiesel increases the radical concentrations, such as O, OH, and HCO, which have an important impact on the generation of PM. Specifically, increasing the O, HCO, and OH radical concentrations emphasizes the oxidation reaction of carbons to CO and CO₂ and minimizes the formation of PM precursors due to the limitation in the available amount of carbon [45–47].

On the other hand, the reduction in CO, HC, and PM emissions with an increasing biodiesel ratio is probably correlated to the obvious rise in CO₂ emission. The higher oxygen content of biodiesel helps to enhance the complete combustion of fuel and minimize the partial oxidation of fuel, as well as the formation of PM and HC. Increasing CO₂ emissions with the reduction in CO, HC, and PM emissions is evidence of the better and complete combustion of fuel. However, the higher oxygen content might not be the only reason for these emission changes. Higher temperatures, especially with high engine loads, can have a similar impact. There is obvious evidence that increasing combustion temperature increases NO emission [48], which results from the reaction of fuel oxygen with nitrogen from the air. This reaction is promoted by increasing both the combustion temperature and the available oxygen. In addition, the use of biodiesel increases the consumed fuel, which results in the increased emission of CO₂ due to the consumption of more fuel [49]. However, this increase in the emission rate is limited to CO₂ only due to the better combustion quality achieved by biodiesel. At the lowest load, CO₂ increases rapidly with increasing biodiesel percentage. However, the percentage increase at higher load values is lower, especially with B50 and B100. This indicates that the available oxygen content in biodiesel up to B50 is enough to promote full combustion of the fuel, which results in CO₂ formation. A similar trend was observed with NO emission, which indicates that other parameters impact the generation of the emitted gases, such as the combustion temperature and time. In addition, the impact of engine design and geometry on the variation in emissions should not be ignored [50]. In conclusion, this work suggests the utilization of waste sunflower oil as

biodiesel to be blended with petroleum diesel by up to 30% to reduce the pollutants emitted from diesel engines.

4. Conclusions

A comprehensive investigation of the effect of blending diesel fuel with biodiesel manufactured from waste sunflower oil on the engine performance and emissions of a four-stroke engine was performed under various load values. Based on the experimental results, it can be concluded that diesel fuel can be blended with up to 30% biodiesel with acceptable performance and a remarkable reduction in CO, HC, and PM emissions. This conclusion is based on evaluating BSFC, BSEC, NE, and BTE values, and the other general points and conclusion are as follows.

- Increasing the blending ratio increases the consumption of fuel and BSEC due to the lower heating value of biodiesel compared to petroleum diesel.
- B10 shows higher Ne than diesel fuel, which is probably due to the higher oxygen content of the biodiesel, while B30 shows a small reduction in Ne, due to the lower calorific value and higher viscosity of biodiesel compared with that of petroleum diesel fuel, and this lowers the fuel flow rate and combustion efficiency.
- B30 showed an acceptable reduction in BTE for the lowest load value. On the other hand, using B30 at the other load values (4 and 6 N.m) showed better efficiencies than that using B10. This variation in the BTE values indicates that there is more than one parameter effect on break thermal efficiency. At lower loads, the impact of increasing the fuel viscosity has more influence than other parameters resulting in an inferior combustion process and reduced BTE. On the other hand, blended fuels have lower heating values compared to diesel, which reduces the heat transfer losses, and enhances the thermal efficiency at higher load values.
- Blending biodiesel with diesel resulted in a cooling impact on the cylinder charge due to the lower heating value of biodiesel and its higher oxygen content. This resulted in a reduction in the peak cylinder temperature, and this reduced machine knocking and noising intensity.
- Increasing the biodiesel blending ratio resulted in a reduction in CO emissions due to the high oxygen content of biodiesel. This high reduction in HC emission was due to the better combustion of fuel resulting from the higher oxygen content of biodiesel. On the other hand, the reduction in CO, HC, and PM emissions with increasing biodiesel ratio was probably correlated with the obvious rise in CO₂ emission.
- The increase in CO₂ emission with an increasing biodiesel ratio was also due to increasing fuel consumption.
- The increase in NO_x emission with an increasing biodiesel ratio was due to increasing fuel oxygen content and its reaction with N₂ in the air at higher temperatures.

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Nomenclature

List of Abbreviation Symbols	Definitions
B100	Pure biodiesel
B10	10% biodiesel and 90% petroleum diesel
BSEC	Brake-specific energy consumption
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CO _x	Carbon oxides (CO & CO ₂)
CV	Calorific value
D	Non-blending diesel
dB	Decibels
FM	Fuel mass flow rate
HC	Hydrocarbons
LHV	Lower heating value (MJ/kg)
m ^o f	Fuel consumption rate (g/s)
N	Speed (rpm)
Ne	Engine effective power
NO _x	Nitrogen oxides (NO & NO ₂)
P.B	Power produced (W)
PM	Particulate matter
T	Engine brake load (N.m)
η _{bth}	Noise intensity

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