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EXPERIMENTAL EVALUATION OF THE COMBUSTION AND EMISSION CHARACTERISTICS OF WASTE NON-EDIBLE RESTAURANT OILS AND HIGH-SULFUR DIESEL

MIQDAM T. CHAICHAN[1, *], NOORA S. EKAB[2], ISAM E. YOUSIF[3]

[1]Energy and Renewable Energies Technology Center, University of Technology, Baghdad, Iraq
[2]Electromechanical Engineering Department, University of Technology, Baghdad, Iraq
[3]Fuel and Energy Engineering Technologies Department, Technical Engineering College-Kirkuk, Northern Technical University, Iraq
*Corresponding Author: : miqdam.t.chaichan@uotechnology.edu.iq

Abstract

Recently, researchers in the field of diesel engines have focused more on finding a green and environmentally friendly that reduces greenhouse gas emissions. Due to using diesel fuel with high sulphur content, Iraq's environment suffers from severe pollution. Using leftover cooking oil to produce biofuel is considered by many researchers as an alternative to conventional diesel fuel. Besides its high viscosity, this biofuel has a low cetane number, which reduces combustion efficiency when used purely. However, when mixed with diesel in certain proportions, as in the current study, unlike diesel fuel, engine performance and emissions are affected in different ways by it. Baghdad restaurants' cooking oil waste was used to produce biodiesel in this study, using di-esterification. This study aims to develop fuels with good specifications, low cost, and reduced sulphur content. A Biodiesel blend from wasted restaurant oil was mixed with Iraqi diesel, which is high in sulphur content, by volume ratios of 20%, 35%, and 50% and tested using a constant engine speed and varying loads. Testing results revealed that adding biodiesel in 20%, 35%, and 50% to pure diesel caused the brake-specific fuel consumption to increase by 2.6%, 5.9%, and 7.35%, respectively. A slight increase in brake thermal efficiency with varying engine loads was observed. Moreover, emissions of CO, HC, NOx, PM, H2S, and SO2 decreased by 18%, 23.4%, 3.5%, 46.4%, 47.5%, and 27.2%, respectively, when operating with a 50/50% biodiesel/diesel fuel mixture, compared to pure diesel.

Keywords: Biodiesel, H_2S, High sulphur diesel, PM, Restaurant waste, SO_2.

1. Introduction

The wasteful use of fossil fuels as an energy source in electric power stations and light and heavy transport vehicles has led to a clear and dangerous increase in environmental pollution, resulting in changes in the global climate and increasing health difficulties [1]. Compression ignition engines (CIE), called diesel engines, are considered one of the most important sources of power production, whether electric or in transportation. The diesel engine outperforms the gasoline engines with better thermal efficiency, higher durability, and greater economic feasibility. What is wrong with these engines is that their emissions can be considered one of the most dangerous sources of environmental pollution.

In overcrowded cities, this seriously threatens the environment and human health. As population density rises worldwide and welfare requirements improve, diesel fuel demand rises due to increasing energy demands [2]. Also, diesel is most used in industrial applications, and the near future portends a decrease in crude oil reserves and, thus, a global energy crisis. All these forced researchers and manufacturers to turn to many ways to reduce fuel expenditures and pollutants emitted. Some researchers deliberately used diesel-water emulsions [3], added alcohols to diesel [4], added nanoparticles to diesel [5], or added renewable biofuels as an alternative to diesel, whether by partial replacement (i.e., mixing it with diesel) or complete replacement as an essential step towards reducing reliance on fossil fuels in addition to reducing the deterioration of the environmental situation and high levels of pollution [6].

Biodiesel can reduce dependence on fossil diesel resulting in several advantages. It is a renewable energy source, and it is non-toxic, with characteristics like diesel, which makes its handling costs equal to the latter. Biodiesel is characterized by ease of storage and the absence of aromatics. In contrast to fossil diesel, biodiesel emits less soot [7]. Among the many fuels used in CEI, biodiesel is the most widely used because it operates the engine without requiring any modification to the combustion chamber or fuel supply system. The use of pure biodiesel or a mixture with fossil diesel reduces emissions of carbon dioxide (CO_2), unburned, or partially burned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) by a high percentage. Various edible and non-edible oils are used to make biodiesel, including soybean, rapeseed, cottonseed, peanut, palm, and sunflower. There has been criticism of using edible sources (considered first-generation biodiesel) concerning their negative impact on global food chains. As a result of these criticisms, biodiesel production has switched to non-edible oils (they are considered the second generation of oils in the production of biodiesel) [8].

Gad et al. [9] used biodiesel (extracted from jatropha seeds) to operate a diesel engine. Compared to petroleum diesel, biodiesel reduces in-cylinder heat release rate, cylinder pressure, and smoke. El-Seesy et al. [10] concluded that biodiesel (extracted from jatropha oils) could produce suitable BSFC and BTE compared to diesel. The adoption of some additives (n-butanol) can improve the combustion properties of biodiesel, which causes an increase in engine performance. Senthil Kumar et al. [11] used biodiesel from lemongrass and peppermint oils to improve engine fuelling and reduce emissions. The diesel increased BTE by 2.4% and reduced carbon monoxide and hydrocarbon emissions. The researchers concluded that it is possible to improve the properties of any biodiesel (extracted from rapeseed) by mixing it with biofuel to form a double-blended diesel, which the study showed is superior to biodiesel from a single source.

Pragadeshwaran et al. [12] found reduced emissions of hydrocarbons, carbon dioxide, and nitrogen oxides by adding Methyl-tertiary-butyl ether (MTBE) to Calophyllum-epiphyllum oil blended in diesel. 12% oxygenated diethyl ether was added to biodiesel extracted from tamarind oil, managed the researchers to obtain an improvement in BTE by 4.2% higher than diesel. It also reduced HC, CO2, NOx, and smoke pollutants by 10.6, 33.3, 10.3 and 27.7%, respectively. Ganesan et al. [13] tested the effect of biodiesel extracted from mustard oil with the addition of ditetrabutyl peroxide (as an oxygenator) on the emitted pollutants of a single-cylinder engine. HC, CO_2, NOx, and particulate levels were decreased by 7.3%, 5.1%, 4.6%, and 3.2%, respectively.

Waste vegetable oils, referred to as "yellow grease," are not considered a controlled waste and are often used as additives in animal feed. It cannot be disposed of in a landfill due to its liquid consistency, but it can be combined with an absorbent material, such as cat litter, for disposal. Throwing it into the sewage system is illegal and can lead to problems in many areas. An alternative is to convert it into biodiesel, which requires a chemical esterification process that removes the methyl or ethyl ester while separating the co-product of alcohol and glycerol. This method is becoming increasingly popular all over the world. Studies conducted in the late 1970s and early 1980s showed that yellow greases, although they could be used directly in diesel engines, would not be suitable for long-term use due to deposits, nozzle coking, and ring sticking [14]. In Iraq, tens of thousands of restaurants throw away at least 10 litters of used vegetable oil daily, from which they can make biofuel. Blending 20% of this disposal oil with diesel fuel would reduce the need for one million litters per day of diesel fuel and significantly reduce emissions. This would benefit the country, allowing unserviceable materials to be used without importing anything from other countries.

Mourad et al. [15] added Virgin sunflower oil in ratios of 0, 5, 15, 25% to ULSD. The study indicated that unlike diesel fuel, NOx emissions from biodiesel increase by 1.1%, and when EGR is added at 25%, NOx concentrations decrease by more than 22%. The engine power output increased by 5.95% through 25% EGR and biodiesel preheating, BSFC reduced by 10.22%, and thermal efficiency increased by 4.43%. In Brazel, Kodate et al. [16] added Safflower oilseed, soybean oil and fat to ULSD to perform B11, B15, B30, and B100 blends. According to the study, safflower-derived biodiesel fuel has similar properties to commercial biodiesel fuel. At full engine load, safflower B11 reduced specific consumption by 2% compared to diesel (D100). CO2, CO, NOx concentrations, and exhaust gas temperature were also reduced compared to commercial biodiesel at high engine loads. If safflower plant biodiesel's high production cost can be reduced, it may be a viable alternative to diesel.

In Saudi Arabia, Attia et al. [17] added castor methyl ester (CME) to ULSD to perform B10, B0 and B30 blends. The results showed that the B10 mixture provides the best performance for the engine, as it caused a relative increase in efficiency, and the levels of CO_2 and hydrochloric acid emissions were the lowest. The B30 mixture reduces exhaust opacity with a slight increase in NOx levels. Sajjad et al. [18] mixed biodiesel extracted from Mustard seeds with ULSD in proportions of 10, 20 and 100%. The results revealed that engine performance and emissions are influenced by fatty acids found in raw materials. As an alternative to diesel fuel, mustard biodiesel can produce power and heat for industrial and transportation purposes. Additionally, commercial synthetic materials and antioxidants can be added to this fuel to improve its properties. Different solvents and/or ultrasonic irradiation can minimize the negative kinematic viscosity effect.

The following conclusions have been drawn from a literature review of diesel-biodiesel blends:

a. Most research has been conducted on low or ultra-low-sulphur diesel fuels.

b. They used various vegetable and animal oils as diesel additives.

c. Most of these blends increased BSFC and NOx and reduced smoke emissions.

d. Engine emissions increase with increasing load and speed.

When examining the available literature on this subject, it was found that using biodiesel extracted from restaurant waste is the cheapest, but it is not the best as an additive.

The novelty of the current investigation could be identified by investigating blends of biodiesel with low or ultra-low sulphur diesel are used. This empirical study provides a possibility to solve the issue of high sulphur in Iraqi diesel fuel by mixing it with sulphur-free fuel. For this purpose, mixing high-sulphur diesel with biodiesel extracted from restaurant waste oils will be adopted at 20%, 35%, and 50%. The effect of this addition on levels of exhaust emissions, especially particulate matter, and NOx, will be studied. Restaurant waste oils are a problem if they are not recycled, and if they are used as biofuels, the expected environmental gains will be high and beneficial. However, diesel with high sulphur content is used in many third-world countries like Afghanistan, Pakistan, Iran, and Iraq. For example, the percentage of sulphur in Iraqi diesel ranges from 1% to 2.5%, depending on the source of the crude oil and the refinery. Refining oil from sulphur is very expensive and burdens the consumer if it is adopted.

Most of the investigations involved low-sulphur diesel, while in this study, diesel with very high sulphur content will be used. The diesel-biodiesel mixture was not treated independently of the diesel, as in this study, where the engine injection timing was modified to suit the diesel-biodiesel mixture. When fossil diesel is mixed with (zero sulphur) biodiesel, the amount of sulphur in the resulting blend will be significantly reduced. The current work studies the possibility of adopting a mixture with a high percentage of inexpensive renewable biodiesel as a primary fuel, which contributes to reducing dependence on fossil diesel.

2. Materials and Methods

2.1. Materials

Physicochemical properties and chemical composition are the main factors in evaluating biodiesel quality. Biodiesel quality is influenced by numerous factors, including feedstock, preparation process, storage media, and transportation environment. Biodiesel should have similar characteristics to petroleum diesel when used directly or as a blend with engine diesel. The quality and properties of biodiesel must meet the International Biodiesel Standards (ASTM D 6751 and EN 14214) [19]. An engine's combustion, performance, and emissions behaviour are also greatly influenced by fuel properties. Cross-esterification is a process used to produce biodiesel by changing one type of ester into another. The fuel was made by mixing 200 ml alcohol and 3.5 g of sodium hydroxide (lye) in a beaker for five minutes. A final step involved heating 1 litter of oil (gathered from several Baghdad restaurants) to 65 °C while stirring for 15 minutes.

The glycerol was then allowed to settle, with the biodiesel separated by washing and boiling to remove moisture. Because waste oils contain high free fatty acids, they are difficult to process with an alkaline catalyst. They can cause soap formation, preventing the separation of biodiesel and glycerol. An acid catalyst may be used as an alternative, as some researchers have suggested that it is more tolerant of free fatty acids [20]. Table 1 lists the characteristics of the two main fuel types. Iraqi diesel fuel was used as the baseline fuel in the tests. Compared to diesel fuel, biodiesel has a higher oxygen content, a lower heat value, and a lower cetane number. Three biodiesel and diesel fuel blends (B20, B35, and B100) were tested, and the engine combustion and emitted pollutants characteristics were compared to the pure diesel outputs.

Table 1. Diesel and biodiesel specifications.

Specification	WR biodiesel	Diesel
Chemical formula	C19H36O2	C17H35
Molecular weight (g)	132	149
Density at 25°C	880	824
Latent heat of vaporization	215	245
Cetane number	41	49
Calorific value (MJ/kg)	40.2	44.8
Flash point	138	65
Fire point	1458	80
Water content (mg/kg)	187	46
Kinematic viscosity at 40°C (cSt)	4.89	2.74
Carbon content (wt.%)	75	86
Hydrogen content (wt.%)	13	13
Oxygen content (wt.%)	12	0

2.2. Testing engine and its accessories

The engine used was a four-cylinder, water-cooled, naturally aspirated Fiat diesel. Table 2 illustrates the main engine's characteristics. The engine is attached to a hydraulic dynamometer that loads the engine by increasing the torque. Exhaust emissions were checked with a Multigas 4880 analyser in which NOx, HC, and CO concentrations were measured. The experimental setup can be seen in Fig. 1. The pure diesel engine runs at an injection timing (IT) of 19° before the top dead center (BTDC). However, since yellow grease increases the viscosity and lowers the cetane number of diesel-biodiesel blends, the ignition delay is longer. Therefore, in trials using a diesel-biodiesel mixture, the injection timing was advanced to accommodate this. Advance injection timing causes a suitable climate for biofuels to evaporate, mix with air, and then self-ignite. Sound pressure was measured with an accurate sound level meter equipped with a microphone, type 4615.

Table 2. The used engine specifications

The parameter	Specification
Diesel engine model	Fiat TD 313 rig
Injection type	Direct injection
Stroke number	4-stroke
Cylinders number	4-cylinders
Bore x Stroke (mm)	100×110
Compression ratio	18:1
Engine speed (rpm)	0-3500
Fuel injection pressure (bar)	40
displacement	3666 cc

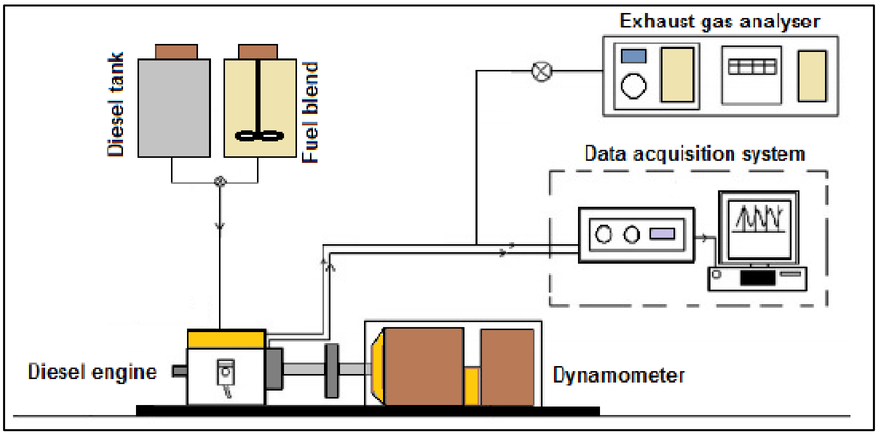

Fig. 1. An engine testing rig schematic.

The equations below were used to assess the engine's performance qualities [21]:

- Brake power (kW):

$$bp = \frac{2\pi \times N \times T}{60000} \quad (1)$$

- - Brake means effective pressure (kN/m^2):

$$bmep = bp \times \frac{2 \times 60}{V_{sn} \times N} \quad (2)$$

- - Fuel mass flow rate (kg/sec):

$$\dot{m}_f = \frac{\rho_f}{time} \times \frac{v_f \times 10^{-6}}{1000} \quad (3)$$

- Air mass flow rate (kg/sec):

$$\dot{m}_{a.act.} = \rho_{air} \times \frac{\sqrt{0.85 \times h_o}}{3600} \quad (4b)$$

$$\dot{m}_{a.theo.} = \rho_{air} \times \frac{12\sqrt{0.85 \times h_o}}{3600} \quad (4a)$$

- BSFC (kg/kW.hr):

$$\text{BSFC} = \frac{\dot{m}_f}{bp} \times 3600 \quad (5)$$

Total fuel heat (kW):

$$Q_t = \dot{m}_f \times LCV \quad (6)$$

- BTE (%):

$$\eta_{bth} = \frac{bp}{Q_t} \times 100 \quad (7)$$

2.3. Standard error

Standard deviation (SD) is the estimate of standard error (SE) based on the sample mean (mean). SE is an important metric for experiment tests because it measures how accurate the sample data is. The following equation is used to calculate the standard error of the sample:

$$\text{Standard Error} = s / \sqrt{n} \quad (8)$$

where s: $\sqrt{\Sigma^n i(x_i-\bar{x})^2 / n-1}$, x_i: i^{th} Random variable, $\bar{x}$: Sample mean, and n: Sample size.

Standard deviation is a statistical term used to measure the accuracy of a sample. It measures the accuracy of sample data, which represents the whole product. The standard deviation is a measurement of variance within a single sample of measurement across multiple samples. At the same time, SE describes variance across multiple samples of a measurement as an indicator of how accurate a given sample is.

Table 3. Accuracies of the experimental instruments used in this study.

No.	Measurement	Accuracy	Uncertainty (%)
1	Engine load	± 2 N	±0.38
2	Engine speed	±10 rpm	±0.3
3	Fuel flow meter	±0.2 cc	±1.15
4	Thermocouples	± 2° C	±1.28
5	Air flow meter	±0.13 bar	±0.47
6	EGR flow meter	±0.2 bar	±0.19
7	NO_x	±3 ppm	±0.27
8	CO	±0.25 %vol.	±0.3
9	HC	±12 ppm	±0.6
10	CO_2	±0.08% vol.	±0.2
11	H_2S	±8 ppm	±0.21
12	SO_2	±7 ppm	±0.48

A deviation from standard values is determined after calibrating the measuring devices. As shown in Table 3, the test measurements have an acceptable accuracy and a total uncertainty less than 3%. Arithmetic mean measurements were taken for each experiment to ensure accuracy, and each experiment was repeated at least three times to validate.

2.4 Tests procedure

The same operating conditions were used in all laboratory experiments to ensure high accuracy. The output data were recorded using all calibrated measurement instruments. Analyses of error and uncertainty were performed for each of the measuring instruments. The surrounding atmospheric conditions were monitored periodically during and before the experiments to ensure stability. To achieve optimum performance, the engine must be warmed up sufficiently (e.g., the engine oil reached 77 to 84°C). In the tests, three mixtures of diesel-biodiesel fuels were prepared and tested:

- B20: adding 20 %vol. of biodiesel to pure diesel,
- B35: adding 35 %vol. of biodiesel to pure diesel, and
- B50 (adding 50%vol. of biodiesel to pure diesel to pure diesel.

The engine injection timing of the B35 and B50 blends has been revised to 30° BTDC for smooth performance, while the elegant B20 and diesel are set to the factory setting (19° BTDC). Data were collected from combustion and emissions characteristics when the engine was operated at variable loads and a fixed engine speed of 1500 rpm. Engine outcome was compared between diesel-biodiesel blends and pure diesel combustion. Before using biofuel, the engine is run for ten minutes with diesel fuel to clean the fuel streams of any biodiesel residue in the fuel stream or combustion chamber and to warm up the engine before using a diesel-biodiesel mixture.

3. Results and Discussions

The influence of engine load on BSFC is shown in Fig. 2. BSFC generally decreases when engine load increases. BSFC is higher at low loads due to the coldness of the combustion chamber, which makes the mixture-burning process difficult, and a large part of the fuel is not oxidized during this stage. The combustion quality improves at medium loads, and the BSFC decreases for all mixtures. The results indicate that increasing the motor load to high loads did not cause a decrease in BSFC compared to medium loads. When using B20, its bsfc was higher than diesel, but by a very limited percentage that did not exceed 2.6%, while when using B35 and B50, this percentage increased to 5.9% and 7.23%. Increasing the percentage of biodiesel in the mixture caused a clear reduction in the resulting blend heating value and cetane number, which reduces the engine's brake power per kg of fuel compared to diesel.

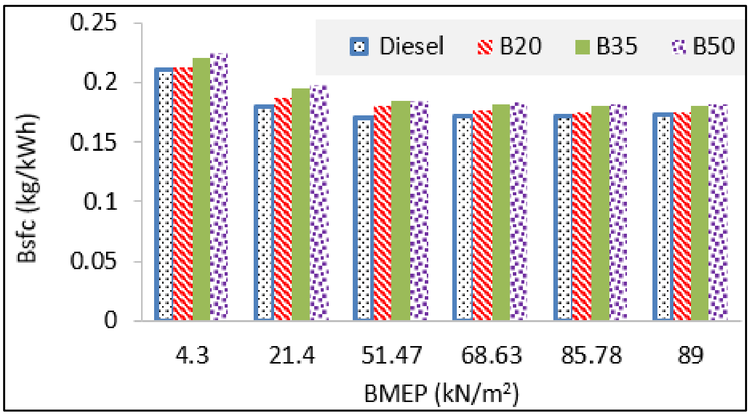

Fig. 2. The effect of load variation on the engine's BSFC for the tested blends.

The BTE increases with increasing load as the combustion chamber temperature increases and the burning process improves, which increases the engine return, as may be seen in Fig. 3. As the oxygen content in diesel-biodiesel increases energy release, BTE is higher in it than in diesel. The average percentage increase in BTE was 0.195%, 2.029%, and 4% for B20, B35, and B50 compared to diesel, respectively. This slight increase was due to the increase in BSFC mixtures. The current findings are consistent with Yesilyurt [22] results.

The EGT changes according to the combustion conditions, as shown in Fig. 4. Practical measurements show a decrease in the EGT when using diesel-biodiesel mixtures compared to diesel. The specific heat of biodiesel-diesel blends is lower than that of diesel. Besides, the choice of injection delivery technology when using a biodiesel-diesel mixture gives EG enough time to cool down and thus lowers its temperatures. EGT decreased by 3.3%, 5.5%, and 7.9% for B20, B36, and B50 compared to diesel. The current study's results align with those from Halwe et al. [23].

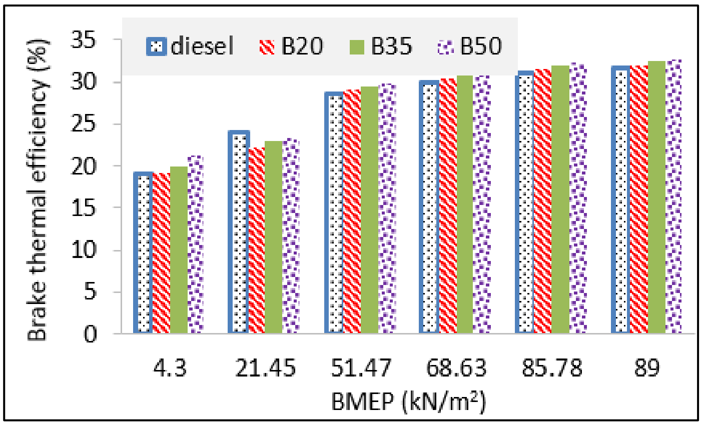

Fig. 3. The effect of load variation on the engine's BTE for the tested blends.

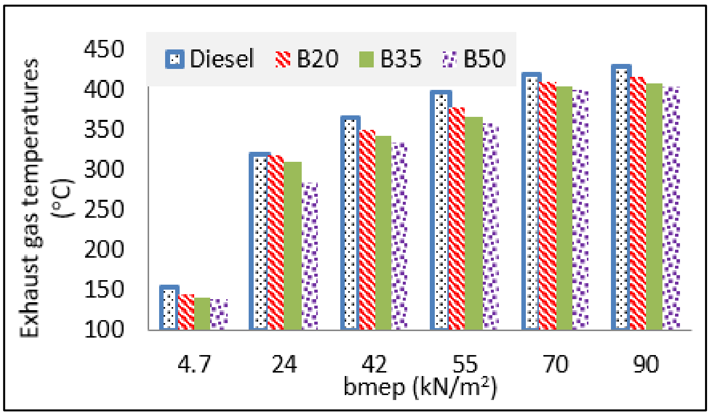

Fig. 4. Engine load variance on EGR for the investigated blends.

Figure 5 shows the engine load influence on the CO levels exhausted of the fuels studied. Several percent of the oxygen in the biodiesel composition is present in diesel-biodiesel mixtures, which affects the emitted CO levels. For example, CO concentrations decreased by 2.9, 11.11, and 18% when B20, B35, and B50 were used compared to diesel, respectively. Oxygen content increases as biodiesel content increases in a mixture, resulting in less CO emitted.

At medium loads, the lowest CO levels are achieved, as carbon in fuel is most likely to be oxidized inside the combustion chamber as the conditions are favorable. While at high loads, the temperature inside the combustion chamber is high, but the fuel pumped to reach these loads is high, and thus the CO concentrations rise. At very low loads, the combustion chambers are cold. Despite the pumping of small quantities of fuel, the deterioration of the combustion quality causes partial oxidation of the fuel and high levels of CO, which are like [24] results.

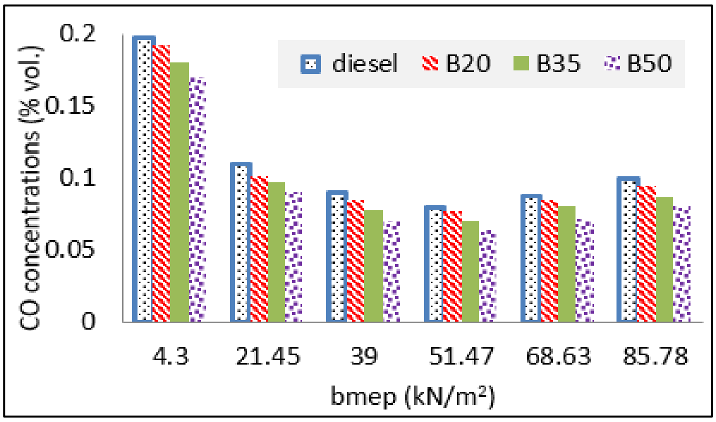

Fig. 5. The effect of engine load variation on CO levels for the investigated blends.

Figure 6 shows the effect of changing engine load on emitted HC levels for all fuels used. The levels of this pollutant were decreased when the biofuel fraction in the mixture was increased, and the greatest reduction was achieved when using B50. This shows the impact of the oxygen available in the biofuel composition. When using B20, B35, and B50, the HC concentrations decreased compared to diesel by 4, 14, and 23.4%, respectively.

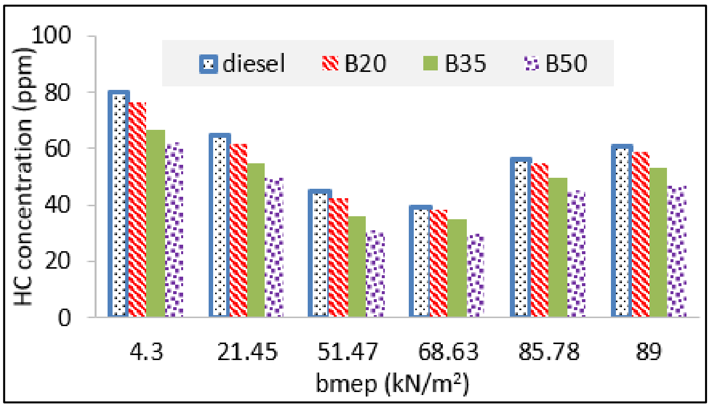

Fig. 6. The effect of various loads on HC levels for the investigated blends.

The lowest concentrations of this pollutant are at medium loads due to the presence of appropriate temperatures to oxidize the injected fuel appropriately. However, at high loads and due to the injection of large quantities of fuel, the combustion quality deteriorates, and the measured HC levels increase. At the same time, the diesel-biodiesel mixtures still produce less than diesel. Those findings agree with those in Rajak et al. [25].

The formation of nitrogen oxides requires three basic factors, which are the availability of oxygen (and this is available in the studied diesel-biodiesel mixtures), the availability of a high combustion chamber temperature (this is available when running with diesel), and finally, the time required for the formation of these oxides (and it has been provided This time when introducing injection timing for B35 and B50 mixtures). However, from reading the practical measurements in Fig. 7, it is noticed that the levels of NOx increased in a limited manner with increasing load for both B20 and B35 (3% and 6.8%, respectively), while for B50, the resulting concentrations were lower compared to diesel (3.5%). These results show the ongoing conflict between the three variables above and which is more likely to be the most important in forming NOx. For example, when using B20, diesel provides a good oxygen ratio with high heat.

As for the case of B35, the presence of oxygen and heat will certainly be affected by the fuel heating value reduction. However, NOx concentrations were higher than diesel due to the difference in injection timing, which gave sufficient time to form these oxides. In the third case (using B50), the oxygen content was increased in the combustion chamber, while advanced injection timing provided sufficient time to form oxides. However, the reduction in the calorific value of the mixture caused a decrease in the temperature inside the combustion chamber and thus limited the levels of NOx emitted. Similar results have been reported in [26].

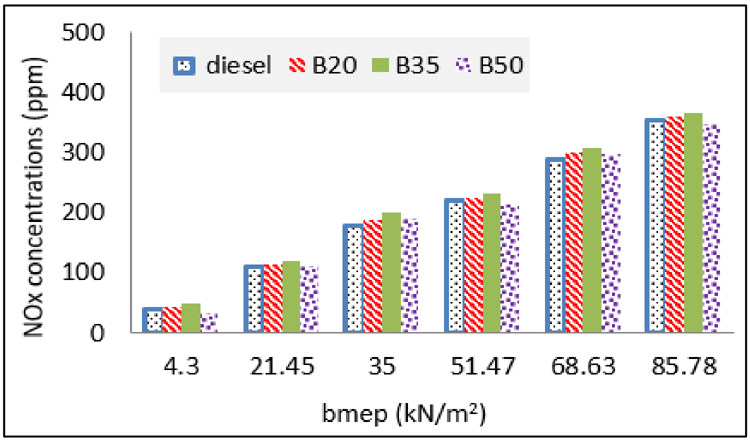

Fig. 7. Engine load variation influence on NOx levels for the investigated blends.

Fuel oxidation improves due to an oxygen abundance in the fuel combination. This abundance is reflected in the reduction of emitted PM concentrations. Increasing the biodiesel fraction in the blend decreased these concentrations, as shown in Fig. 8. The percentages of decrease in PM levels when using B20, B35, and B50 were in the range of 5, 29.7, and 46.4. % compared to diesel, respectively. When B50 is used, PM concentrations are at their lowest levels due to the abundance of oxygen in the mixture, even at high loads, as Fig. 8 demonstrates. At high loads, oxygen availability and high combustion chamber temperature cause a large part of the sulphur to interact with hydrogen and oxygen, thus reducing its contribution to the formation of nuclei of particulate particles. Kumar et al. [27] also reports similar results.

Sulphur presence in diesel reduces its cetane number and becomes a nucleus for the accumulation and agglomeration of carbon atoms, which causes an increase in PM concentrations. Also, oxidizing produces dangerous gases such as H2S, which produces sulfuric acids when interacting with exhausted water vapor. The environment, animals, and plants are very vulnerable to these acids.

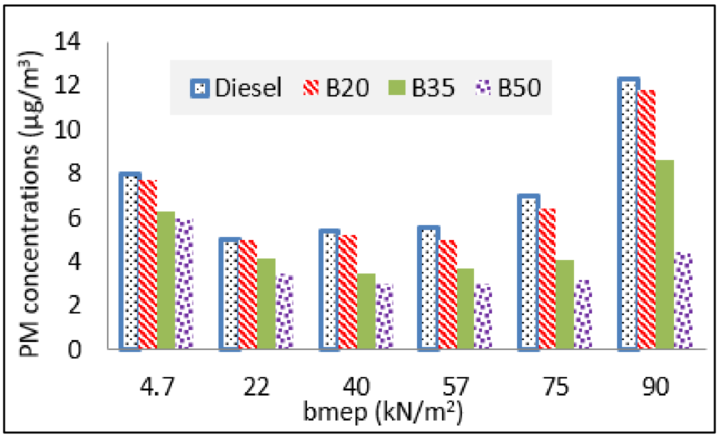

Fig. 8. The effect of various engine loads on PM levels for the investigated blends

Figure 9 shows the effect of load and the use of the studied mixtures on the emitted H2S concentrations. Practical measurements show that reducing the percentage of diesel in the mixture will inevitably reduce the concentration of sulphur in it, thus reducing the levels of H2S emitted. The emitted H2S levels decreased by about 18.3, 27.6 and 47.5% for mixtures B20, B35, and B50 compared to diesel. One of the most important achievements of adding biodiesel to Iraqi diesel is that sulphur concentrations have been greatly reduced. The above results are similar to those of Wang et al. [28].

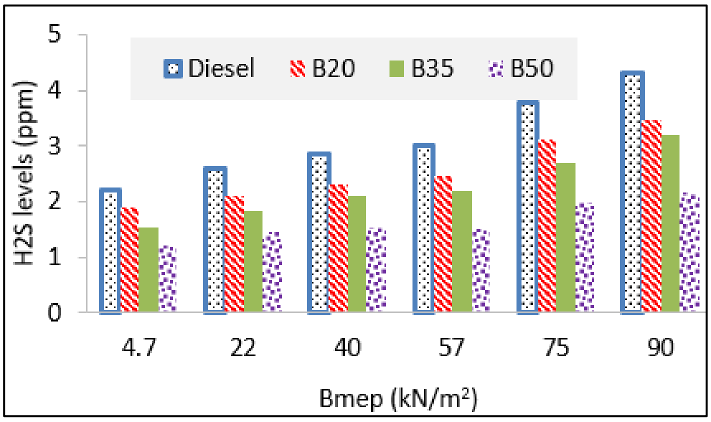

Fig. 9. Engine loads influence on H2S levels for the tested mixtures.

SO2 is one of the components that appears in the exhaust gas. Oxygen and fuel sulphur react to form it, as shown in Fig. 10. In most studies examining many alternative fuels, such a pollutant is not studied or dealt with because the diesel fuel used is ULSD, so a very small percentage of sulphur participates in building particulate PM particles only. This study deals with high sulphur content diesel (Iraqi-origin diesel), so the SO2 concentrations are clear. This gas can interact with the rest of the gases in nothingness and form fumes of sulfuric acids such as sulfuric acid and sulphur. Therefore, its effects will become serious, affecting the exhaust system, environment, and human health. Adding biodiesel (sulphur-free) to diesel reduces the sulphur content in the mixture, thereby minimizing and limiting its effects after combustion. When the engine ran with B20, B35, and B50, the SO2 concentrations decreased by 10.1, 18.2, and 27.2% compared to diesel. Added biofuel's influence is clear in reducing the levels of this pollutant, but it is less than in the case of its effect on H2S emissions. Hydrogen reacts quickly with combustion components and forms H2S molecules faster than oxygen reacts with sulphur to form SO2. SO2 lowest levels were achieved at medium loads due to the availability of oxygen, good combustion temperatures, and sufficient reaction time. The SO2 levels increased at high loads due to higher fuel injected into the cylinder to reach the required performance at the used speed.

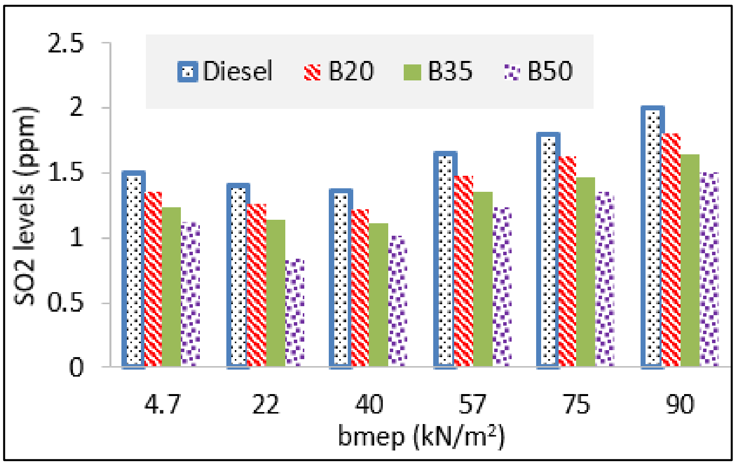

Fig. 10. Engine load variation impact on SO2 levels for the tested blends.

4. Conclusions

Biofuel extracted from restaurant waste oils was synthesized after purification and chemical esterification and added to Iraqi diesel (which has a high sulphur content) at various ratios.

The test results indicated that the BSFC increases when adding biodiesel to diesel and has the highest consumption when working with B50, as the BSFC increased by a maximum of 7.2%. When operating with B50 (compared to diesel fuel), NOx emissions decreased by 3.5%. Using B20 and B35 mixtures as fuels resulted in higher NOx concentrations of 3% and 6.8%, respectively. When B50 was tested, the maximum reduction in CO and HC levels were 18% and 23.4%, respectively, compared to diesel. SO2 and H2S were reduced by 27.2% and 47.5% compared to diesel, respectively.

The addition of biodiesel extracted from restaurant waste oil has a high viscosity and a lower cetane number than diesel. Therefore, when added at high rates, the injection timing must be advanced to address the delay period. This addition can reduce the harmful effects of high-sulphur diesel, although treating this type of diesel and reducing its Sulphur content will be more effective.

The study recommends investigating the possibility of benefiting from using post-engine pollutant treatment systems such as catalysts and particulate filters.

Nomenclatures

$\dot{m}_{a_{act.}}$	Actual air flow rate, kg/s
$\dot{m}_{a_{theo..}}$	Theoretical air flow rate, kg/s
$\dot{m}_f$	Fuel mass flow rate, kg/s
Q_t	Total fuel heat, kW

Greek Symbols

η_{bth}	Brake thermal efficiency
ρ_f	Fuel density, kg/ m^3

Abbreviations

BSFC	brake specific fuel consumption
CIE	Compression Ignition Engine
H_2S	Hydrogen sulphide
LCV	Lower calorific value
N	engine speed
NOx	nitrogen oxide
PM	Particulate matter
SO_2	Sulphur dioxide
T	engine torque

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