International Journal of Energy Production and Management
Vol. 10, No. 1, March, 2025, pp. 71-80
Journal homepage: http://iieta.org/journals/ijepm

Waste to Wealth by Oil Blending from Restaurants Waste and Mixing with Diesel and Butanol to Improve the Ternary Fuel Characteristics

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https://doi.org/10.18280/ijepm.100108

Received: 12 December 2024
Revised: 12 February 2025
Accepted: 6 March 2025
Available online: 31 March 2025

Keywords:
waste restaurant oil, brake thermal efficiency, specific fuel consumption, circular economy

ABSTRACT

The demand for vehicles has increased significantly in the last two decades as a result of the rise in the global population and improved living capacity. The popularity of using products from bio-based sources has also increased due to the need to reduce air pollution resulting from burning fossil fuels while maintaining or increasing the efficiency of engines. In this study, biodiesel (produced from restaurant waste oil) with small amounts of butanol alcohol was added to conventional Iraqi diesel and tested. Adding butanol as a low-dose stimulant to the diesel-biodiesel mixture to improve engine performance and eliminate pollutants is a modern method that has not yet been approved and requires many studies before it is accepted as a vehicle fuel. The engine showed good performance when operating with the proposed mixtures under different load conditions. The D90W5B5 mixture provided the highest cylinder pressure, which was superior to diesel. The tested blends, D90W5B5, D80W10B10, D70W15B15, and W100, caused a decrease in NOx emissions compared to diesel by 16.57%, 25.48%, 33.14%, and 39.76%, respectively. As well as reduced the total suspended particles by 19.1%, 22.02%, 34.66% and 49.7%, respectively. One of the most important results obtained is that these mixtures reduced the Sulfur dioxide (SO_2) and Hydrogen sulfide (H_2S) emissions by 3.9%, 8.66%, 10.98%, and 97.7%, for the first pollutant and by 6.15%, 8.89%, 15.57%, and 97.8%, for the second one, respectively.

1. INTRODUCTION

The various types of biofuels are characterized by being similar to the properties of diesel while producing fewer exhaust pollutants when burned. Biomass production and use in engines has become a hot topic of current research due to its effects as engine fuel. One of the most important benefits of biofuel is its ability to reduce emissions compared to conventional diesel fuel [1], with a slight increase in nitrogen oxide emissions. For this reason, gas recirculation systems have been developed to reduce levels of this pollutant [2]. Researchers in the field of biofuel production are still trying to find new solutions that reduce emissions and increase engine performance. Some of these attempts are made by examining different mixing ratios and using the latest technologies in mixing operations [3].

Biodiesel extracted from vegetable oils can be used in diesel engines without adding modifications to these engines if it is mixed with diesel at a rate not exceeding 20% [4]. The direct use of vegetable oils without treating them through the stratification process will cause incomplete combustion, high soot emissions, and accumulation of carbon deposits inside parts of the combustion chamber due to the glycerin in them, which causes high viscosity [5]. Many types of biodiesels extracted from different origins have been studied in detail in the literature. These studies were devoted to examining everything related to the use of these oils, from their production stage to their performance characteristics and the pollutants emitted from burning them as fuel or mixed with diesel [6]. These studies have shown that running a diesel engine with biodiesel reduces HC, CO, and particulate matter (PM) emissions with a limited increase in NOx emitted [7].

Many studies have investigated using low-carbon alcohols such as ethanol and methanol as additives to diesel in compression ignition engines [8]. The alcohols under consideration have properties that include low lubricity, high heat of vaporization, high autoignition temperature, low cetane number, and low solubility, all of which are not useful when using ethanol and methanol in diesel engines [9]. On the other hand, ethanol is insoluble in diesel, while methanol displays a similar property, which prompted researchers to look for an emulsifier to enhance the complete miscibility of simple alcohols in diesel fuel. Based on this hypothesis, biodiesel has proven beneficial because it can prevent the separation of diesel and alcohol, which means better mixture stability than adding alcohol alone. Blends such as biodiesel-ethanol/methanol or biodiesel-ethanol/methanol-diesel can combine the amount of alcohol is small. The researchers used these mixtures and found that they contribute to reducing nitrogen oxides and particulate matter together [10].

When comparing the two additives, butanol appears more reliable than ethanol and methanol. It has properties such as higher cetane number, lower heat of vaporization, better heating value, and higher fuel miscibility with diesel. The fact that butanol has a relatively larger CN means free fuel ignition and less ignition delay compared to other variants [11]. Also, butanol has shown that ignition of butanol can be achieved at a lower temperature as well as a lower inlet air temperature than ethanol or methanol [11]. Butanol has a higher calorific value than methanol or ethanol, so the amount of this fuel required in mixtures with other components to obtain a similar power output within engines running on alcohol mixtures is less [12]. One of the most important properties of butanol is that it can be mixed with diesel without separation of the mixture, as is the case with methanol or ethanol. Therefore, butanol can be considered a better diesel additive compared to methanol and ethanol [13].

Many researchers have studied the effect of adding butanol to diesel on engine performance and pollutants. For example, Karabektas and Hosoz [14] added isobutane to diesel and observed a decrease in brake power (BP) and an increase in both brake-specific fuel consumption (BSFC) and brake thermal energy (BTE). The study also showed that CO and NOx levels decreased while HC concentrations increased. Doğan [15] studied the effect of adding n-Butanol to diesel and concluded that this addition caused an increase in BSFC and BTE and decreased EGT. This addition also caused a decrease in CO and NOx concentrations and an increase in HC concentrations.

Many researchers have also investigated the effect of mixing butanol with biodiesel and adding them together to diesel on engine performance and pollutants. For example, Yilmaz et al. [16] mixed diesel, biodiesel, and butanol together and proved that the BSFC of the engine increased while the EGT decreased. The study also showed that the levels of CO, NOx, and HC decreased. Atmanl et al. [17] studied the effect of mixing n-butanol with biodiesel extracted from vegetable oil and concluded that this addition increased BSFC and decreased BTE. This addition also caused a decrease in the concentrations of CO, NOx, and HC together.

Şahin and Yılmaz [18] studied the physical and chemical properties of biodiesel extracted from cooking oil (originally canola oil), as well as blended with butanol. The study showed that adding butanol reduces the density of the mixture and reduces the viscosity. Adding butanol to a biodiesel blend reduces the flash points and calorific values of the blend. Kumar et al. [19] practically tested running a diesel engine with a biodiesel mixture (extracted from royal poinciana) added to diesel with the addition of 1-butanol. The results showed that the mixture consisting of 90% diesel, 3% biodiesel, and 3% Butanol (D90RP7B3) gave the best BTE and lowest BSFC. It also showed that the heat release rate (HRR) for this mixture was ideal. Emissions of this mixture, such as CO, CO_2, HC, and NOx, were reduced by 14.12%, 8.33%, 11.1%, and 18.8% compared to diesel.

Converting restaurant waste oils into bio-oils and using them as additives to diesel fuel offers promising opportunities for waste-to-wealth management that is consistent with sustainable resource management. Very significant research has been conducted on the possibility of using this approach, which converts the mentioned material into useful biofuel. Based on the findings of Alptekin and Canakci [20], the feasibility of using waste frying oils in biodiesel production was determined, as the biodiesel obtained was by international standards in terms of its physical and chemical properties. Likewise, Demirbas [21] emphasized the environmental and economic advantages of waste cooking oil, concluding that it is cheaper than virgin vegetable oil and produces fewer greenhouse gases.

The waste-to-wealth concept focuses on sorting waste generated from operations and looking for opportunities to transform it into valuable products, including energy [22]. Hence, the field of waste cooking oils generated by the catering sector remains largely unexplored in this context. Yaakob et al. [23] also found that the current global WCO production is about 29 million tons per year and most of it is disposed of in landfills or directly into water bodies with serious consequences for the environment. Thus, the waste-to-wealth system has the potential to convert waste oil into biodiesel for economic gains by preventing the harmful effects of wrong disposal. The waste-to-wealth model can, therefore, be implemented by having appropriate collection channels and treatment systems with appropriate policies and incentives to encourage the use of waste bio-cooking oil [24]. In other words, changing restaurant oils to biodiesel is a positive approach if the government comes up with the right policies and technology.

Restaurant waste oil is a substance that is difficult to dispose of, and when thrown into heavy water drains, it may cause blockages, so it is collected and transported to refineries to deal with it. In a densely populated city like the city of Baghdad, the capital of Iraq (inhabited by 9 million people and reaching 15 million people in the morning), there are a very large number of restaurants that use hydrogenated oils for cooking and frying. This oil can be converted into biofuel through a common and cheap chemical process (esterification), and a high percentage of these oils can be obtained as biodiesel, ranging from 74% to 85%, depending on the type and source of the oil used. Butanol is a type of alcohol that can be purchased from local markets at reasonable prices. Butanol was mixed with prepared biodiesel and then added to conventional diesel to examine the effect of these additives on engine performance and pollutants compared to diesel. For purely experimental purposes and to ensure the stability of the samples and that the components did not separate when inserted into the engine, they were mixed using ultrasound for 15 minutes. A small amount of butanol and biodiesel blend was used.

Many researchers have tested butanol in several research projects involving biodiesel from palm, pyrolysis blends, and jatropha, but it has not been tested on biodiesel produced from restaurant waste. Also, it is rare to test blends using high sulfur content (as in this study) because most countries use low or ultra-low-sulfur diesel. However, Iraqi diesel has a high sulfur content from 10000 to 25000 ppm. This content causes a deep pollution effect, which impacts human health and the environment.

The main objective of this research is to find fuel that can operate diesel engines while reducing exhaust emissions, especially sulfur ones. This study will focus on the proposed fuel's effect on the engine's performance, combustion properties, and pollutants. Biodiesel will be extracted from restaurants' waste oils and chemically treated to make them suitable for use in diesel engines. Specific proportions of butanol were added equal to the proportions of biodiesel addition. In the practical experiments, the engine speed was maintained at a constant (1500) while changing the engine load. During all the experiments, the performance specifications and pollutants emitted from the engine will be measured and compared to the operation of the engine with pure diesel fuel under the same conditions.

2. MATERIALS AND METHODS

2.1 The tested fuels

Restaurant waste oil is carefully filtered from food residues and carbon materials resulting from cooking and frying. The transesterification process then takes place, which is concerned with removing glycerin from the oil to become biodiesel. In this study, biodiesel was prepared in vitro from waste cooking oils used in snack restaurants. In Iraq, sunflower oil is widely used in homes and restaurants. The preparation process begins first by removing suspended materials and moisture present in the used oil through several methods: sedimentation, drying, and filtration. Methanol and KOH are added as catalysts in the process to produce biodiesel in the transesterification process. In this process, one type of ester is converted into another type (biodiesel). The quantities added were 200ml of methanol and 3.5g of sodium hydroxide (lye) in a bowl and mixed well for 5 minutes. After that, one liter of restaurant waste oil was added after it was filtered from impurities to methanol and sodium hydroxide, and the ingredients were well for 15 minutes. The mixture is heated to a temperature of 65℃ for 15 to 25 minutes while stirring. In the final step, heating and stirring are stopped and the glycerin is allowed to separate and settle to the bottom of the flask, as shown in Figure 1, while the biodiesel (ester) is separated. The final product is now washed and then heated to a boiling point to remove any moisture that may remain in the oil. These steps are clarified in detail by Mahapatra et al. [25], and the interested reader can refer to them.

Butanol was added to the biodiesel in equal proportions of 5%, 10%, and 15% to the total mixture. Some previous literature reported that adding high butanol content severely damages the piston crown, leading to complete failure. For this reason, the percentage of butanol in specific proportions used in this study was as suggested by Mendiara et al. [26]. Table 1 shows the tested blend specifications.

Figure 1. Separating biodiesel from glycerin after the transesterification process

Table 1. Diesel-biodiesel-butanol properties

Properties	Diesel	W100	D90W5B5	D80W10B10	D70W15B15
Hydrogen in weight%	0	11	8	10.4	9.8
Carbon in weight%	86	77	68	60	50
Pour point	16-34	12	10	8	6
Kinematic viscosity @ 40℃ in CST	1.2- 4.2	5	4.06	3.72	2.98
Flashpoint (℃)	68 - 85	70	65	60	40
Cetane Number	55	49	47	46	40
Cloud point (℃)	6 - 16	7	6	5	4
Oxygen in wt.%	0	1.9	1.2	0.9	0.8
Sulfur in weight	1%	-	0.8	0.6	0.4
Fire point (℃)	185 - 345	320	240	200	180
Calorific Value (kJ/kg)	43021	45021	42012	40012	38012

2.2 Testing procedure

The engine used in the current study is a Fiat diesel engine. Table 2 displays the engine characteristics. Experiments begin by warming up the engine for 15 minutes. The experiments were conducted at an average engine speed of 1500rpm, which represents the speed of an engine operating on city roads. The load on the motor is changed using a dynamometer. The engine heating process is carried out using diesel, and when the engine cooling water temperature reaches the required temperature of 90℃, the engine is started according to the type of mixture to be tested. After testing each mixture, the engine runs for a quarter of an hour with diesel to clean the combustion chamber of any residues.

Table 2. Specifications of the engine

Parameter	Specifications
Engine type	Fiat TD 313
Cylinders number	4
Injection	Direct injection
Engine cooling	Water cooling
Air system	Natural aspirated
Number of valves/cylinders	2
Bore (mm)	100
Compression ratio	17
Injection pump	1
Plunger dia.	26mm
Holes/nozzle number	10
Nozzle hole dia.	0.48mm
Spray angle	160°
Nozzle opening pressure	40Mpa

The following equations were used to assess the engine's performance qualities [25]:

Brake power (kW):

$$bp = \frac{2\pi \times N \times T}{60 \times 1000} \quad (1)$$

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):

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

Air mass flow rate (kg/sec):

$$\dot{m}_{a,act} = \frac{12\sqrt{h_{o \times 0.85}}}{3600} \times \rho_{air}\ kg/s \quad (4)$$

$$\dot{m}_{a,theo} = V_{s.n} \times \frac{N}{60 \times 2} \times \rho_{air}\ kg/s \quad (5)$$

BSFC (kg/kW.hr):

$$BSFC = \frac{\dot{m}_f}{bp} \times 3600 \quad (6)$$

Total fuel heat (kW):

$$Q_t = \dot{m}_f \times LCV \quad (7)$$

BTE (%):

$$\eta_{bth} = \frac{bp}{Q_t} \times 100 \quad (8)$$

2.3 Uncertainty analysis

Uncertainty analysis was used to critically compare the statistical accuracy of the study and the experimental results. Through this analysis, possible anomalies observed in instrument calibration processes can be found, which enables data errors to be predicted. To measure uncertainty, the procedure recommended by Al-Kayiem et al. [27] was used. The following equation was used to determine the various experimental measurement errors:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{0.5} \quad (9)$$

W_R is the resulting uncertainty, R is the independent variable function (x_1, x_2, ..., x_n) while (w_1, w_2, ..., w_n) stands for independent variables uncertainties. The uncertainty in the engine's performance, emissions, and combustion characteristics (listed in Table 3) was 2.13%, which represents a high accuracy and low uncertainty value.

Table 3. Uncertainties in the experimental instrumentations

Instrument	Parameters	Specifications	Accuracy	Uncertainties
Speed sensor	Engine rpm	dr100m	±8 dr100m	±0.17%
Burette meter	Fuel quantity	0-1200 cc	±0.28cc±1.5%	±1.2%
Stopwatch	Time (sec)	-	±0.17s	±0.24%
Manometer	Air flow rate	0-500	±2.8mm	±0.63%
AVL gas analyzer	HC	0–11000 0–5600 0–14%	±14ppm	±0.54%
	NOx,		±12ppm	±0.62%
	CO,		±0.05% vol.	±0.67
GT-521	TSP	0-2000	±10μg/m^3	±0.53
	H_2S	0-1000	±9ppm	±0.71
	SO_2	0-1000	±12ppm	±0.84

3. RESULTS AND DISCUSSION

3.1 Combustion characteristics

3.1.1 Cylinder pressures

The increase in cylinder pressure can be referred to as acceleration and deceleration, which causes the piston and cylinder to change rapidly as well as the combustion chamber pressure to change. The main factors affecting the pressure increase in the cylinder are combustion delay, combustion duration, and the nature of the combustion cycle. The faster the crank rotates, the more heat is released, causing a higher-pressure rate to rise in the cylinder. Figure 2 shows the crank angle at which the highest cylinder pressure is reached. The pressure increase is achieved by mixing D90W5B5. Butanal's reaction and size as a flammable alcohol led to more efficient combustion than diesel in suitable conditions. Increasing the butanol content from 5% to 10% and decreasing the cetane number of the D80W10B10 mixture results in a very slow and low pressure of more than 65 bar in the cylinder.

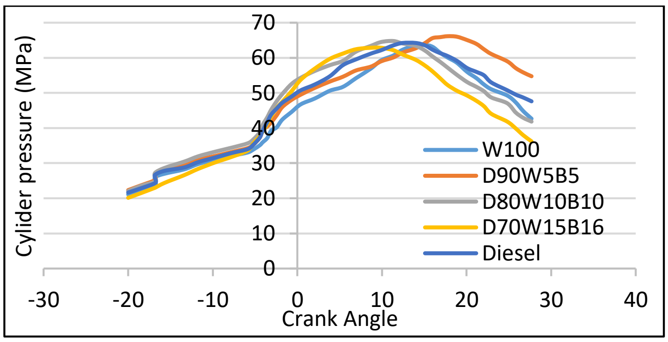

Figure 2. Cylinder pressure variation with a crank angle for the tested blends

Increasing butanol in the blend reduces its activity and as a result, reduces the resulting cylinder pressure. This can be attributed to the high heat it took from the combustion chamber temperature to evaporate and get ready to ignite, which in turn reduces the chamber temperature and, hence, the cylinder pressure.

3.1.2 Heat release rate (HRR)

The amount of heat required to ensure combustion or the rate at which combustion begins is measured by HRR. The amount of heat generated due to different crank angles during the time the piston moves between BDC and TDC is compared to the HRR. At higher temperatures, the increase in pressure causes displacement of the piston and cylinder due to angular rotation, resulting in a heat release measured in degrees KJ/CA [28]. The maximum convective heat transfer rate represents the energy change in this process, resulting in the heat release rate. Figure 3 shows that the maximum heat release rate was reached for composites D80W10B10 and D90W5B5, followed by a rating of 85kJ/CA and a rating of 83KJ/CA. The final difference in HRR obtained for the D80W10B10 blend is 12.5% better than D90W5B5. This is because D80W10B10 has a higher oxygen content but a lower heating value, resulting in a lower HRR than the D90W10B10. The impact of low butanol added was obvious on the heat released rate as it was the highest as indicated by the figure.

3.1.3 Ignition delay

The time from the beginning of combustion to its end is defined as the ignition delay time. This usually occurs over a clear distance because the phase change involves a change in the opposite direction [29]. Figure 4 shows the crank angle variation for different groups. The D90W5B5 mixture has a very short hysteresis angle of 14° to 19°. This is because its viscosity is lower than other mixtures. The most important factors that affect ignition or combustion delay are the compression ratio, air-to-fuel ratio, crank angle, and cylinder pressure. Keeping these factors constant, the greatest influence remains on the type of fuel. The results show that the best fuel with the shortest ignition delay time is D90W5B5. The ignition delay time for biofuels is the highest due to the high viscosity of the fuel.

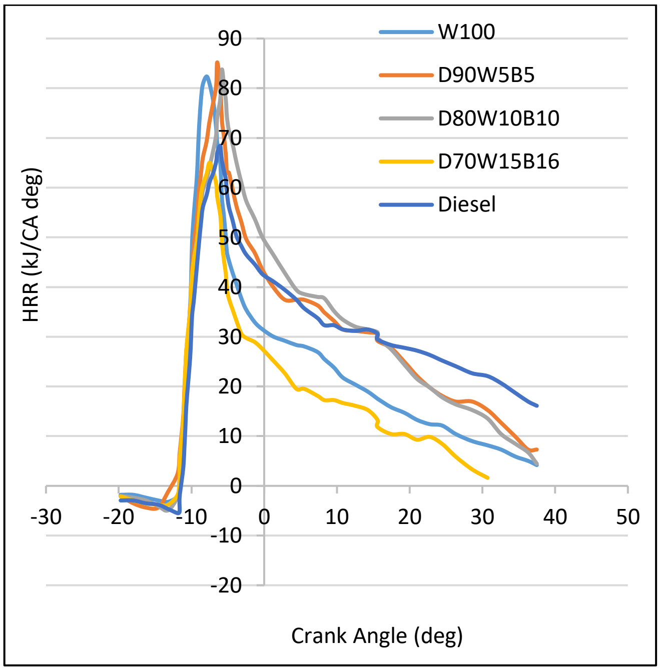

Figure 3. Heat release rate for tested blends at variable crank angles

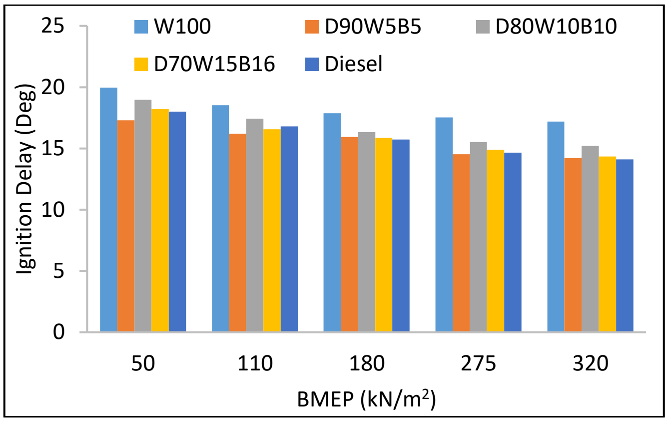

Figure 4. Ignition delay for the tested blends at variable engine loads

3.2 Engine performance

3.2.1 Brake thermal efficiency

BTE is defined as heat capacity and is scientifically called an efficient brake. In other words, brake heat generation indicates energy efficiency by ignoring the thermodynamic heat loss of the engine due to the release of chemical energy [16].

Figure 5 shows the achievement of brake temperature depending on the weight of the load. Under the best conditions (100% load), brake temperature is best, followed by 32% for diesel. However, the best temperature sensor is D90W05B05, followed by 31%. The best calorific value can be achieved by D90W5B5. Adequate mixing of these mixtures with a high percentage of butanol requires good mixing of oxygen and de-oxygen mixtures, allowing good combustion to achieve high combustion temperatures. The reduction in BTE for the blends and W100 compared to diesel can be attributed to the lower heating value of these fuels.

3.2.2 Brake specific fuel consumption

Brake-specific fuel consumption (BSFC) expresses the mass fuel flow rate divided by the brake power (energy produced). This definition is widely used in industry, as it measures the fuel efficiency of a diesel engine. The units of BSFC are typically grams per kilowatt-hour (kg/kW h). This definition is used to compare the fuel efficiency of different diesel engines and to evaluate engine performance under different operating conditions.

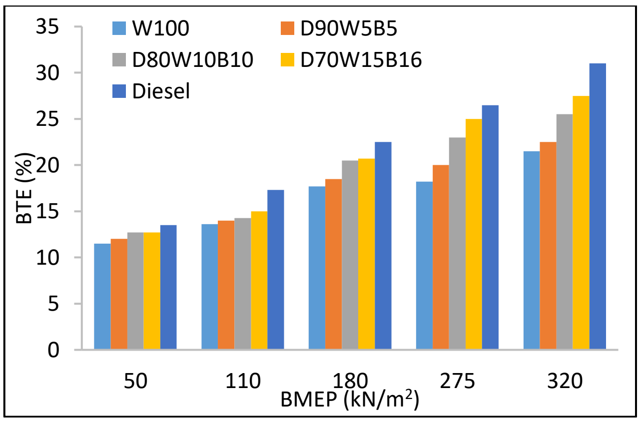

Figure 5. BTE for the tested blends at variable engine loads

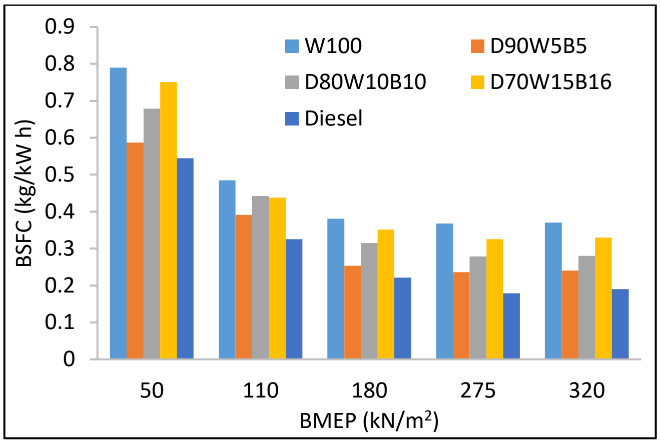

Figure 6. Specific fuel consumption for the stated blends at variable engine loads

Figure 6 shows the factors affecting the BSFC for the used blends due to different loads. The figure shows that the BSFC for all mixtures studied is high when the engine is running at low load. These values decrease with increasing engine load, with diesel remaining the lowest BSFC value. The results show that D90W5B5 follows diesel in terms of lower consumption because its calorific value is high. It is 6.11% higher than diesel. D90W5B5 mixture has advantages over others due to the low freezing point of the mixture and its good calorific value, which speeds up the process of mixing different quantities to obtain the best results. Another reason why the D90W5B5 mixture achieves a very low BSFC is that the increased butanol content and reduced volume make the cylinder pressure too high for optimal performance; The addition of more than 5% butanol causes a decrease in pressure in the cylinder, which accelerates the mixture and reduces the calorie content [30].

3.3 Emissions

3.3.1 Emissions of CO

Insufficient structure of carbon atoms and oxygen atoms causes incomplete combustion and oxidation of carbon, producing CO. CO inhalation causes lung failure and may lead to death. The recommended concentration of carbon monoxide emissions from internal combustion engines ranges between 0.2 and 0.5%, and if it exceeds 0.5%, it causes eye diseases and enters the danger stage, especially in closed spaces such as garages [31]. Figure 7 shows the levels of CO emitted when the engine operates at different loads. The combustion of the W100 emitted the lowest CO concentration at the various loads tested. As for diesel, the levels of CO emitted from it were the highest for all loads tested, and its concentrations increased at low loads. It is also evident that lower emission was achieved for the D80W10B10 mixture because the higher butanol content allows the mixture to oxidize faster, emitting lower CO levels than diesel. Compared to diesel combustion, the CO concentrations decreased by 12.59%, 13.46%, 11.6%, and 31.97% for D90W5B5, D80W10B10, D70W15B15, and W100, respectively.

3.3.2 Emissions of HC

Hydrocarbon gases are small molecular pollutants produced by incomplete combustion. These pollutants, which people inhale at levels above 50ppm, cause stomach and eye damage. The incomplete formation and oxidation of hydrogen molecules and carbon molecules at 400°C leads to the formation of hydrocarbon gases. Figure 8 shows the emission patterns for the mixtures tested at varying engine loads. The figure clarifies that the highest concentrations of HC when burning diesel, followed by D90W5B5. The least studied type of HC production is biodiesel, W100, which is 39.6% less than diesel fuel. Since W100 has slower ignition delay than other mixtures, it has enough time to oxidize carbon molecules with sufficient oxygen available [32]. The results show that increasing oxygenates in the mixture results in lower HC levels. Compared to diesel combustion, the HC concentrations decreased by 16.57%, 25.48%, 33.14%, and 39.76% for D90W5B5, D80W10B10, D70W15B15, and W100, respectively.

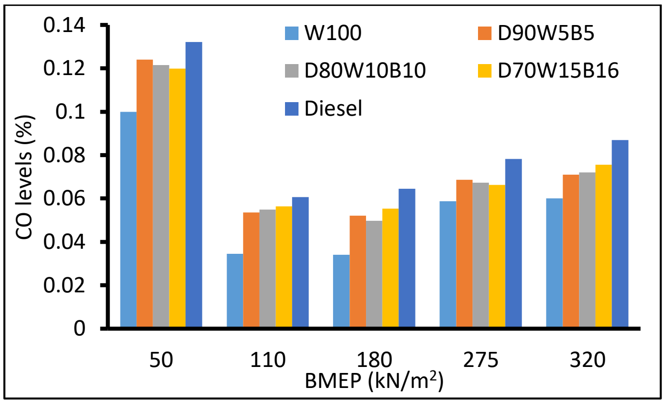

Figure 7. CO levels emitted by the tested blends at variable loads

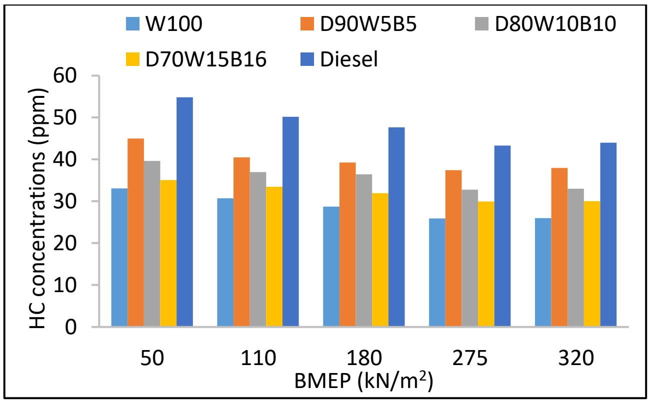

Figure 8. Emitted HC pollutants for the tested blends at variable engine loads

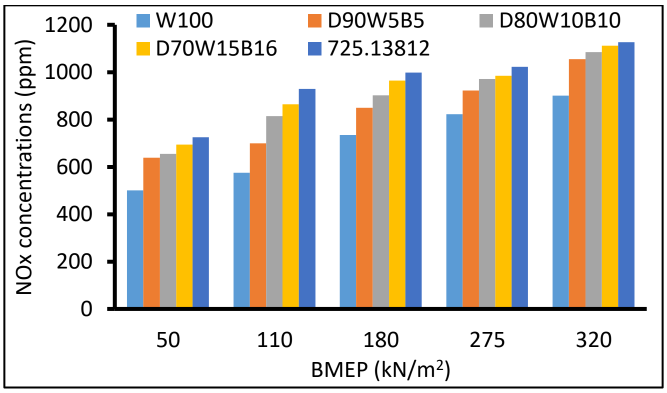

Figure 9. NO_X concentrations for the tested blends at variable engine loads

3.3.3 Emissions of NOx

The emissions resulting from complete or partial oxidation of nitrogen at high temperatures are called nitrogen emissions. These emissions are pollutants or originate from extremities and pose risks to humans in the form of serious health problems such as respiratory and eye problems. Figure 9 shows the evolution of nitrogen emissions from low load to high load. That increased load tends to produce more NOx. The W100 emits lower NOx emissions than diesel and other blends despite the presence of oxygen in its chemical composition. The reason can be attributed to its low calorific value and long ignition delay period. When comparing the percentage of decrease in NOx concentrations with what is emitted from diesel combustion, these concentrations were found to decrease by percentages of 17.01%, 20.40%, 23.41%, and 25.08% for D90W5B5, D80W10B10, D70W15B15, and W100, respectively.

3.3.4 Sulfur dioxide

Iraqi diesel is characterized by high levels of sulfur in its composition, ranging from 10,000 to 25,000ppm (1% to 2.5%) depending on the source of the crude oil. This high percentage of sulfur makes this fuel one of the worst types in the world [33]. The presence of sulfur in this high percentage is due to its high percentage in Iraqi crude oil. Iraqi refineries were destroyed several times in previous wars, and no new refineries were built, so the ones currently available are old and ineffective in ridding diesel of sulfur [33]. Figure 10 declares the sulfur deposits in the engine as a result of burning other types of fuel. Sulfur dioxide levels are highest when the engine is operating at high loads and lower when operating at moderate loads. Operating the engine on high loads requires injecting more and more fuel, which increases the SO_2 emissions rate. This is because the heat of combustion is higher at medium loads, which leads to better oxidation of sulfur and less formation of aromatic compounds and fine particles. Adding oxygenates to diesel reduced sulfur dioxide levels by 3.9%, 8.66%, 10.98%, and 97.7% for D90W5B5, D80W10B10, D70W15B15 and W100, respectively, compared to regular diesel.

3.3.5 Hydrogen sulfide

If a person is exposed for four continuous hours to hydrogen sulfide at a concentration of 100ppm or higher, it causes loss of consciousness and may lead to death. Figure 11 shows that operating the engine with all tested mixtures reduces the concentrations of H_2S emitted as a result of the decrease in sulfur concentrations in its content. Specifically, the W100 which emits near-zero levels. This fuel is sulfur-free, so traces of H_2S gas released are the result of residual sulfur components or diesel fuel residue in the bore. When the engine runs on a mixture of biodiesel and butanol (both of which do not contain sulfur), the H_2S gas emitted from the combustion of the two mixtures is reduced in proportions close to the proportions of the reduction in sulfur in the fuel content. The levels of H_2S emitted are lower compared to diesel by 6.15%, 8.89%, 15.57%, and 97.8% for blends D90W5B5, D80W10B10, D70W15B15, and W100, respectively.

Although the concentrations of SO_2 and H_2S have not reached dangerous levels, if they are emitted into closed spaces such as tunnels and garages, they can accumulate to reach such levels that are dangerous to human and animal health in addition to their environmental damage. It is noted that the percentage of decrease in the formation of both SO_2 and H_2S is somewhat less than the percentage of reduction of sulfur in the blend, and it is believed that the remaining percentage is involved in the formation of soot.

3.3.6 Total suspended particles

The oxidation process improves with the availability of oxygen in the combustion chamber (as is the case for the mixtures studied), and as a result, the oxidation process improves, and the levels of total suspended particles (TSP) decrease. As Figure 12 shows, when oxygenates are blended with diesel, the TSP decreases according to the oxygenate mass fraction added. The availability of oxygen as a result of this addition helped in this decrease in TSP levels, which improves fuel oxidization, which in turn leads to a reduction in total suspended particles. Compared to diesel, TSP decreased by 19.1%, 22.02%, 34.66%, and 49.7%, D90W5B5, D80W10B10, D70W15B15, and W100, respectively.

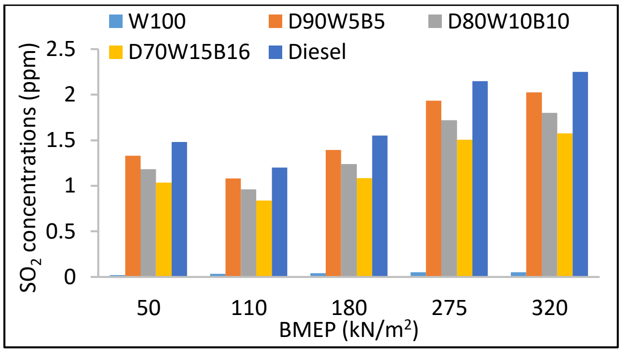

Figure 10. SO_2 concentrations for the tested blends at variable engine loads

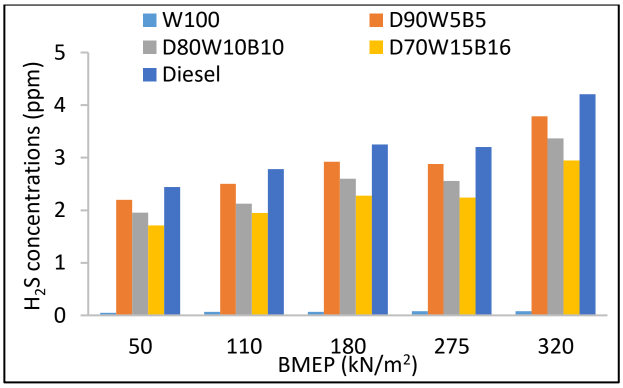

Figure 11. H_2S concentrations for the tested blends at variable engine loads

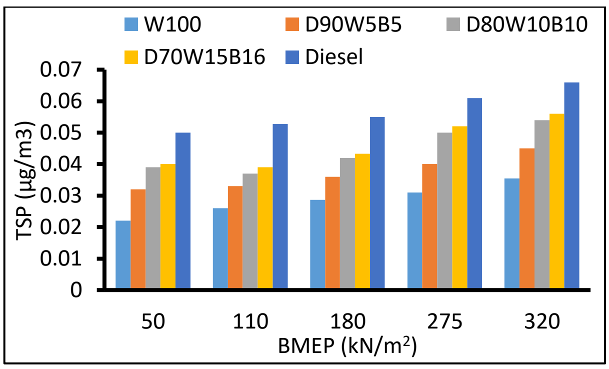

Figure 12. TSP concentrations for the tested blends at variable engine loads

3.4 Comparison with other studies

Table 4 lists the results of some studies that included adding several types of biodiesels and butanol to diesel at different additional fractions. It must be emphasized that the comparison in such circumstances may not be fair due to many variables, perhaps the first of which is the type of diesel used. In this study, diesel with a high sulfur content was used, while the studies listed in the table all used diesel with a low or ultra-low sulfur content. The type of basic material from which biodiesel was extracted varies from one study to another. The rates of adding butanol were different, in addition to the difference in the butanol type used in some studies differs from the current study. Also, the type of engine used. For example, Karabektas and Hosoz [14] and Čedík et al. [34] used a single-cylinder engine, and the rest used four-cylinder engines. With all this, this comparison can give indications about the general trend of the study results. It is noted that adding butanol and biodiesel to diesel caused an increase in BSFC (all studies agreed on this). The increase in BSFC was elevated by adding more butanol to the blend due to its lower heating value, density, and viscosity compared to diesel and biodiesel. All studies also agreed that such an addition causes a decrease in BTE. Regarding pollutants, the studies differed, while all emissions were reduced in the current study, as is the case with Čedík et al. [34]. As for the rest of the references, these pollutants varied between an increase and a decrease.

Table 4. A comparison between recent study results and other studies

Reference	Blend Type	Engine Type	Test Type	BTE (%)	BSFC (%)	CO (%)	HC (%)	NOx (%)	PM (%)
This study	D90W05B05 (Diesel 90%+Waste restaurant oil 5%+butanol 5%)	Fiat 3333cc	100% load	-1	+6.11	-12.6	-16.6	-17.0	-19.1
[14]	ISB10 (Diesel 90%+Isobutanol 10%)	Superstar	100%	-0.8	+2.06	-11.3	+22.9	-8.9	-
[16]	B40D40B20	Kubota GL7000	92% load	-	+14.1	0	-32	+3.2	-
[17]	TB1 (Diesel 60%+bio-Cotton oil 10%+n-butanol 30%)	Land Rover turbocharged	100% load	-15.49	+29.4	-15	+83.3	+114.1	-
[32]	NSME25B10GO90 (Diesel 65%+bio-*Nigella sativa 25%*+n-butanol 10%+Graphene nanoparticles (90ppm)	Kirloskar TV1	100%	-3.22	+5.7	+1	+2.3	+8.6	+6
[34]	C20B10 (Diesel 70%+bio-coconut oil 20%+Butanol 10%	Zetor 1204 (tractor engine)	100%	-	-	-21.7	-18.8	-5.9	-41.5

4. CONCLUSIONS

In this study, biodiesel produced from restaurant waste was mixed with butanol, and the effect of the proportions of the mixtures added to the diesel on the engine's combustion specifications, performance, and pollutants emitted from it. The study was performed at different engine loads and at constant engine speed. The importance of the study revolves around reducing the high sulfur content in diesel through additives that improve the quality of combustion. This study demonstrates that combustion and emission results are better for biodiesel and butanol blends than for diesel. The D90W5B5 mixture had the highest cylinder pressure, followed by the D80W10B10 mixture and then the diesel. These two mixtures have high braking efficiency due to good calorific value and high oxygen content. The D90W5B5 also has the lowest ignition delay when used. It also has the lowest specific brake fuel consumption after diesel. The W100 mixture achieved the lowest CO emissions, while the diesel was the highest. HC emissions were lower when the engine was running on W100 fuel compared to the maximum values emitted by diesel. The percentage of NOx emitted from the combustion of the blends was lower than the combustion of diesel by 16.57%, 25.48%, 33.14%, and 39.76% for D90W5B5, D80W10B10, D70W15B15, and W100, respectively. Sulfur dioxide pollutants decreased by 3.9%, 8.66%, 10.98%, and 97.7%, respectively. Hydrogen sulfide levels were reduced by 6.15%, 8.89%, 15.57%, and 97.8%, respectively. Total suspended particles were reduced by 19.1%, 22.02%, 34.66%, and 49.7%, respectively. Because biodiesel is sulfur-free, SO_2 and H_2S emissions were at very low levels, close to zero.

It is recommended to perform logistical and cost-effective studies and analysis of restaurant waste to a biodiesel approach in future studies. Studies must also include a field study, the cost of collection, the cost of transportation, and the cost of treatment, in addition to the environmental impact by reducing landfill pollution. These studies make it possible to propose several additional criteria to add a more realistic use of waste. Future studies must also focus on technical-economic studies and social and economic studies because of their importance to the economy and society.

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NOMENCLATURE

BDC	Bottom dead center
BP	Brake power
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon Monoxide
CO_2	Carbon dioxide
CA	Crank Angle
D100	Pure Diesel
D90W5B5	90% Diesel 5% Waste restaurants oil biodiesel and 5% butanol
D80W10B10	80% Diesel 10% Waste restaurants oil biodiesel and 10% butanol
D70W15B15	70% diesel 22% Waste restaurants oil biodiesel and 8% butanol
EGT	Exhaust gas temperatures in ℃
HC	Hydrocarbons
H_2	Hydrogen dioxide
H_2S	Hydrogen sulfide
HRR	Heat Release Rate
LCV	Lower calorific value
$\dot{m}_{a,act}$	Actual air flowrate
$\dot{m}_{a,theo}$	Theoretical air flowrate
$\dot{m}_f$	Fuel mass flowrate
N	Revolutions per minute
NOx	Nitrogen oxide
PPM	parts per million
SO_2	Sulfur dioxide
TDC	Top dead center
Q_t	Total fuel heat
Vs.n.	Swept volume per stroke
ρ_{air}	Air density
ρ_f	Fuel density
η_{bth}	Brake thermal efficiency