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The Effect of Eichhornia Crassipes Biodiesel/LPG Dual-Fuel on Performance and Emissions in a Single-Cylinder Compression Ignition Engine

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HIGHLIGHTS

- The combustion was enhanced with the addition of E.
- The engine operation was smooth and had less fuel consumption when using biodiesel and LPG.
- Engine running on dual fuel mode (40%ECB-LPG) is more economical.
- HC emission decreases with ECB.

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ABSTRACT

This study investigates the effects of Eichhornia Crassipes Biodiesel (ECB) with liquefied petroleum gas (LPG) dual-fuel on diesel engine performance and exhaust emissions characteristics. A four-stroke, single-cylinder and water-cooled diesel engine was used. The engine was operated with pure Iraqi diesel (PID) as a reference fuel, 40% ECB-60% PID, and duel fuel mode (DFM) (40% ECB-60% PID-2.4 *l*/min LPG). The experimental testing was carried out at 1500 rpm constant engine speed, compression ratio 18, and time injection 23° bTDC under various load conditions (25%, 50%, 75%, and 100%) full load. Using a gas analyzer, the engine emissions, including carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NOx), were measured. An OPABOX smoke unit was used to determine the smoke intensity. The result manifested that the 40% ECB reduced the thermal brake efficiency (BTH) by 7% at partial load, compared with the PID. Exhaust emissions tests at full load displayed a reduction in CO_2, CO, HC, and smoke by 44.4%, 70.34%, 31%, 76%, and 47%, respectively, with increasing NOx emission by 17.02% compared with the PID. The (LPG- 40% ECB) DFM at full load elucidated a reduction in CO_2, CO, and smoke by (52.38%-14.28%), (81.48%-37.5%) and (86.28 %-41.7%), respectively, while there was an increase in HC and NOx emission by of (15.38%-40%) and (34.2%-20.07%), respectively, compared with the PID and 40% ECB, where the BTH in DFM was higher than 40% ECB by 9.07%. Finally, the brake-specific fuel consumption (BSFC) decreased by (10.11%-11.2%) compared with PID and 40% biodiesel.

1. Introduction

The continuous depletion of petroleum reserves and anxiety around the high levels of pollutants in the exhaust of vehicles has prompted investigators to search for another renewable source as well as fewer energy sources of pollution [1] [2]. Clean combustion of alternative gaseous fuels and their availability at an attractive cost compared to conventional liquid fuels is a major reason for increasing their use for compression ignition engines in dual fuel [3] [4]. For replacing the petroleum fuels utilized in the internal combustion engines, the biodiesel fuel offers a good solution to the 'Fossil Fuel Depletion' crises as well as the 'Environmental Degradation'. Many of investigators are effectively following the non-valid oils utilization for the biodiesel universal manufacture due to its cleanser burning nature. The biodiesel is defined by ASTM as "A fuel comprised mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats'' [5]. Biodiesel can be used directly as a substitute fuel in a Diesel engine or blended in various percentages with fossil Diesel [6]. Biodiesel has various characteristics that make it an excellent alternative fuel for engines, and the most notable advantages of utilizing biodiesel over Diesel fuel are its low aromatics, biodegradable, low Sulphur, nontoxic, and the oxygen-containing molecules' existence, which suppress the emissions of the Sulphur dioxide generation, HC, and CO through the procedure of combustion. [7] [8].

Eichhornia crassipes (water hyacinth), an aquatic plant, is originally from Brazil. It is considered one of the fastest and most widespread colonial plants [9].This plant consumes too much oxygen and water, so it is harmful to aquatic organisms and

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causes a significant decrease in the amount of oxygen in the areas where it grows. EC has a high cellulose and hemicellulose content per unit volume of dry matter, which favors its biomass as a potential bio-energy crop. It has been a source of interest in recent studies to blend and characterize biodiesel. In a review article [10], the authors showed that Eichhornia crassipes, with its low percentage of lignin content, is an attractive biomass source for the biofuel industry. A group of researchers [9] and [11] reported their findings on a blended biodiesel from Eichhornia Crassipes mixed with pure Diesel and examined the feasibility of fueling biodiesel blended from the Eichhornia Crassipes in Kirloskar, a single-cylinder, four-stroke, and air-cooled DI Diesel engine as an alternative energy source. In their tests on pure Diesel and mixture samples of 10%, 20%, 30%, 40%, and 100% volumes of biodiesel mixture, the results revealed that the engine's thermal efficiency improved, while the HC and CO emissions were reduced. However, the added blends caused somewhat higher emissions of NO_X and CO_2.

Ref [12] depicted the effect of mixing 10%, 20%, and 40% Eichhornia crassipes was measured under various operating conditions. The results elucidated that the mixtures' viscosity and density rose with the addition of biodiesel, but the calorific value decreased. The engine test displayed that the biodiesel blends improved the brake thermal efficiency. The exhaust analyses exhibited a small decrease in the emissions of CO and HC and an increase in NOx compared with the pure Diesel. Ref [13], [14] and [15] investigated the effect of biodiesel blends on the performance and exhaust emission of the Diesel engine. The result showed that the biodiesel fuel enhanced the performance of the engine and reduced the CO, HC, and smoke emissions, while the NOx emissions slightly increased. Also, the results revealed that biodiesel is a feasible solution to mitigate the drastic impact of fossil fuels on the environment and economy.

LPG is a colorless gas derived from the petrol, usually consisting primarily of propane (C_3H_8), butane (C_4H_{10}), or a mixture of these two constituents which is derived from natural gas and crude oil [16-18].It is probably the third most widely used fuel after petrol and Diesel , and the potential benefits of using LPG in Diesel engines are both economical and environmentally friendly [19,20]. It significantly reduces the CO, CO_2, emissions, particulate matter, and smoke density in comparison with Diesel engines [21]. Ref [22] investigated LPG as a primary fuel for Didacta's T85D single-cylinder, direct injection, and air-cooled Diesel engine. The PID was used as a pilot fuel for the DFM, and the engine was operated at various percentages of LPG, loads, and speeds. The results indicated that the LPG enhanced the BTH and BSFC with a reduction in the emissions of CO2, CO, HC, and NO_X.

Ref [23] depicted the performance and emissions of a single-cylinder, air-cooled, constant speed, DI Diesel engine that was modified to use LPG in dual fuel mode, where LPG fumigated into the air manifold. The results indicate that the Diesel +LPG fueled engine produces fewer NO_X, CO_2, and smoke emissions as compared to Diesel fuel, but in spite of this, higher HC and emissions, especially at partial loads.

Ref [24] conducted an experiment using the Ricardo E6 single-cylinder variable compression indirect injection Diesel engine. The engine was operated using three fuels, including PID, 30% LPG, and 60% LPG. The LPG was mixed with air as a gas and ignited with a small pilot mist of Diesel fuel. From the experiment, it was found that the BTH improved by 3% in the dual fuel mode, especially at low load. And, a reduction in CO, HC, and CO_2 emissions was noticed with the LPG operated dual fuel mode. Also, the BSFC of the engine fueled with LPG was lower than that of the Diesel fuel under the optimum injection timings.

Ref [25] carried out an endurance test of 60 hours on a single-cylinder horizontal-kind Diesel engine. Through this test, three fuel samples, including 25%biodiesel (waste cooking oil biodiesel 25% and 75% Diesel fuel), 25%biodiesel+LPG, and D100 (%Diesel as a reference), were correspondingly used for evaluating the engine performance as well as the level of noise. These tests have been performed at constant speed (1300 rpm) and with a variation of load. Nevertheless, the analysis of the results showed that for the (25%biodiesel+LPG) fuel, the brake specific fuel consumption reduced with the brake power increase, and the brake thermal efficiency rose with the increase in brake power.

Accordingly, from the studies in the above literature, it can be seen that the Diesel engine process in dual fuel mode is fruitful and enhances the performance and emissions of the engine. Therefore, the aim of the present investigation is to study the effects of using 40%ECB and 40%ECB+LPG on the performance and exhaust emission of a single-cylinder compression ignition engine. They have been experimentally studied with load variation and constant speed.

2. Experimental Setup

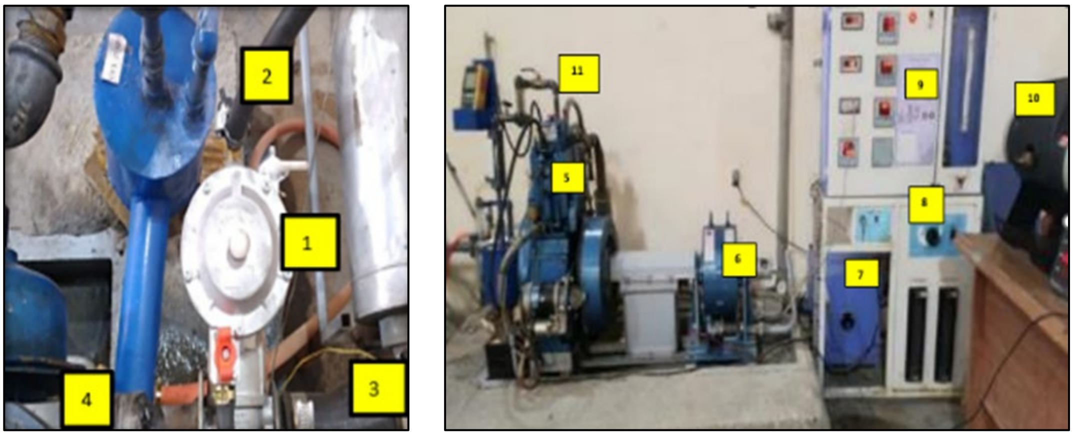
2.1 Test Equipment

The whole set of experiments were conducted on a VCR Diesel engine. Table 1 depicts the main specifications of the engine. In this investigation, an eddy current dynamometer with a water-cooling system was used to determine the torque generated by the engine as shown in Figure (1-b). The CO_2, CO, NOx, and HC concentrations were measured via the (EGMA-CG-450), a multi-gas emissions analyzer. A TEXA-OPABOX (AUTOPOWER) smoke meter model was used for measuring and displaying the smoke concentration in the exhaust gases. An air box with an orifice system was employed for measuring the flow rate of air via a pressure gauge scale (water manometer).

The gas carburetor was connected with the intake air manifold as evinced in Figure (1-a) to control the entering LPG and mix it with the air. The amount of LPG was measured by an LPG flow meter with a range of (0-2.4 l/min). An inductive pick-up sensor, in conjunction with a digital rpm indicator, was used to detect and display the engine speed on the control panel. While thermocouples (type K) were used to measure the temperatures of fresh air and exhaust gases, The schematic diagram of the experimental setup is shown in Figure 2. All experimental work was done in the laboratories of the College of AL-Musayyib Engineering Technology/University of Babylon.

Table 1: Test engine specifications

Engine Model	VCR Diesel Engine
Engine Type	1 cylinder, 4 stroke
Combustion Type	Compression Ignition (Self-ignition)
Cooling System	Water Cooled
Fuel System	Direct Injection System
Time Injection	23° bTDC
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	18
Speed	1500 rpm



(a) **(b)**

Figure 1: (a) Entrance gas system, and (b) Rig used in experimental work

1) LPG Carburetor
2) LPG Entrance
3) Air entrance
4) Air +LPG mixture
5) VCR engine
6) Eddy current dynamometer
7) Air tank +Orifice
8) Dynamometer control
9) Control panel
10) Smoke meter
11) LPG system

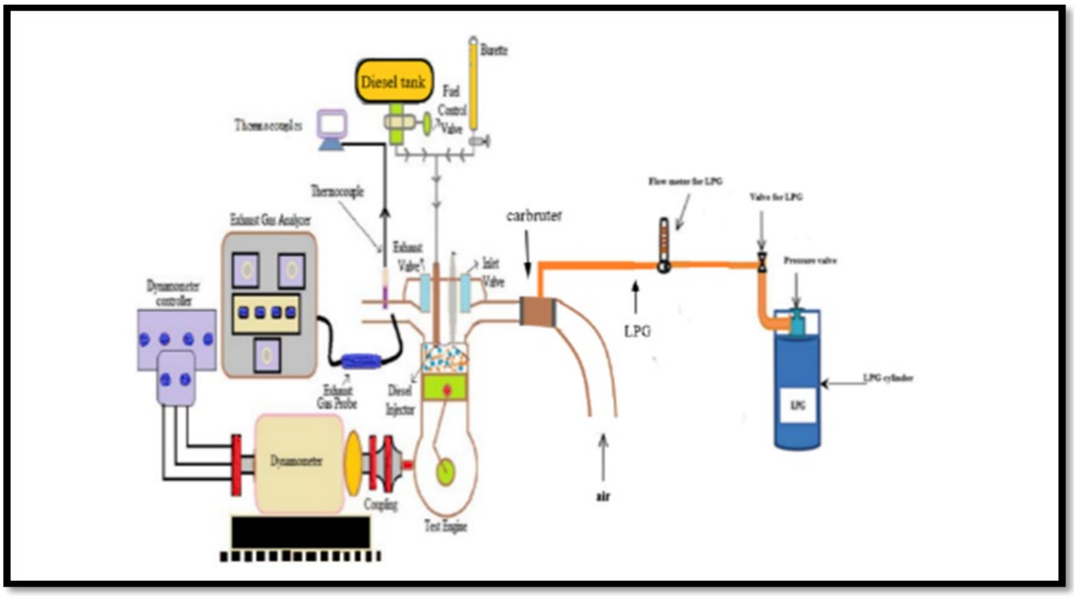


Figure 2: The schematic diagram of the experimental setup

2.2 Used Fuels

Pure Iraqi Diesel was used as a reference in the experimental work. In the tests, biodiesel was extracted from the Eichhornia Crassipes oil at a mass of 40%ECB (40%biodiesel-60% Diesel). The LPG content consisted of a mixture of gases, including ethane ($0.06C_2H_6$), propane ($0.3C_3H_8$), and butane ($0.6C_4H_{10}$). Table 2 lists the properties of the utilized fuels.

Table 2: Physical properties of the Diesel – 40%ECB-LPG

	Property	Unit	PID	(40 % ECB)	LPG
1	Normal state	-----	Liquid	Liquid	Gaseous
2	Density at 15°C	kg/m^3	823	843.8	1.85
3	Carbon Residue (on 10 % Residue)	% m/m	0.08	-----	------
4	Flash point	°C	62.5	Flammable	−105
5	Cetane Index	----	52.6	50.45	<3
6	Calorific Value (Net)	kcal/kg	10288.6	10228.75	10986.91

2.3 Characterization of Biodiesel

At the beginning, the parts of the plant were separated from each other (leaves, petioles, and roots). The roots were removed because they absorb heavy metals, and then the leaves and petioles were washed manually with tap water and distilled water to remove any solid particles. Then, they were dried in the oven to be ready for grinding. After the sample was powdered, it was pre-treated with 1% NaOH for 2 hours. A total of 10 kg of Eichhornia crassipes was treated with a 6% sulfuric acid catalyst and a methanol to oil ratio of (5:1) in a hydrodynamic cavitation reactor at 65°C with circulating liquid glycerol for 45 min. After a period of time, the mixture is divided into two layers: the upper layer is the liquid fatty acid (biodiesel), and the lower layer is the glycerin collected at the container's bottom. The produced biodiesel comprises some methanol residues, glycerin, soap, and sodium hydroxide as shown in Figure 3. This residue can be eliminated by adding distilled water to the biodiesel as well as better shaking the mix for around 1 minute. Then, the mix was left to re-separate into water and two biodiesels. The procedure of washing was repeated many times, utilizing pure water every time to ensure the highest fuel purity, as formerly recommended. A 50-liter hydrodynamic cavitation reactor was used to produce Eichhornia crassipes oil biodiesel. The reactor consists of a double-lever glass, a diaphragm pump, and an air compressor for driving the double diaphragm pump, which acts as a power dissipation apparatus in the hydrodynamic cavitation reactor.

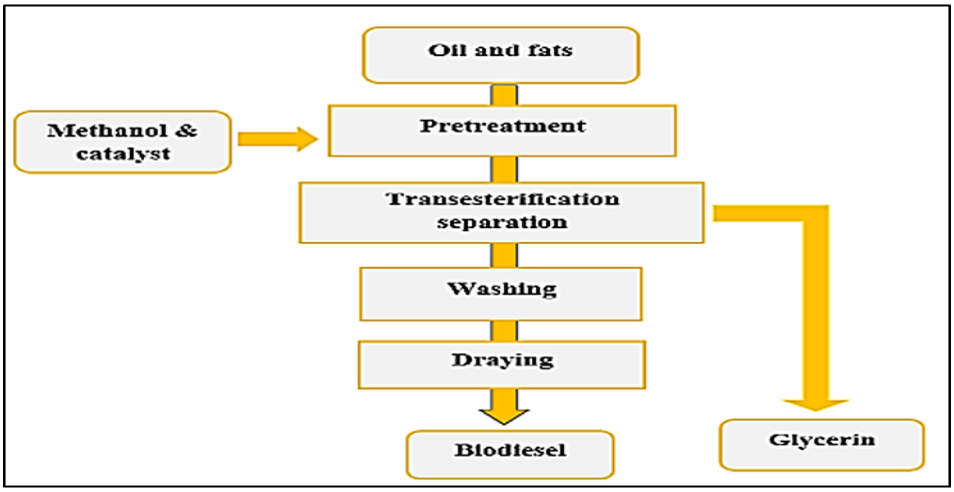


Figure 3: The schematic of the biodiesel fuel preparation

2.4 Test Procedure

Three fuels (Diesel, 40% ECB, ECB, and 40% ECB-2.4 l/min LPG) were tested in this study. They were operated at various loads and constant speeds of up to speeds of up to 1500 rpm, started on PID and warmed up. Then, parameters like the speed of operation and load were measured. With a dual fuel mode, the engine was started with a pilot fuel, and after a steady state, 2.4 l/min of LPG was added to the engine by the carburetor in the intake air manifold. Fuel consumption and temperatures were measured by an interment of measurement. An exhaust gas analyzer and a smoke meter were used to measure exhaust emissions and smoke density. Every reading was repeated three times to obtain the mean value.

2.5 Performance Evaluation Parameters

1) Mass flow rate of fuel (kg/h)

$$\dot{m}_f = \frac{\dot{v}_f * \rho_f}{1000} \tag{1}$$

2) Brake-specific fuel consumption (kg/kW.h)

$$BSFC = \frac{\dot{m}_f\ Diesel\ + \dot{m}_f\ LPG}{BP} \quad (2)$$

3) Brake power (kW)

$$BP = \frac{2\pi * N * T}{60 * 1000} \quad (3)$$

4) Brake thermal efficiency (%)

$$\eta_{bth} = \frac{BP}{(\dot{m}_f * LCV)Diesel + (\dot{m}_f * LCV)LPG} * 100\% \quad (4)$$

2.6 Error Analysis

Instrument selection, condition, calibration, environment, observation, reading, and test preparation can cause experiment errors and uncertainties. As a result, an error analysis must be performed to determine the correctness of the experiments. The magnitudes of error in various measured parameters, namely fuel consumption, brake power, and exhaust emissions, were estimated from the instruments' minimum output values and accuracy using the root-mean-square method. Table 3 shows the percent of error of the instruments used in this study.

Table 3: Percentage of uncertainty

ID	Measurement quantity	Percent of error
1	Brake power (B. P)	±0.09
2	Brake thermal efficiency (BTH)	± 0.09
3	Brake specific fuel consumption (BSFC)	± 0.09
4	Carbon monoxide (CO)	± 0.01
5	Carbon dioxide (CO2)	± 0.1
6	Oxidizes of nitrogen (NOx)	1 ppm
7	Unburned of hydrocarbon (HC)	1 ppm

3. Results and Discussion

3.1 Analysis of Brake Thermal Efficiency

Figure 4 shows the brake thermal efficiency with the variation of load for the test fuels. At partial (low) load conditions, there is no difference between 40% ECB and PID in BTH. The lower calorific value, high viscosity of biodiesel and high fuel consumption caused a slight reduction in BTH by 2% at the partial (intermediate) load conditions in comparison to the PID. But, at full load conditions, the BTH of 40% ECB is the same as that of PID. This behavior is due to the presence of oxygen in ECB that leads to improvements in the combustion process and an increased rate of heat release with lower fuel consumption. This result is in agreement with [26] and [27]. The higher BTH was obtained with a dual fuel (40%ECB-LPG) mode, and the ignition delay, uncontrolled combustion, and post-combustion phases occurred in a short time due to the better atomization of the LPG fuel in the cylinder. In addition, the higher calorific value of LPG leads to lower fuel consumption in comparison to the 40%ECB and PID fuels. Thermal efficiency increased by 9.07% compared with the 40%ECB, respectively. This result is in agreement with [28] .

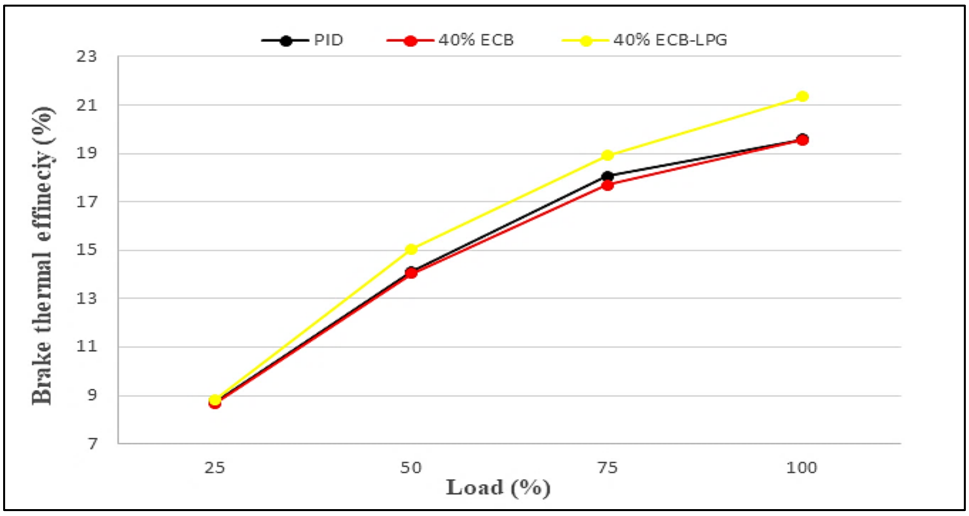


Figure 4: Comparison of brake thermal efficiency with increasing the percentage of load

3.2 Analysis of Brake Specific Fuel Consumption

Figure 5 indicates the variation of brake specific fuel consumption with the variation of load for the test fuels, and it is observed that by increasing the load, cylinder pressure and temperature increase, which improve the combustion process, resulting in a decrease in BSFC for all modes of operation. There is a slight increase in BSFC by 1.4% with 40%ECB due to the lower calorific value, the high viscosity of biodiesel, and higher fuel consumption to produce the same output power in comparison with Diesel. But, at a full load, it can be noted that the BSFC is the same as the PID due to the oxygen content of 40%ECB, so the higher pressure and temperature inside the cylinder with a more efficient combustion process. With a dual fuel mode, the BSFC gradually decreases with the load. The BSFC of (40%ECB-LPG) is lower than that of 40%ECB and PID modes by 11.2% and 10.11%, respectively, owing to the better LPG mixing with air and the high LPG heating value, which lead to the higher temperature of the flame and the operative combustion with low mass used in this resulted mode. This result agrees with[7] and [29].

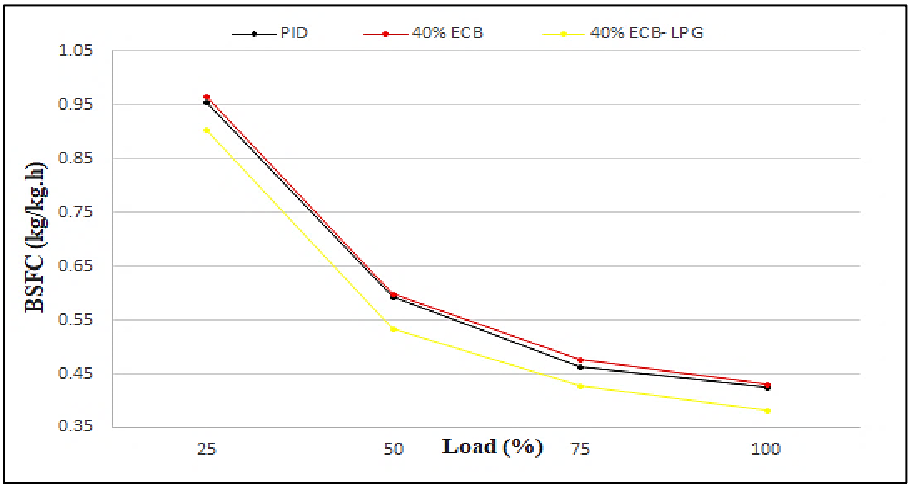


Figure 5: The BSFC comparison with increasing the load percentage of the load

3.3 Analysis of CO Emissions

Figure 6 demonstrates the variation of CO emission with the variation of load for the test fuels, and at a partial load, the CO emission decreases with increasing the load until 75% of its full load, but at a full load, it would be increased due to the high amount of fuel injection inside the combustion chamber with a constant air flow rate. Using 40%ECB as a fuel elucidates a clear reduction in the CO emissions of biodiesel compared to the PID. The average reduction is 80% and 70.37% in partial and full loads, respectively. The CO emission of the (40%ECB-LPG) mode is higher than 40%ECB by 79% at a partial load due to the poor flame propagation characteristics of the lean LPG air mixture at various few ignition centers originating from the pilot biodiesel blend. The lean, consistent charge causes a partial combustion, or in the worst state, a combustion absence. However, at full load, CO emissions are reduced by 37.5% and 81.48%, respectively, compared to 40% ECB and PID, due to the enhancement effect of LPG and ECB in the combustion strategy. Similar results can be found in other researchers' works [9].

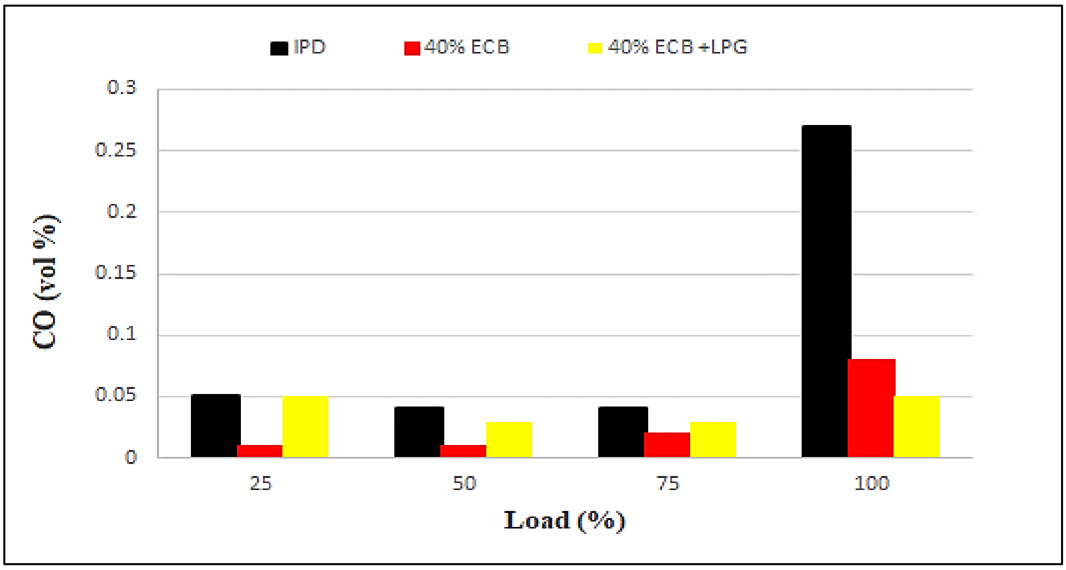


Figure 6: Comparison of CO emission with increasing the percentage of load

3.4 Analysis of CO_2 Emissions

Figure 7 demonstrates the variation of CO emission with the variation of load for the test fuels. The amount of CO_2 emissions increased with the increase in engine load, and this is due to the increase in fuel consumption at higher engine loads. A lower amount of CO_2 emissions were emitted for 40%ECB compared to the Diesel fuel at full load due to the lower ratio of C/H and oxygen content in biodiesel blends that led to the combustion improvement of low carbon emissions [30] and more reduction in CO_2 emissions with the duel fuel mode. This is because of the clean combustion of the LPG fuel due to the lower carbon to hydrogen ratio of LPG. The second reason may be the high emission of the hydrocarbons in the dual fuel mode and the incomplete combustion as revealed by the high CO and HC emissions. The reduction in CO at full load is 52.38% and 14.28% in comparison with PID and 40%ECB, respectively. This result agrees with [31].

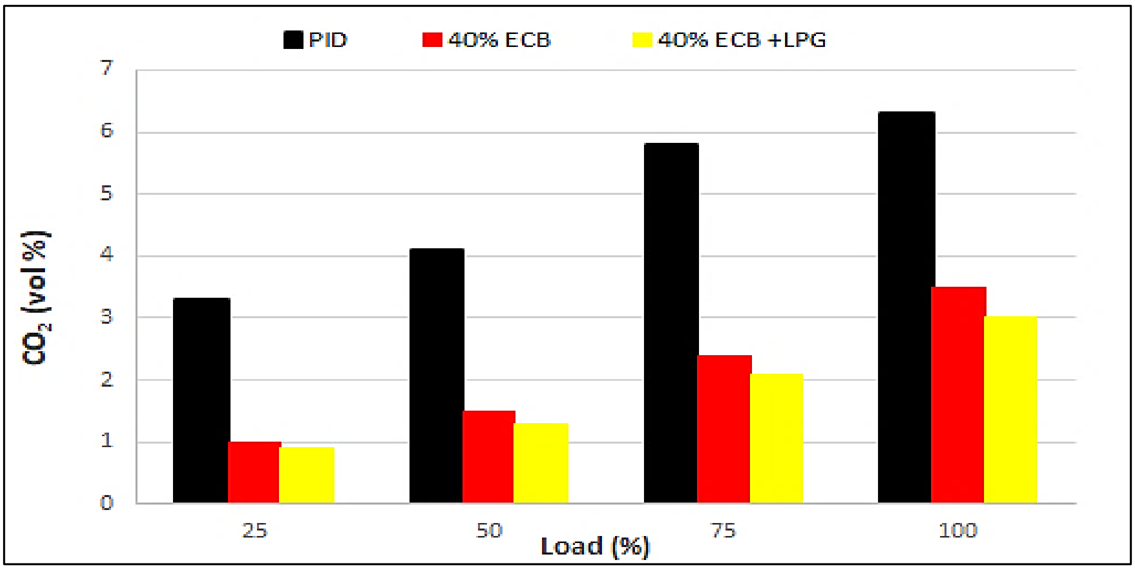


Figure 7: Comparison of CO_2 emission with increasing the percentage of load

3.5 Analysis of HC Emission

Figure 8 portrays the emissions of unburned hydrocarbons (HC) for Diesel, 40%ECB, and 40%ECB-LPG with the variation of load. At a part load, the HC increased by 11% with 40%ECB compared to the PID, but it decreased by 31% at a full load due to the oxygen content in the ECB and the enhancement in combustion efficiency. The overall HC emission levels using 40%ECB-LPG mode is higher than 40%ECB and PID, owing to the charge of LPG, which leads to a consistent, low-temperature combustion that results in less comprehensive combustion (the pilot fuel's small quantity cannot spread rapidly and widely enough to ignite completely the whole pre-mixed fuel mixture). On the other hand, there is not enough time for the whole LPG fuel to reach the auto ignition temperature, so that leads to the escape of the part of non-burned LPG fuel with exhaust. But it's also noticed that the emissions of HC for the dual fuel mode can be enhanced with the augmented load of the engine. At a full load, the HC increased by 40% and 15.38% in comparison to the 40%ECB and PID, respectively. This result is in agreement with the research work [32]

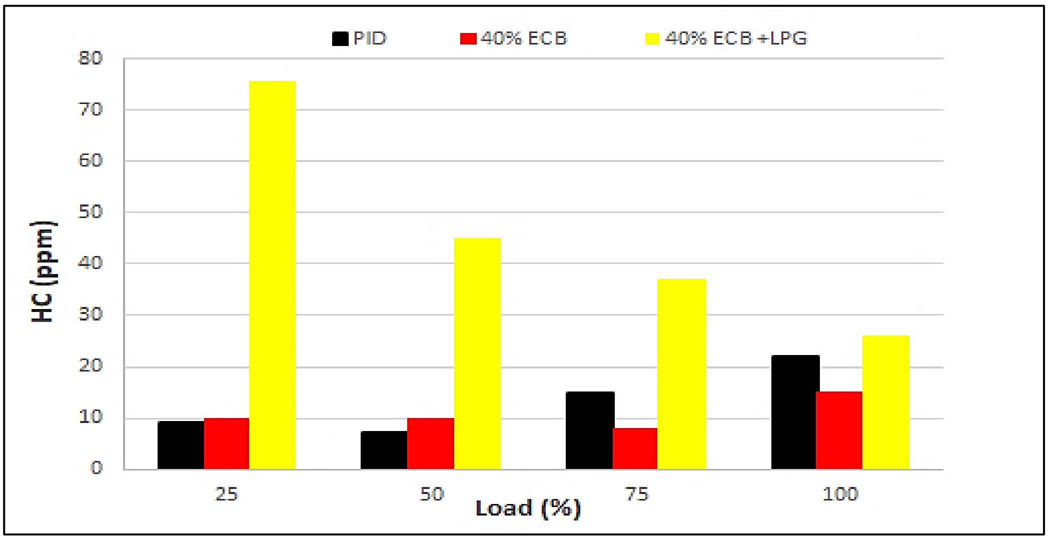


Figure 8: Comparison of HC emission with increasing the percentage of load

3.6 Analysis of NOX Emissions

Figure 9elucidates the variation of NOx emission with the variation of load for the test fuels. The NOx emission at a partial load was decreased by 16.6% with 40%ECB. It is due to the higher viscosity that causes poor mixing as well as partial combustion, resulting in a lower peak in-cylinder temperature. At the state of full load, 40%ECB makes a higher NOx emission quantity by 17.02%, and that means the further oxygen concentration causes a whole combustion as well as raises the peak in-cylinder temperature, resulting in higher emissions of NOx. On the other hand, at a partial load, the NOx emission decreased with 40%ECB-LPG by 61.11% and 54.86% in comparison with the PID and 40%ECB, respectively. That is due to the decrease in the fresh air as well as the high self-ignition temperature of LPG, which raises the delay of ignition into the decreased peak temperature of the cylinder in comparison to the ECB and PID. With the higher load of NOx emission, the increase in air to fuel ratio with the LPG (lower fuel consumption) and oxygen content of biodiesel leads to more heat release inside the cylinder and more NOx formation. The percentage of increasing NOx at a full load is 34.2% and 20.7% in comparison to the PID and 40%ECB, respectively. This result is in agreement with [33].

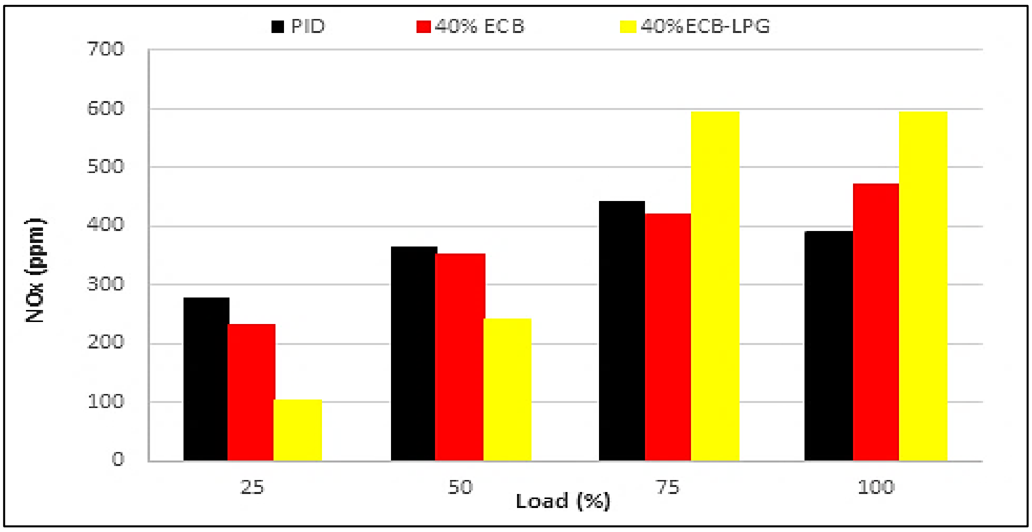


Figure 9: Comparison of NOx emission with increasing the percentage of load

3.7 Analysis of Smoke Opacity

Figure 10 manifests the changes in the smoke opacity for PID, 40%ECB, and the dual fuel mode (40%ECB-LPG) at different loads. The smoke opacity increases with an increase in load owing to an increment in the fuel quantity. There is a significant reduction in smoke with 40%ECB and dual fuel mode (40%ECB-LPG), and that is due to the enhanced biodiesel combustion because of the increased oxygen concentration. This smoke is highly emitted through the phase of diffusion-combustion, as the biodiesel is an oxygenated fuel. So, increasing the biodiesel concentration in the Diesel enhances the diffusion combustion and therefore reduces the smoke opacity [29]. Moreover, LPG has a low C/H ratio [34], so the combustion of LPG produces fewer particulates than Diesel and 40%ECB. With 40%ECB, the percentage of smoke reduction at a full load is 76.47% in comparison with the PID. When compared to PID and 40%ECB, the reduction with (40%ECB-LPG) is 86.28% and 41.7%, respectively. This result agrees with[35] and [36].

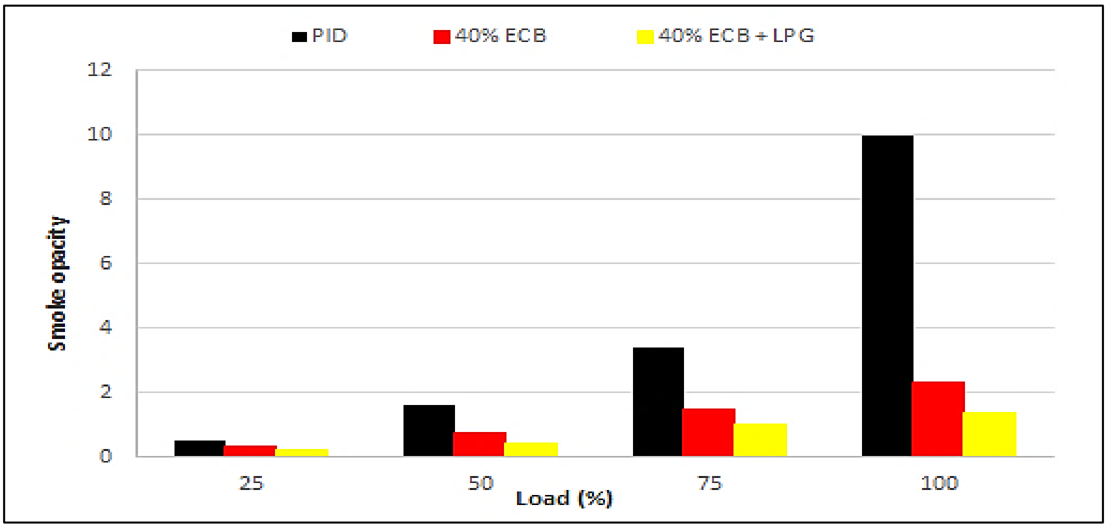


Figure 10: Comparison of smoke opacity with increasing the percentage of load

4. Conclusions

In the present study, an experimental work was carried out to examine the effects of E. Crassipes Biodiesel with and without LPG. The LPG enters the engine through the intake air manifold, so the engine operates in dual fuel mode without any modification. According to the analysis of the experimental work, the following can be concluded:

1) The combustion has been enhanced with the addition of E. Crassipes biodiesel with and without LPG compared to the pure Diesel, and the BTH was slightly reduced with 40%ECB by 2% at partial load and was the same as Diesel at full load. Biodiesel was more efficient when using a pilot fuel in a dual fuel mode, and the BTH improved by 9.06% in comparison to the 40%ECB without LPG.
2) The engine operation is smooth and there is less fuel consumption when using biodiesel and LPG.
3) An engine that runs on dual fuel (40% ECB-LPG) is more cost effective. The reduction in BSFC is 11.2% and 10.11% in comparison to the biodiesel blend (40%ECB) and PID, respectively.
4) There is a clear reduction in CO, CO_2, smoke and an increase in NOx emissions at high load for the two modes of operation (40% ECB) mode and dual fuel mode (40%ECB-LPG) compared to the PID mode.
5) HC emissions decrease with biodiesel but increase with LPG at all loads due to the escaped part of the fuel with the exhaust.

Nomenculture

Symbol	**Definition**
a TDC	After top dead center
ASTM	American Society for Testing and Materials
BSFC	Brake specific fuel consumption
BTH	Brake thermal efficiency
bTDC	Before top died center
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct Injection
ECB	Eichhornia Crassipes Biodiesel
40% ECB	40 % Eichhornia Crassipes Biodiesel+ 60% diesel
EGT	Exhaust gas temperature
HC	Unburned hydrocarbon
LPG	Liquefied petroleum gas
LPG – 40% ECB	2.4 l/min (LPG) + 40% Eichhornia Crassipes Biodiesel
NOx	Nitrogen oxides
ppm	Part of million
PID	Pure Iraqi diesel

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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