


## Article

# Environmental Risk Mitigation by Biodiesel Blending from *Eichhornia crassipes*: Performance and Emission Assessment

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**Abstract:** The aggressive growth of *Eichhornia crassipes* (Water Hyacinth) plants causes severe damage to the irrigation, environment, and waterway systems in Iraq. This study aims to produce, characterize, and test biofuel extracted from the *Eichhornia crassipes* plant in Iraq. The extracted biodiesel was mixed at 10%, 20%, and 40% with neat diesel to produce three biodiesel samples. The methodology consists of the physiochemical properties of the samples that were characterized. The performance of the IC engine fueled by neat and biodiesel samples was measured under various operational conditions. The exhaust gases were analyzed to estimate the compounds to assess the environmental impact. The results showed that the density and viscosity of mixtures increase and the calorific value decrease with biodiesel. The engine test showed that the diesel + 10BE, diesel + 20BE, and diesel + 40BE enhanced brake thermal efficiency using 2.6%, 4.2%, and 6.3%, respectively, compared to neat diesel. Exhaust tests show a slight reduction, of 0.85–3.69% and 2.48–6.93%, in CO and HC emission, respectively. NO<sub>x</sub> is higher by 1.87–7.83% compared with neat diesel. The results revealed that biodiesel blended from *Eichhornia crassipes* is a viable solution to mitigate the drastic impact on the environment and economy in Iraq. The blended biodiesel has good potential to be mixed with the locally produced diesel from oil refineries.

**Keywords:** biofuel; *Eichhornia crassipes*; emission of biodiesel; fuel technology; water hyacinth plant; waste to wealth



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## 1. Introduction

### 1.1. Background and Research Literature

Oil and natural gases, which are depleting resources, represent the main economic pillar of Iraq and the main source of energy for power production and transportation. Meanwhile, emissions caused by combustion have considerably increased environmental pollution in the country [1]. In the last few years, scientists in Iraq have directed their interests in discovering alternatives to fossil fuels. One of these alternatives is vegetable oils to produce biofuels as renewable energy, which is environmentally friendly, renewable, and biodegradable [2,3]. Biodiesel is a better lubricant than diesel oil that lengthens engine life. Several vegetable oils, such as castor, sunflower, and palm trees, are available in Iraq. However, all these vegetable oils have high values and important uses other than biodiesel production. A certain raw material must be readily available during selection. Also, it must not be useful for another purpose rather than being used for biodiesel production. Hirkuade and Padalkar [4] have reported waste-fried oil methyl ester blend and [5] reported biodiesel production from used cooking oil. Benjumea et al. [6,7] characterized and reported biodiesel blended from palm oil. In contrast, the authors of [8] have reported their experimental result about a diesel engine's performance and emission assessment fueled with methyl chloroformates of a rubber seed oil.

*Eichhornia crassipes* (*E. crassipes*), also named Water Hyacinth, has been a source of interest in recent studies to blend and characterize biodiesel. In their review article, the

authors of [9] shows that *E. crassipes*, with its low percentage of lignin content, is an attractive biomass source for the biofuel industry. On the other hand, [10] reported lastly that metal-contaminated *E. crassipes* is viable to produce bioethanol, while another study by [11] reported that the ethanol-generating capacity from *E. crassipes* was quite comparable to that obtained from other agricultural waste.

Khan et al. [12] extracted bioethanol from the *E. crassipes* plant and carried out experiments to understand the potential of this biofuel using a single-cylinder diesel engine of 3.5 kW. The experimental results revealed that 10% blend (90% petrol-diesel and 10% bioethanol) stands out in terms of engine parameters such as enhanced brake power and appreciable brake thermal efficiency. In addition, the emission levels, such as CO and unburned HC, were comparatively lesser than other blends except for NO<sub>x</sub>, which eventually depends on the engine construction.

Two studies carried out by a group of researchers in India reported their findings on blended biodiesel from *E. crassipes* mixed with neat diesel. Venu et al. [13,14] examined the feasibility of fueling biodiesel blended from *E. crassipes* in a compression engine as a potential alternative energy source. The feedstock to produce the biodiesel is sourced from Pondicherry district, Tamil Nadu, India. They tested neat diesel and mixture samples of 10%, 20%, 30%, 40%, and 100% volumes of biodiesel mixture. They concluded that the engine's thermal efficiency is improved while HC and CO emissions are reduced. However, added blends resulted in slightly higher levels of CO<sub>2</sub> and NO<sub>x</sub> emissions.

Two review articles on the *E. crassipes* have been published in 2020, one by [9] and another by [15]. The first article discusses the potential of *E. crassipes* in various applications, not only biofuel extraction. The second article reviewed the previous works on the extraction procedures, characterization, engine fueling performance, and environmental consequences of mixing the blended biofuel with diesel. Both articles are worthy of being visited.

### 1.2. *Eichhornia Crassipes* (Water Hyacinth) in Iraq

The presence of *E. Crassipes* in water bathmats slows down water flow and leads to sludging. Reduced water flow adversely affects irrigation systems. Investigations demonstrated that this water plant causes considerable loss of water resources through evapotranspiration.

The *E. crassipes* is an aquatic plant that can tolerate a wide range of habitat conditions (e.g., winds, temperature, pH, salinity, current, and drought), as shown by [16,17]. It grows in fresh water at an optimal pH 7.0, a phosphorus concentration of 20 ppm, and adequate nitrogen. It can also survive up to 13 days in seawater and has features that make it well adapted for long-distance dispersal and the successful colonization of diverse habitats. The *E. crassipes* reduce the effective capacity of water reservoirs by up to 400 m<sup>3</sup> of water per hectare. A dry climate, such as that in Iraq, causes water levels in reservoirs to fall quickly, thereby causing a major impact on the hydroelectric structures of water reservoirs and streams. Traveling using boats becomes difficult or impossible because of *E. crassipes*, thereby resulting in water transport problems.

In recent years, rivers and irrigation water streams in Iraq have been suffering from the rapid and wide growth of *E. crassipes* plants because it inhibits water flow in the Tigris and Euphrates rivers and their tributaries in the provinces of Wasit and Dhi-Qar. Figure 1 shows the distribution of the *E. crassipes* plant in the rivers of Iraq. The quantitative statistics of the water hyacinth plant extracted by the Directorate of Aquatic Treatment indicate that the quantities increased from 350 sq. km in 2006 to 860 sq. km in 2016 in the southern part of Iraq. This condition led the authorities in charge of water resources to pay high costs to remove these plants from the rivers without benefiting them.

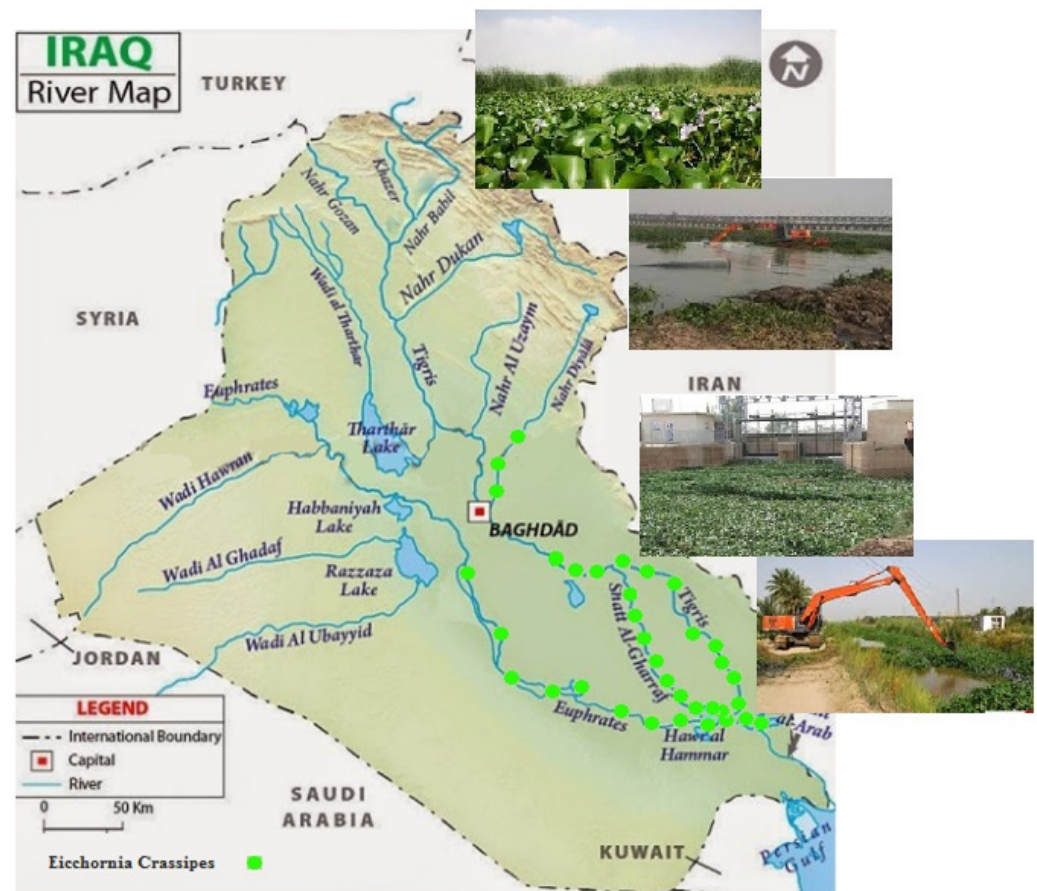


Figure 1. Distribution of *E. crassipes* in Iraqi rivers.

The growth of *E. crassipes* plants in Iraqi water streams and rivers represents a severe problem to the health, fishery, and agriculture industries in Iraq. The massive growth of *E. crassipes* plants affects the environment and various socioeconomic factors in Iraq. Unfortunately, this harsh plant is not utilized by any means in Iraq and the Middle Eastern region.

As for the sustainability and supply chain, the areas rich with *E. crassipes* with massive scale availability are shown as green dots in Figure 1. These are concentrated in the southern and eastern parts of Iraq. The process and optimization of the exhaustive supply chain could be assimilated utilizing the model proposed by [18].

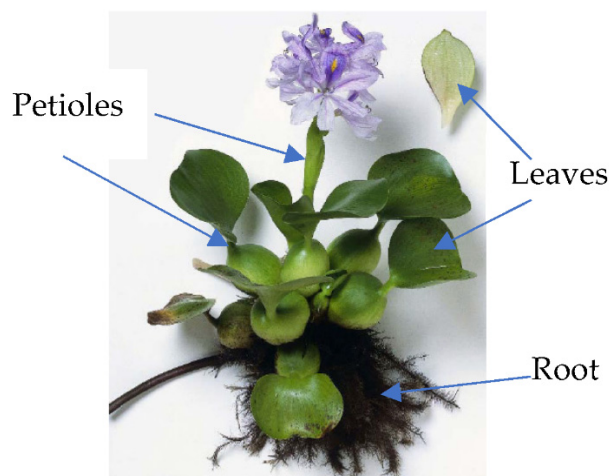
### 1.3. Motivation and Research Objective

The aggressive growth of the *E. crassipes* plant causes severe environmental and socioeconomic problems in Iraq. This plant represents a strong promise in the biofuel industry due to its fast growth with no human nursing or attention. Hence, the motivation of the current research is to assess the validity of the potential use of extracted biodiesel from *E. crassipes* as added biofuel to the neat diesel produced in Iraqi refineries. This research is the first attempt to produce biodiesel from the *E. crassipes* plant in Iraq and assess its technical and environmental characteristics. In addition to pure diesel, three mixed blends were prepared and subjected to characterization and evaluation as fuel for internal combustion (IC) engines. Each mixture consisted of neat diesel (D) and 10%, 20%, and 40% by volume of biofuel blended with *E. crassipes*. Investigation results are presented as fuel blend characteristics, engine performance at various operational conditions, and exhaust gas analysis to assess the environmental impact.

## 2. Materials and Methods

### 2.1. Biodiesel Production Procedure

In the current investigations, biofuel ethanol was produced in two steps: saccharification and fermentation. The stationary fermentation method was adopted. For saccharification, intact fungal organism *Aspergillus Niger* was used as a source of cellulose enzyme. The plant is shown in Figure 2.



**Figure 2.** A single plant of *Eichhornia crassipes* (water hyacinth) extracted from a harvested batch from Dhi-Qar marsh—Iraq.

Leaves, petioles, and roots were separated from the *E. crassipes* plant. The roots were discarded because they absorb heavy metal pollutants from water. The leaves and petioles were washed manually with tap water and distilled water to remove any solid particles. Subsequently, they were sundried and pre-treated with 1.0% NaOH for two hours. About 30 kg was brought from the site to the University of Technology for characterizations and testing.

To characterize the bio composition of the plant, the following procedure has been followed [19]:

- A small amount of the stems and leaves were taken to the chemical department laboratory for bio composition characterization. The small amount was rinsed with distilled water and left to dry at room temperature. The sample was further dried in an electric oven at 110 °C for a day to remove the moisture.
- The dry sample was ground into powder using a grinding mill, and the particles were sieved using a 300 µm standard sieve.
- A sample of 100 g of the powder was tested by Fourier transform infrared spectroscopy (FTIR) machine. The wavelength resultant was compared to a standard chart to identify the percentage of cellulose, hemicellulose, and lignin.

The test results are shown in Table 1.

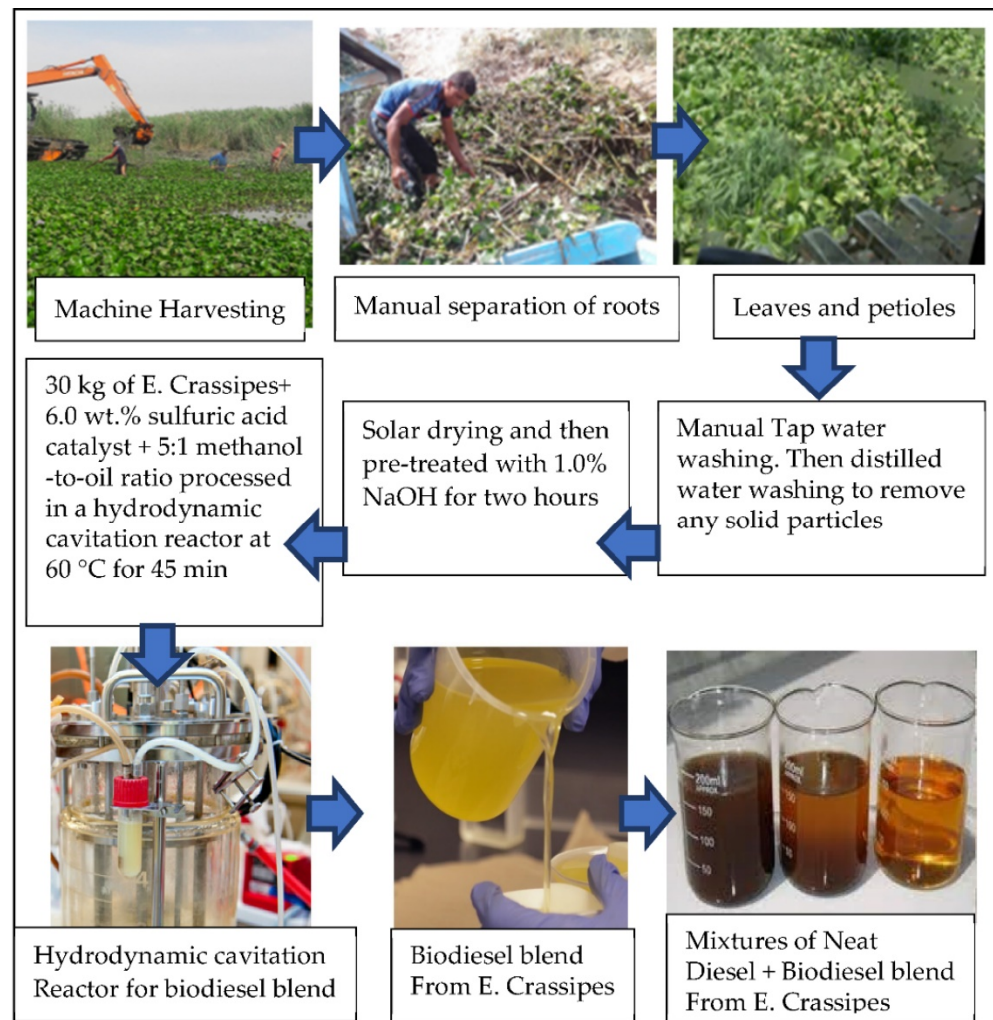
**Table 1.** Components of *Eichhornia crassipes* (Water Hyacinth).

Components	Values in g per 100 g Dry Matter
Hemicellulose	28.87
Cellulose	32.56
Lignin	4.16

To blend the diesel from the 30 kg of *E. crassipes*, 6.0 wt.% sulfuric acid catalyst and a methanol-to-oil ratio of 5:1 was processed in a hydrodynamic cavitation reactor at 60 °C using circulating liquid glycerin for 45 min, as recommended by [17]. A hydrodynamic



cavitation reactor with 50 L capacity was used to produce *E. crassipes* oil biodiesel. The reactor consisted of a diaphragm pump, double-jacked glass, and air compressor to operate the double diaphragm pump, which acted as a device to dissipate the energy in the hydrodynamic cavitation reactor [20–22]. Outlines of the laboratory production of biodiesel from *E. crassipes* plant are presented in Figure 3.



**Figure 3.** Outlines of the biodiesel blending process of the current investigation.

Mixtures of fuel blends were prepared from diesel and blended biodiesel from *E. crassipes* (BE). The mixture consisted of 90% D and 10% BE by vol. (D + 10BE). The second fuel blend contained 80% D and 20% BE by vol. (D + 20BE), and the third fuel blend contained 60% D and 40% BE by vol. (D + 40 BE). These samples were subsequently used to fuel the experimental diesel engine setup to measure their performance and emission characteristics.

## 2.2. Diesel and Biodiesel Characterization

The physiochemical properties of the four fuel samples, D, D + 10BE, D + 20BE, and D + 40BE, were measured following the ASTM and EN standards fuel characterization procedure. The standard procedures followed for the characterization and the equipment, with their accuracies, are as below:

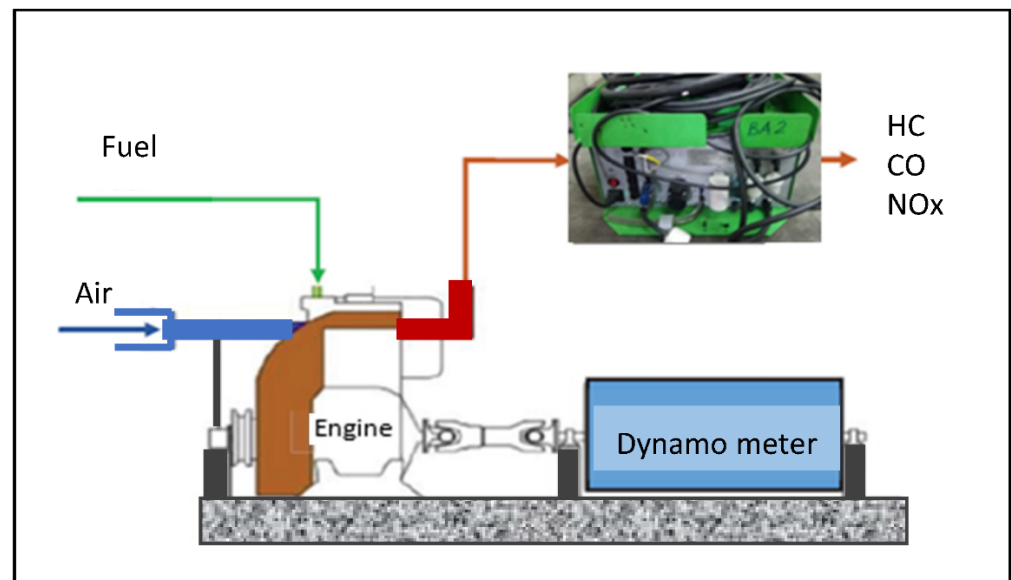
- Density: Anton Paar Densometer (model DMA 4500M with a resolution of  $0.00001 \text{ g/cm}^3$  and accuracy of  $0.000005 \text{ g/cm}^3$ ) was used to measure density following the ASTM D-5002 standard method.

- Viscosity: Anton Paar Lovis rolling ball viscometer (model 2000 M/ME with viscosity measuring range of 0.3 mPa.s to 10,000 mPa.s and accuracy of up to 0.5% of the reading) was used to measure viscosity according to the 2000M/ME method.
- Flashpoint was obtained using a CPP 5Gs analyzer, with an accuracy of 0.1 °C, following the ASTM D-2500 procedure.
- Pour point temperatures were found using a CPP 5G analyzer, with an accuracy of 0.1 °C following the ASTM D-97 testing procedure.
- Cold filter plugging point was obtained using an FPP 5Gs analyzer, with two infrared detection barriers, following the ASTM D-6371 standard test procedure.
- The Oxidation stability was obtained using an 873-CH-9101 Metrohm analyzer, with an accuracy of 0.3 °C, following EN-14112 standard testing procedure.
- The Cetane number was analyzed using SHATOX SX-100K equipment, with 1.0 Cetane level measurement error, following the ASTM D-613 standard method.
- Ramé-hart, Model 260, with an accuracy of  $\pm 0.10^\circ$ , was used to measure the surface tension according to the pendant drop method.
- Pregl–Dumas method was adopted to determine the diesel contents of Carbon, Nitrogen, Hydrogen, and Oxygen by CHNS analyzer.
- Gas chromatography with the flame ionization detector has been used to determine the fatty acid components.

Previous researchers discussed in this article's literature, such as [3,5,9,10,12,13,19], have also used the abovementioned standard procedures and equipment.

### 2.3. Experimental Setup

The experimental setup utilized in the current investigations consisted of a diesel engine type TWD290F with a BEA 460 Bosch gas analyzer supplied with specialized software for data acquisition attached to the engine exhaust. The experimental setup is shown schematically in Figure 4. The combustion performance was achieved using a direct injection single-cylinder diesel engine with specifications provided in Table 2.



**Figure 4.** Layout of the experimental setup comprises a four-stroke single cylinder engine type TWD290F, dynamometer, and BEA 460 Bosch gas analyzer.

**Table 2.** Test engine specification.

Parameter	Values
No. of cylinders and Strokes	1 Cylinder; four-stroke
Cylinder bore	85 mm
Stroke	88 mm
Displacement volume	653 cm <sup>3</sup>
Compression ratio	21.5:1
Maximum speed	3200 RPM
Injection timing	21° BTDC

The experimental system enables measurement of engine speed, engine torque, fuel flow rate, airflow rate, and all relevant temperatures and pressures. The software automatically optimizes the gas analysis. The experiments were performed at an engine speed of 2000 RPM at different throttling positions (20–100%). The engine's maximum power is 6.6 kW at 3200 RPM.

Experiment data were recorded after around 4 min of the starting or changing operation status, where the engine reached a stabilized operation status. The measurements were performed at steady-state operational conditions.

#### 2.4. Uncertainty Analysis

Error analysis in the experiments is essential to provide a level of confidence in the results. It could be achieved by determining the repeatability and reproductivity of the results. All experiments were repeated thrice. The variants of the predicted values of performance factors and exhaust emissions were used to calculate the uncertainty using the percent relative standard error,  $\emptyset$ , as shown in Equation (1):

$$\emptyset \% = \left( \frac{SE}{Y} \right) \times 100, \quad (1)$$

where  $SE$  is the standard error, and  $Y$  is the mean of the collected data. The standard error is calculated using Equation (2):

$$SE = \frac{\sigma}{\sqrt{k}}, \quad (2)$$

where  $\sigma$  is the standard deviation, and  $k$  is the repeatable readings of performance, combustion characteristics, and emission parameters.

Overall experimental uncertainty,  $\sigma_n$ , was calculated using Equation (3):

$$\sigma_n = \sqrt{\sigma_1^2 + \sigma_2^2 + \dots + \sigma_i^2}, \quad (3)$$

where  $\sigma_n$  is the total uncertainty, and  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_i$  are the uncertainties of the individual parameters.

The accuracies and uncertainties of the measured parameters are given in Table 3.

**Table 3.** Uncertainties of the measured parameters.

Parameters	Maximum Value Limit	Accuracy	Uncertainty
Speed (rpm)	6500	±1 rpm	±1.75
Torque (N·m)	450	±0.2 N·m	±0.77
BSFC (g/kW·h)	-	±2.12 g/kW·h	±0.89
CO (vol. %)	20%	±0.02 vol. %	±1.56
NOx (ppm)	10,000 ppm	±2 ppm	±3.21
HC (ppm)	5000 ppm	±2 ppm	±1.85

### 3. Thermodynamic Analysis

Thermodynamic analyses were carried out for a full load (engine throttle positioned at 100%) at maximum power, which the engine presents at 2000 RPM. Energy and exergy analyses were used, and the first and second law efficiencies were obtained. The overall engine was assumed to be a control volume with a steady-state open system, as shown in Figure 5. In this analysis, air and fuel charges were entered into the engine, and exhaust gas charges exited from the system boundary after losing heat and work. The inlet air and exhaust gases were acceptably presumed as ideal gases. The environmental conditions were considered as 1 atm and 25 °C. The kinetic and potential energy were neglected for fuel, air, and exhaust.

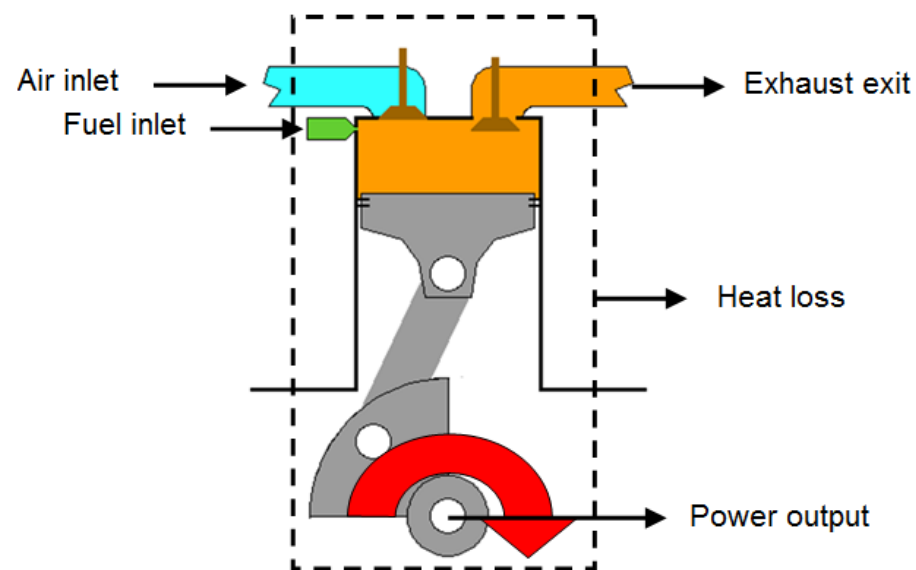
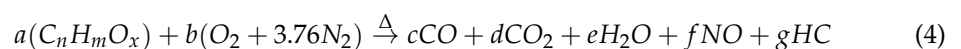


Figure 5. Schematic of the thermodynamic open system.

The molar rate and fractions were estimated from the combustion equation. Fuel and airflow rates were measured experimentally, and the emissions, including CO<sub>2</sub>, CO, NO, and HC, were known. Hence, the residual species' molar rates could be determined. Consequently, all molar rates could be placed in the combustion equation. NO<sub>2</sub> was not observed in the emissions, and PM has been neglected since they were sufficiently low [23].



The thermomechanical and chemical exergy of the air and fuel were ignored at the inlet because fuel and air enter the control volume as reference state conditions. Therefore, only the chemical exergy factor  $\phi$  of fuel was evaluated as follows:

$$1.0401 + 0.1728 \frac{x_1}{x_3} + 0.0432 \frac{x_2}{x_3} + 0.2169 \frac{x_4}{x_3} \left( 1 - 2.0628 \frac{x_1}{x_3} \right) \quad (5)$$

Herein,  $x_1, x_2, x_3, x_4$  are the mass fractions of hydrogen, oxygen, carbon, and sulfur of liquid fuel, respectively. The overall chemical exergy of fuel is:

$$\dot{Q}_{in} = \dot{m}_f \phi H_u \quad (6)$$

The power output was taken from experimental results. The power was predicted from the measured torque and speed, using Equation (7):

$$\dot{W} = \frac{2\pi NT}{60} \quad (7)$$



Exhaust energy,  $\dot{Q}_{exh}$ , was evaluated from the thermodynamic tables, as per [23], considering each emission gas species' enthalpy values and molar flow rate, as in Equation (8):

$$\dot{Q}_{exh} = \dot{m} (h_{exh} - h_i) \quad (8)$$

Heat losses exit from control volume is calculated from the difference between the inlet and exit energy. Herein, the air energy was ignored since it enters as reference state temperature:

$$\dot{Q}_{loss} = \dot{Q}_{in} - \dot{W} - \dot{Q}_{exh} \quad (9)$$

The exergy of the exhaust gases,  $\epsilon_{exh}$ , is the sum of thermomechanical and chemical exergies species. The thermomechanical exergy,  $\epsilon_{exh}$ , was evaluated from thermodynamic tables for each species as follows:

$$\epsilon_{exh} = (h - h_i) - T_i(s - s_i) \quad (10)$$

The chemical exergy in the exhaust gases,  $\epsilon_{chem}$ , was evaluated using standard molar chemical exergy,  $\eta_{ch}$  table, Model II by [24] and using molar fractions,  $\psi$ , as follows:

$$\epsilon_{chem} = \sum \psi \cdot \eta_{ch} + RT_i \sum \psi \cdot \ln \psi \quad (11)$$

The exhaust exergy rate can be defined as the sum of the chemical and the thermomechanical exergy multiplying molar rates:

$$\dot{E}_{exh} = \sum \dot{m} (\epsilon_{exh} - \epsilon_{chem}) \quad (12)$$

The work exergy rate is equal to the power output:

$$\dot{E}_w = \dot{W} \quad (13)$$

The heat loss exergy, which consists of friction, radiation, and cooling water losses, etc., was assumed, in actuality, to occur from the 363 K engine cylinder block to the 298 K reference environment [25]. The heat loss exergy rate can be defined as:

$$\dot{E}_{heat} = \sum \left( 1 - \frac{T_i}{T_w} \right) \dot{Q}_{loss} \quad (14)$$

The exergy destruction rate is obtained from the exergy balance and the difference between the inlet and outlet exergies as follows:

$$E_{in} - E_{out} = E_w + E_{exh} + E_{heat} \quad (15)$$

Therefore, the first law efficiency is obtained as the ratio of the power output,  $W$ , to the fuel energy rate,  $Q_{in}$ , in Equation (16):

$$\eta_1 = \frac{W}{Q_{in}} \quad (16)$$

The second law efficiency, which is referred to as exergetic efficiency, could be estimated using Equation (17):

$$\eta_2 = \frac{E_w}{E_{in}} \quad (17)$$

#### 4. Results and Discussion

The acquired data from the experimental measurements were clustered to highlight the effect of the added biodiesel on the pure diesel. One batch of results presents the influence of the added biodiesel on the performance of the IC engine. The second batch of

results presents the exhaust gas analysis and the emissions, which are important for the environmental consequences.

#### 4.1. Characterization Results

The mixtures of neat diesel and biodiesel have been characterized as described in Section 2.2. The properties of diesel and the blends are presented in Table 4. The trend of the characteristic changes with the addition of biodiesel to the neat diesel is similar to the data of [13], but with different values. For example, the measured calorific values for D + 20BE, D + 20BE, and D + 40BE are 42.2, 41.8, and 39.4, respectively, while, for the current Iraqi diesel and mixtures, they are 44.82, 42.67, and 42.15. This difference in the calorific values showed some differences in the other characters between the two studies.

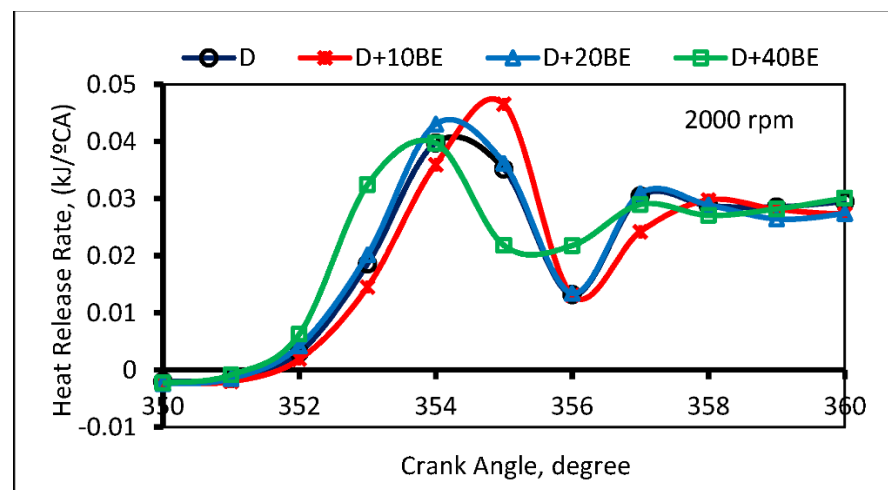
**Table 4.** Measured properties of fuel blends.

Property	D	D + 10BE	D + 20BE	D + 40BE
Density (kg/m <sup>3</sup> )	823	834	847	859
Kinematic viscosity at 33 °C (10 <sup>-6</sup> m <sup>2</sup> /s)	4.32	4.38	4.46	4.51
Calorific value (MJ/kg)	45.3	44.82	42.67	42.15
Flash point (°C)	52.5	73.1	94.3	107.5
Pour point (°C)	-7.6	-8.5	-9.2	-10.3
Cetane number	47	49	51	54
Oxidation stability (h)	104.3	93.11	80.2	47.3

#### 4.2. Heat Release Rate

The gross amount of heat release rate (HRR) is the sum of the heat transfer to the chamber of the cylinder and the net heat transfer. The estimation accuracy of the HRR depends on many factors such as the accurate measurement of the in-cylinder pressure, the accurate determination of the TDC location, and the assumptions adopted in the HRR prediction model. The heat release model proposed by Krieger and Borman [26] is adopted in the current investigation. Specific heat ratios are considered as constant at 1.35.

Figure 6 presents the measured heat release rates under different fuel mixtures at various crank angles at maximum power. The combustion start timing could not be determined precisely as all results are taken in 720 °CA. However, it can be said that more fuel ignited at the beginning of the combustion for D + 40BE, and the ignition delay is longer for D + 10BE compared to neat diesel fuel. A higher Cetane number is found in D + 40BE, and a high viscosity and density are dominant for D + 10BE, corresponding with engine geometry.



**Figure 6.** Variation of heat release rate under different fuels at 2000 RPM.

Moreover, the results presented in Figure 4 display the peak heat release rates. The maximum heat release rate is reached by suddenly burning D + 10BE, which is waiting before ignition. The test engine produces its maximum torque at 2000 rpm. The cases of diesel–biodiesel experimented by [13] have shown lower HRR than pure diesel.

#### 4.3. Cylinder Pressure

Figure 7 shows the in-cylinder maximum pressure results. Later ignition causes lower pressure due to expansion and cooling for D + 10BE. The D + 40BE fuel blend has nearly higher peak pressures than pure diesel fuel except at high engine rotational speeds, 2700 and 3000 rpm, as the reason mentioned above. The cetane number dominates, and early ignition increases the pressure with a higher Cetane number. D + 20BE generally has similar results with pure diesel fuel.

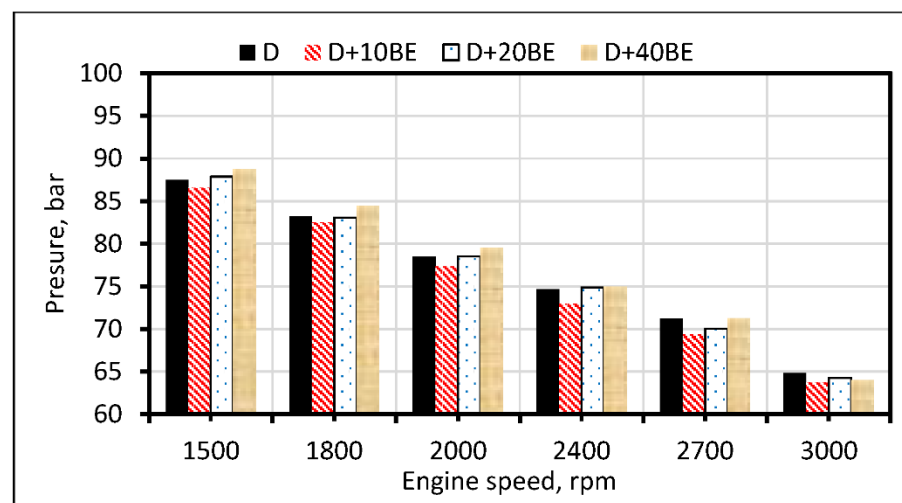


Figure 7. In-cylinder pressure peak values under different engine speeds.

#### 4.4. Brake Thermal Efficiency

The brake thermal efficiency (BTE) has been adopted as a performance indicator. The variation of BTE, for the four fuel samples with their blends, D, D + 10BE, D + 20BE, and D + 40BE, at varying loading conditions is presented in Figure 8. The break efficiency of D, D + 10BE, D + 20BE, and D + 40BE fuels increases with the load by up to approximately 90% loading condition, and then begins to decrease.

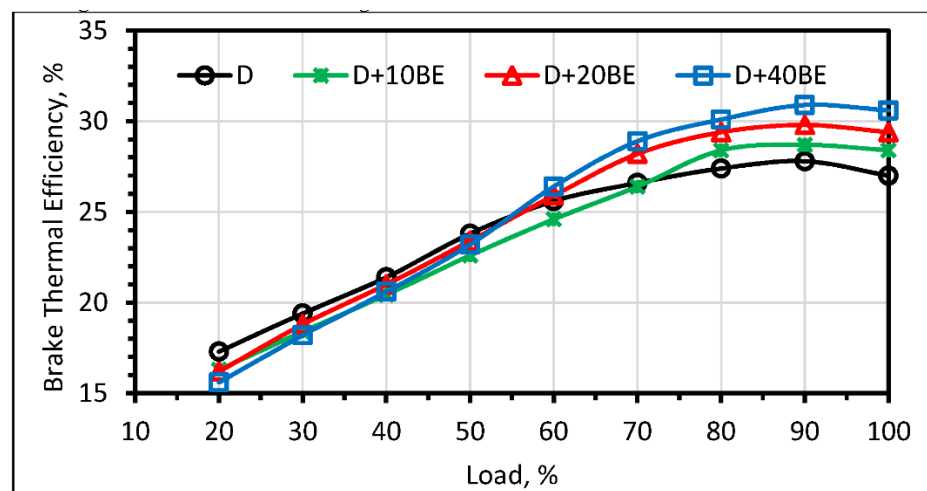


Figure 8. Variation of BTE for all fuel blend samples at various engine loads.

At high loading conditions, the D + 40BE blend shows the highest BTE among all other samples since the increase in the biodiesel ratio reduces the volumetric heating value of the blend, thereby causing a decrease in brake power. In addition, the high density and viscosity have resulted in uneven combustion, reducing the brake power [25].

#### 4.5. Brake-Specific Fuel Consumption

Figure 9 shows the BSFC changing trend at various engine loads. The BSFC decreased with the increase in engine load for all of the tested fuel samples, thereby demonstrating good combustion. The D + 10BE, D + 20BE, and D + 40BE fuel blends exhibited higher fuel consumption than diesel at all loading conditions. The increase in the BSFC resulted from the low heating value and the high viscosity and density, thereby causing a greater amount of fuel to be injected into the combustion chamber than the D fuel [25]. These results are consistent with the findings of [26–28].

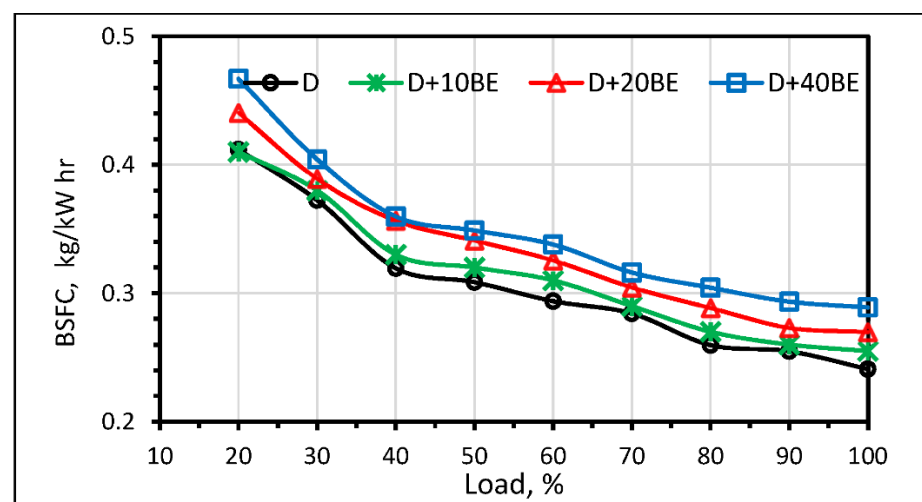


Figure 9. BSFC variation for all fuel blend samples at various engine loads.

#### 4.6. Environmental Assessment Results

The consequences of adding biodiesel to the neat diesel changes the chemical composition of the mixture. Hence, the exhaust gases are changing in terms of emission. The resulting HC, CO, and NO<sub>x</sub> have been measured to evaluate the emission characteristics. All of the characterization parameters have been evaluated at different loading conditions of the test engine, varying from a 20% load to a 100% full load.

Figure 10 displays the CO emission of neat diesel and a mixture of diesel and bio blends at various engine loads. Results show that the CO emissions increase with the engine load because CO emissions are extremely dependent on the air–fuel ratio [13,17]. In addition, the results revealed that CO emission is the highest in neat diesel, followed by D + 10BE, D + 20BE, and D + 40BE fuel blends in all cases of the loading conditions. This effect is evident during full loading conditions but is not so vital at low loads because of their low values. The decrease in CO emissions for the D + 10BE, D + 20BE, and D + 40BE fuel blends may be attributed to the added oxygen percentage in the fuel blend, thereby confirming the remarkable combustion of the fuel. Refs. [12–14] also claimed similar results of slight reductions of CO percentages in the exhaust gasses of their testing engines using the various percentages of diesel with *E. crassipes* blends. As experienced by [13], the current investigation demonstrates that the CO of diesel fuel is higher than the mixtures of diesel with biodiesel at all engine loadings. This is due to oxygen deficiency in diesel fuel overriding the mixtures which have intrinsic fuel oxygen content. The presence of O<sub>2</sub> in the fuel enhances the combustion rate and encourages the faster switch of CO to CO<sub>2</sub>.

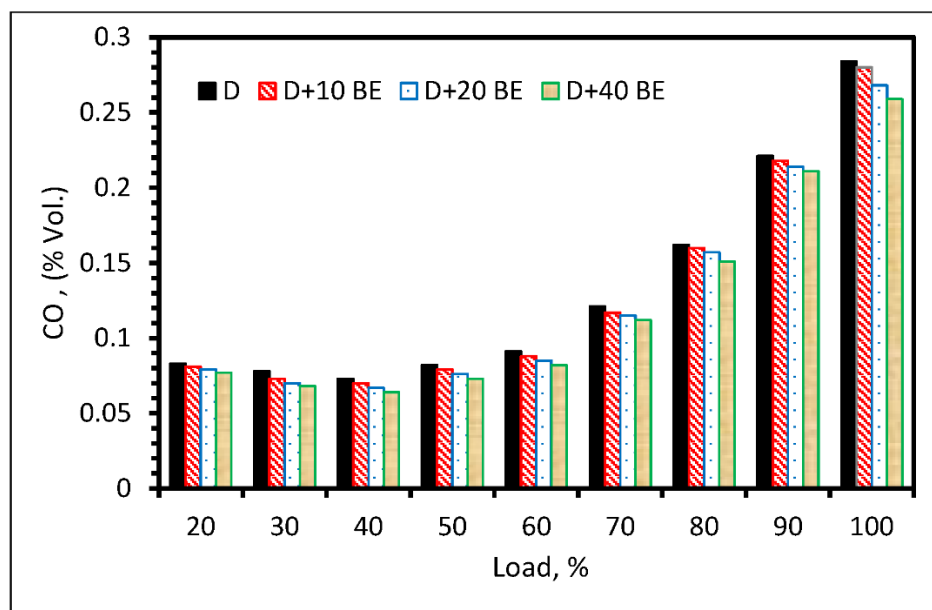


Figure 10. The variant of CO emission for tested fuel blend samples at various engine loads.

The variation of NOx emission at various engine loads of the considered fuel blends is shown in Figure 11. The engine load increased with the increase in NOx emission. However, the values of the NOx emissions for D + 10BE, D + 20BE, and D + 40BE are above that of pure diesel. Khan et al. [12] also observed slightly higher NOx.

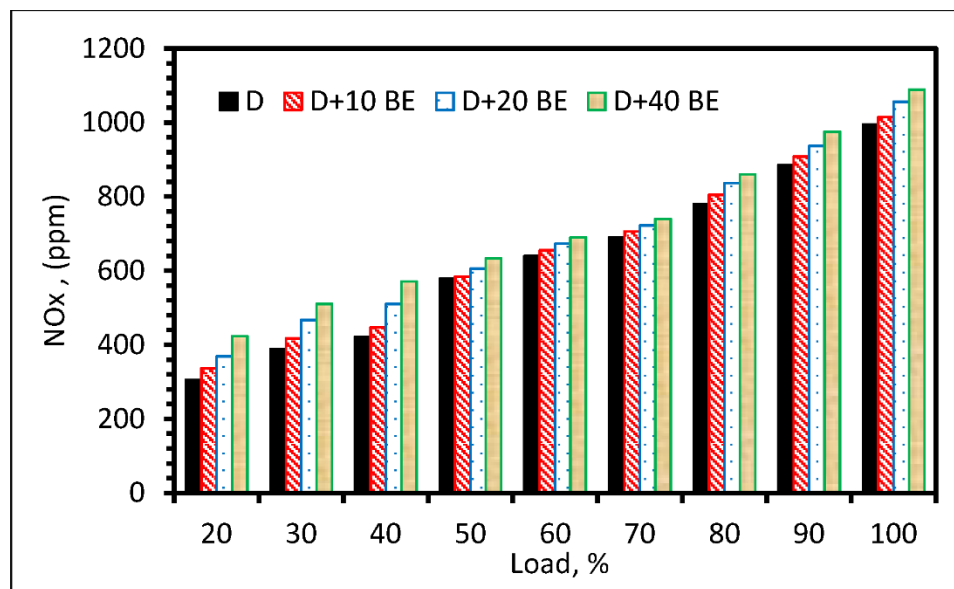


Figure 11. The variant of NOx emission for the tested fuel blend samples for various engine loads.

HC emission at various engine loads for the studied fuel blends is presented in Figure 12. The HC emission changes are similar to the CO emission. Thus, HC emission is the highest for diesel and lessens for the fuels D + 10BE, D + 20BE, and D + 40BE fuel blends. The reasons for such comportment of HC emission are described in CO emission. The low carbon-to-hydrogen ratio and oxygen component in biodiesel fuels have caused improved combustion, reducing HC emissions [29,30].



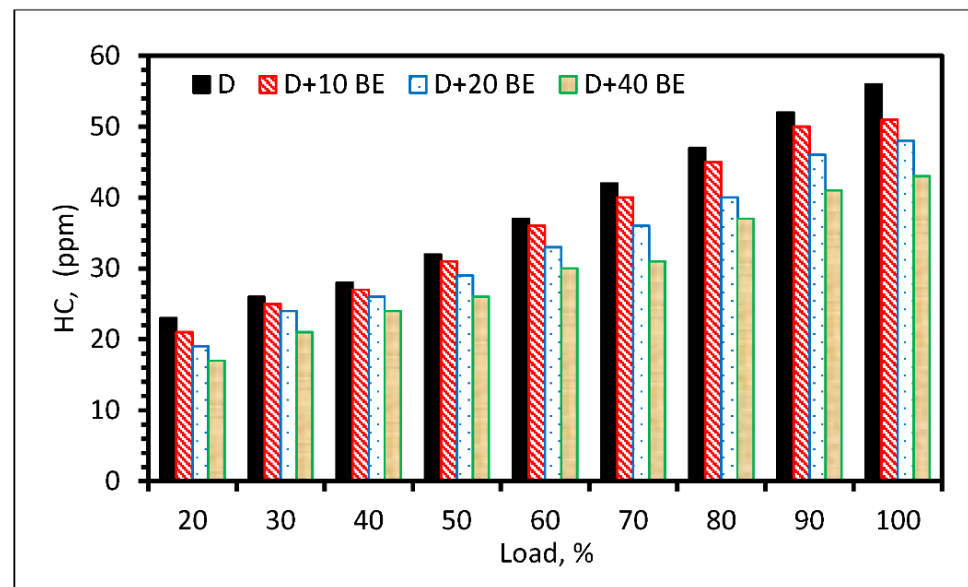


Figure 12. The variant of HC emission for all fuel blend samples for various engine loads.

## 5. Conclusions

The current research aims to assess the suitability of blended biofuel from *E. crassipes* plant as an additive to neat diesel in Iraq. The combustion performance and emissions characteristics of biofuel produced from the *E. Crassipes* plant, and their biodiesel blends have been investigated and compared with neat diesel as baseline fuels. The physicochemical properties of all the considered fuel samples (e.g., D, D + 10BE, D + 20BE, and D + 40BE) are measured according to the ASTM standards. The following conclusions are drawn based on the obtained results:

- Fuel properties: The density and viscosity of the fuel blend increase, and the calorific value decreases with the addition of biofuel.
- The engine performance of IC has been enhanced with the addition of *E. crassipes* biofuel. Compared with the neat diesel, the biodiesel blend of D + 10BE, D + 20BE, and D + 40BE enhanced brake thermal efficiency by 2.6%, 4.2%, and 6.3%, respectively.
- The reduction percentage of CO is 0.85–3.69% and 2.48–6.93% of HC compared with the neat diesel. The increasing percentage of NO<sub>x</sub> compared with pure diesel is 1.87 to 7.83%.
- The assessment results of 40% biofuel extracted from the *E. crassipes* and mixed with neat diesel demonstrate a remarkable effect on the engine performance with reduced emission.

The results encourage using the *E. crassipes* biodiesel blend as an additive to the commercial diesel in Iraq as a potential application. In addition, it resolves the problem of dealing with these plants, as the current practice is to dry the harvested plants under open solar drying. This practice would never eliminate the problem as the seeds survive and grow on a larger scale. Further investigations using different types and amounts of surfactant added to the diesel fuel and blends are recommended.

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## Abbreviations

bTDC	Before the Top Dead Centre
BSFC	Specific Fuel Consumption
<i>E. crassipes</i>	<i>Eichhornia crassipes</i>
HC	Hydrocarbon
HRR	heat release rate
PH	Potential of Hydrogen
ppm	parts per million (1 ppm = 1 mg/L = 1/1 million = 0.000001)
NOx	Oxides of Nitrogen

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