Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0016

RESEARCH ARTICLE

Novel study on implication of butanol oxygenated additive with water hyacinth biodiesel to investigate the performance and emission parameters

Maneesh Singh[1], Prashant Saini[2,*], Srishti Mishra[3]

[1]Department of Mechanical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, 273010, India
[2]Department of Mechanical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, 273010, India
[3]Department of Mechanical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, 273010, India

Abstract

Fossil fuels are being depleted at an alarming rate due to growth in industrialization, transportation, the power and agricultural sectors, and motorization globally. Hence, the development of alternative fuels is an emerging research need to meet energy demands in such sectors. Waterhyacinth, a problematic invasive weed, is abundantly available, and n-butanol (sustainable, green, and dependable) is a longer-chain, oxygenated alcohol additive with outstanding fuel properties. With this motivation, the present research explores the performance and emission characteristics of a vertical, 4-stroke, water-cooled, single cylinder CI engine that runs on ternary fuel blends consisting of water-hyacinth biodiesel (WHB), n-butanol, and diesel under variable loads. Conversion of water hyacinth oil into WHB was carried out by transesterification, using NaOH (1% by wt.) as a catalyst and methanol (20 ml) as a solvent. The solutions were mixed with constant stirring for 150 minutes at 60 °C using a magnetic stirrer. Thereafter, the solution was transferred into a separating funnel and kept undisturbed for 24 hrs, allowing glycerol and water hyacinth biodiesel to separate from the solution. In predetermined proportions, n-butanol (0%, 5%, and 10%, by vol.) and diesel (80%, 75%, and 70%, by vol.) were mixed with WHB (fixed at 20% by vol.) using a magnetic stirrer. Three blends were formed and named WHB20D80, WHB20D75B5, and WHB20D70B10. The fuel properties of ternary blends are examined according to ASTM standards. Experiments reveal an increase in brake specific fuel consumption of 8.0% and a decrease in brake thermal efficiency of 3.87% for WHB20D75B5 compared to diesel. Decreases in carbon monoxide of 5.5%, 16.6%, and 25% and in unburned hydrocarbon emissions of 5.80%, 11.76%, and 17.64% were observed for WHB20D80, WHB20D75B5, and WHB20D70B10, respectively. Additionally, it has been observed that CO_2 and NOx emissions were higher than diesel. WHB20D75B5 may be used effectively and safely in compression-ignition engines without engine modifications.

Keywords: Water hyacinth biodiesel, n-Butanol, transesterification, performance and emissions analysis

Cite this article as: Singh, M., Saini, P., & Mishra, S. (2026). Novel study on implication of butanol oxygenated additive with water hyacinth biodiesel to investigate the performance and emission parameters. Journal of Thermal Engineering, 12(3), 2–13. https://doi.org/10.47481/jten.0016

1. Introduction

Energy has played a vital role on both economic and cultural fronts in developing and developed countries. fossil fuels like gas, coal and mineral oil are playing the major role in satisfying the world's energy needs. Diesel engines dominate the transportation sector because of their superior thermal efficiency. As fossil fuels are being depleted at a rapid rate, scientists have accelerated research to identify suitable alternatives for use in diesel engines without any engine modifications. The fact that there can be several alternatives for energy like hydrogen fuel, biofuels etc. Now a days different varieties of biodiesels like waste plastic oil, waste cooking oil, waste pyrolysis oil and biomass oil have become trending and attractive sources of energy. For the current unmodified diesel engines, several advantages of biodiesel like improved cetane number, enhanced lubricity, high availability of O_2 and safer transportation make them suitable to use as alternative fuels. The term 'first generation biodiesel' used for the conventional sources of biodiesels such as feedstocks of olive, sunflower, palm, corn, etc. There were certain limitations to it, which included food security threats, an increased number of consumers, and sometimes the fear

*Corresponding Author
E-mail Adress: psme@mmmut.ac.in

Submitted: 11 November 2025; **Accepted:** 20 November 2025

This paper was recommended for publication in revised form by Editorin-Chief Ahmet Selim Dalkılıç

of starvation in developing countries. Hence, the best solution may be to develop feedstock from non-edible/non-food sources, thereby conserving vegetable oil. Now, the ‘second generation’ biodiesel is derived from non-edible oils such as jatropha oil, pongamia oil, animal fats, tamarind oil, and karanja oil. Recent trends in producing biodiesel from algae and seaweeds are considered the ‘third generation’ of biofuels. Hyacinth biomass was found to be best suited for producing biodiesel. This invasive plant exists in sufficient quantity all around the globe, mainly in tropical regions where marshy wetlands and backwater is available which supports the growth of aquatic weed [1].

Water hyacinth, also known as Eichhornia crassipes, is regarded as one of the world’s most invasive and noxious weeds. It has capacity to yearly produce $14x10^7$ daughter plants and to cover 1.4 km^2 of water area. Colonization by water hyacinth can cause serious problems such as choking of waterways, sewage blockages, and chaotic flooding. Livelihoods are adversely affected by it because of the rapid decline in fish populations in water bodies, the clogging of irrigation canals, and sedimentation. It causes substantial, constituting both an economic and an ecological disaster, and results in a decrease in the biodiversity of body water. Various diseases like dengue, malaria, encephalitis, and filariasis spread widely due to water hyacinth colonization, since low-oxygen, densely vegetated surroundings help snails and mosquitoes proliferate more rapidly. This is why using this biomass to make biodiesel could be a solution to two problems eliminating this plant and creating green fuels to combat pollution and future shortages of fossil fuels. Following conventional practice, these plants are removed manually or mechanically on a regular basis to keep the water body clean. For the total elimination of the invasive weed water hyacinth, several methods, such as biological, physical, and chemical, have been used. Water hyacinth is already abundantly available at low cost and is sustainable across multiple domains (economic, ecological, energy, and waste management); hence, it can be used efficiently and effectively. Water hyacinth biomass has several applications, including energy briquettes, biodiesel, fertilizers, biochar, natural gas, methane, xylitol, biogas, ethanol, and compost products. But the current trend finds it more profitable and effective in producing biodiesel [2-3]. Water hyacinth spreads mainly by seed and expands uncontrollably through vegetative budding. Although it is highly sensitive and restricted by its growth environments which includes oxygen stress, availability of nutrients, light, temperature [4]. Biodiesel has two main drawbacks: high viscosity and a higher auto-ignition temperature than diesel. Oxygenated additives are typically added in modest amounts to reduce these downsides, to increase the fuel-bound oxygen (to assist combustion), and to retain lubricity at normal levels. Yadav et al. [5] reviewed the engine characteristics of diesel-biodiesel produced from various biomass resources and recommended that blending of higher chain alcohols with biodiesel may further improve the engine characteristics. Recently, higher-chain alcohols (n-butanol, n-pentanol, hexanol, decanol, etc.) have emerged as possible oxygenated fuel additives to enhance the fuel properties of both diesel and biodiesel. They have a straight-chain structure with the OH group at the terminal carbon, making them renewable additives. N-butanol and diesel blends impact the output and emissions of a heavy-duty diesel engine with multiple injections and varying exhaust gas recirculation (EGR) ratios. Due to its increased heating value, good solubility with diesel, and lack of corrosion to existing fuel pipes, n-butanol is a more promising alcohol for use in diesel engines [6]. Several researchers use different types of bio-oil for conversion into BD and for blending with FD and alcohol to assess its impact on diesel engines. Alagu et al. [7] analyzed that biodiesel made up of water hyacinth biomass, is a viable alternative source of energy. Khan et al. [8] revealed that eichhornia crassipes plant can produce bioethanol which may be an effective fuel when mixed with diesel.

Mohammed et al. [9] found that, compared to pure diesel, adding eichhornia crassipes biodiesel both with and without LPG improves combustion and the engine operates smoothly and uses less fuel. Hoang et al. [10] studied and found that there are several other types of biodiesels exists as an alternate fuel of diesel such as microalgae-based biofuels. Mishra et al. [11] observed that the amount of 15 kg of green micro-algae produces 1 kg of dried algae. Kumar et al. [12] analyzed, the mixture of lemongrass biodiesel and diesel have potential to be a fossil fuel substitute. Saini et al. [13] investigated the performance of the diesel engine using corn-oil biodiesel and revealed that it has potential to be a promising alternative fuel. Elumalai et al. [14] prepared the blends of diesel fuel and pyrolytic oil (produced by pyrolyzing used tyres) to power the diesel engine. Yadav et al. [15] utilized the waste plastic oil biodiesel-diesel blends to run the engine and enhanced the engine characteristics by incorporating thermal coating of pistons. Ardebilli et al. [16] utilized the fuel oil/diethyl-ether to investigate the diesel engine performance and exhaust emissions. Ramakrishnan et al. [17] studied and found that pentanol, Calophyllum inophyllum, and diesel fuel blends improve the efficiency and emissions of a diesel engine. Aldhaidhawi et al. [18] observed that rapeseed biodiesel, whether it is pure or combined with diesel, has a lower thermal efficiency and higher BSFC. Truong et al. [19] revealed that higher chain alcohol mixing with pure diesel/biodiesel results significantly improve in fuel blend properties at low temperatures. Yesilyurt et al. [20] revealed that higher alcohol percentage with biodiesel/diesel blends causes a decrease in BTE and an increase in consumption of fuel. Singh et al. [21] experimented and found that biodiesel produced by eucalyptus oil with diesel blends have a higher viscosity and density than diesel, which can be reduced by adding alcohols. Tipanluisa et al. [22] investigated the effect of butanol higher chain alcohol additive with diesel/biodiesel blends on engine performance and emission parameters. Ahmad and Saini [23] studied the effect of n-butanol with diesel and mango seed biodiesel and found enhanced engine performance and reduced emissions. Nanthagopal et al. [24] observed that alcohol has a larger latent heat of vaporization, adding more of it to the mixture provides a cooling effect that reduces NOx emission, hence, higher chain alcohols as an additive may partially replace diesel/biodiesel. Nour et al. [25] revealed that higher chain alcohols, when mixed with diesel/biodiesel blends increases NOx and reduces HC and

CO emissions compared to pure diesel. Sherma et al. [26] revealed that solketal can be used as a valuable component in biodiesel/diesel blends to reduce the toxic emissions of fossil fuels.

Reddy et al. [27] observed that, employing the Exhaust Gas Recirculation (EGR) technology helps in successful reduction of hazardous NOx emissions. Raja et al. [28] found that with increasing EGR rates, release of HC and CO increases throughout the engine loads. Rahman and Aziz [29] observed that adding hydroxy with WHB in CI engines can improve performance and emission characteristics. Wahhab et al. [30] investigated that Eichhornia crassipes biodiesel has excellent ability to get mixed with locally produced diesel. Appavu et al. [31] found that BSFC values get reduced and BTE get increased when concentration of pentanol increased in fuel. Prasad et al. [32] detected tamarind biodiesel can be used as a replacement of diesel fuel. Reddy et al. [33] observed blending diethyl ether in mango seed biodiesel improves the performance and decrease the emissions. Kumari et al. [34] found that lemon peel biodiesel can work effectively in diesel engines. Raju et al. [35] investigated that combination of hexanol with mahua seed biodiesel/diesel blends can be an effective alternative fuel in diesel engines. Maniamuthu et al. [36] studied the effect of butanol additive with Delonix regina biodiesel and reveal enhanced engine performance and reduced emissions. Yamini et al. [37] investigated the effect of isobutanol and diethyl ether additives with subabul seed biodiesel and reported increase in brake thermal efficiency by 7.4% with 10% diethyl ether and by 4.71% with isobutanol.

A review of the literature found that various researchers use different types of alcohol additives with biomass-derived BD in diesel engine performance and emissions analyses. Moreover, limited work has been conducted on the combination of higher-chain alcohol additives with WHB and diesel in diesel engine operation. Biodiesel generation from various renewable biomass, mixing of lower and higher chain alcohols, and their use in unmodified diesel were all covered in the above literature analysis. Although ethanol and methanol have been the most tested for blending with diesel fuel, their low calorific value and high enthalpy of evaporation negatively affect engine characteristics. Also, their low flash points and high vapor pressures require stricter safety measures during handling and storage of fuel. The use of ethanol and methanol in CI engines is precluded due to their low lubricity and poor miscibility with diesel fuel. Because of their greater surface-to-volume ratio, higher-chain alcohols (oxygenated fuel additives) in biodiesel-diesel blends exhibit enhanced thermophysical properties and increased rates of heat transport. Compared with lower-chain alcohols, butanol has outstanding properties such as better engine compatibility, a higher flash point, greater energy density, lower vapor pressure, lower volatility, reduced hygroscopicity, lower explosiveness, and lower corrosiveness. Therefore, butanol was selected for this study because it is more readily miscible with diesel than methanol or ethanol, owing to its improved blend stability at low temperatures. Furthermore, research on the use of water hyacinth (Eichhornia crassipes) biomass-derived oil as a sustainable fuel for diesel engines is lacking. Moreover, the ternary blend of WHB, diesel, and n-butanol as a fuel has not been examined in diesel engines so far, to the best of the authors' knowledge. This has prompted authors to investigate this biomass for its potential in crude oil production, biodiesel production, and the incorporation of n-butanol, a renewable, clean, and dependable oxygenated alcohol additive.

To fill this research gap, this study experimentally investigates the performance and emissions characteristics of a 4-S single-cylinder diesel engine fueled by ternary mixtures of WHB, diesel, and n-butanol at different engine loads. Contemporary research novelties can be described in two ways: (i) Extraction of crude WHO from sustainable water hyacinth biomass (a problematic invasive weed for waste-to-energy), and preparation of biodiesel by transesterification; (ii) Mixing n-butanol (a sustainable, clean, and dependable oxygenated additive that enhances fuel properties) with WHB-diesel ternary blends using a magnetic stirrer. The prepared test fuels are named WHB20D80, WHB20D75B5, and WHB20D70B10. The Fuel qualities of the blends are determined according to ASTM standards. Experimental investigations are carried out to analyze the performance and emissions characteristics of the prepared blends at different engine loads, with results compared with those of fossil diesel.

2. Material and methods

This section addresses biodiesel preparation, blending procedures, fuel sample preparation, and properties of fuel blends. Details about them are provided below.

2.1. Biodiesel preparation

Water hyacinth oil for biodiesel production was purchased from a regional market in Gorakhpur, Uttar Pradesh, India. All chemicals/reagents of analytical grade (AG) for lab experimental purposes were obtained from Eastern Scientific Emporium, Gorakhpur, Uttar Pradesh. The diesel used in the blending process was procured from the local petrol pump (Nayara Petrol Pump, Gorakhpur, U.P., India). The water hyacinth plant, which is generally found in lakes, ponds, and open water bodies, is shown in Figure 1. Additionally, the crude oil from water hyacinth biomass has been extracted by chemical extraction (Soxhlet extraction provides a higher oil yield than mechanical extraction) to determine the oil content. It has been found that 220 ml of crude oil was obtained from one kilogram of water hyacinth powder. The detailed procedure and method for crude oil extraction from a biomass is reported in [23]. WHO is extracted from water hyacinth plants using a Soxhlet apparatus, shown in Figure 2(a), and the mixture of n-hexane and WHO is separated by a distillation unit, as shown in Figure 2(b).

Figure 1. Water hyacinth biomass

Figure 2. Extraction of oil (a) Soxhlet apparatus (b) Distillation unit

To convert WHO into pure water-hyacinth biodiesel (WHB), the transesterification process is used. In trans-esterification process, a total of 100 ml crude water hyacinth oil, 20 ml methanol (CH_3OH dehydrated) and 1% by wt. of sodium hydroxide (NaOH) were used. Sodium hydroxide was used as a catalyst. As shown in Figure 3, in the very first step sodium hydroxide (NaOH) and methanol (CH_3OH) are mixed and stirred till pellets of NaOH get completely dissolve into methanol and become completely invisible. The mixing of methanol and NaOH takes about 90 minutes at a speed of 500 to 600 rpm on a magnetic stirrer. After that, with the help of a magnetic stirrer, water hyacinth oil was blended with the mixture of NaOH and methanol for 150 min. Constant heating throughout the blending process was applied, maintaining the temperature between 60 °C and 65 °C (close to the methanol boiling point, 64.7 °C). After the completion of the blending process, the blend is transferred into a separating funnel and left untouched for 24 hrs. During this period, the glycerol fraction of the blend settles to the bottom, and biodiesel appears at the top. Then, with the help of a separatory funnel, glycerol is separated from biodiesel.

Figure 3. Experimental setup for preparation of biodiesel. (i) Mixing of NaOH and Methanol (ii) Transesterification (Mixing of NaOH-Methanol blend with WHO) (iii) Separation.

The crude water hyacinth biodiesel is then washed with warm water and dried at 100 °C for about 30 minutes. After drying, the resulting product is pure water hyacinth biodiesel. The biodiesel yield was calculated using the following formula:

$$\text{Biodiesel Yield (\%)} = \frac{\text{Total volume of WHB}}{\text{Total volume of oil in sample}} \times 100 = (85 \text{ ml} / 100 \text{ ml}) \times 100 = 85\ \% \quad (1)$$

In this study, the homogeneous catalyst was used to produce biodiesel from water hyacinth biomass. Heterogeneous catalysts (a combination of two nanoparticles) prepared by the sol–gel method may be used to enhance biodiesel yield and further improve the properties of blends. Moreover, the optimization of the biodiesel preparation process may be part of further research. The by-product glycerol (found 15% by vol.) has a wide range of applications in pharmaceuticals and personal care items (soaps, creams, and lotions). Glycerol is also used in certain medical treatments, such as the preservation of tissues and organs for transplantation and some medical imaging techniques.

2.2. Blending procedure and fuel preparation

In the present work, WHB is blended with diesel and alcohol (n-butanol) in different proportions by volume. A total of three consecutive blends were prepared, named WHB20D80, WHB20D75B5, and WHB20D70B10. All mentioned blends contain a fixed 20% WHB by volume, with diesel at 80%, 75%, and 70% and butanol at 0%, 5%, and 10%, respectively. Butanol is used in this study because of its beneficial characteristics, such as low viscosity, high volatility, better oxygenated nature, and safe combustibility which makes it one of the most promising alcohol additions [23]. Also, n-butanol enhances the combustion quality during the diffusion combustion phase, and its low hygroscopic nature makes it less corrosive which aids in fuel delivery system than other alcohols [24]. All the components, in their defined proportions, are placed in a beaker and stirred with a magnetic stirrer for 30 minutes, one by one, and then stored in different vessels, as shown in Figure 4. Figure 5 shows the flowchart of overall procedure used in the current study. Table 1 presents the important physical and combustion properties of all blends.

Figure 4. Blended mixtures of WHB20D80, WHB20D75B5, and WHB20D70B10

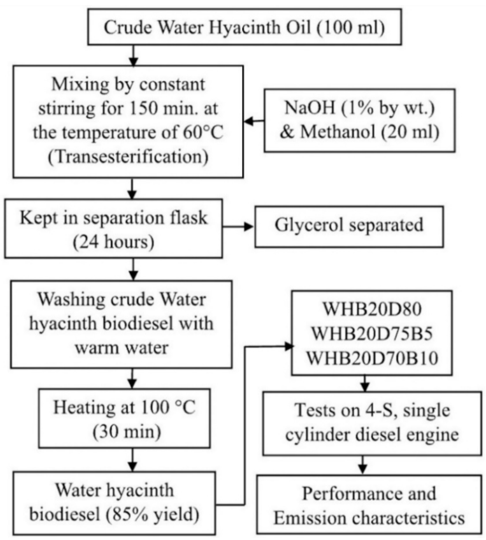

Figure 5. Flow chart of current analysis

Table 1. Properties of testing fuels

Fuel Properties	Diesel (D)	Butanol (B)	WHB100	WHB20 D80	WHB20 D75B5	WHB20 D70B10	ASTM Std.	Apparatus used
Density (kg/m³)	830.4	810	887	846	827	823	D-1298	Hydrometer
K.V. (mm²/sec)	2.76	2.63	3.96	2.86	2.72	2.68	D-445	Viscometer
Flash point (°C)	61	35	212	98	81	77	D-93	Pensky martin
C.V. (kJ/kg)	42970	33100	36900	41850	42410	41930	D-240	Bomb calorimeter
C. N.	48	17	53	47	45	44	D-613	Petroleum quality analyzer

3. Engine test procedure

In this study, prepared test fuel blends were tested by varying the load from 0-5 kg on a 4-S single-cylinder vertical water-cooled non-turbocharged Kirloskar agricultural Diesel engine. All the specifications of the test engine are listed in Table 2.

Table 2. Test engine specifications

Engine Type	4-S, Single cylinder, Water-cooled, Vertical, CI engine
Stroke	139.7 mm
Bore	120 mm
Compression Ratio	17.5:1
Cubic Capacity (cc)	1580 cm³
Rated Output	7.5 kW
Rated Speed	1500 rpm
Capacity of Fuel Tank	4 L
Spray Hole Diameter	0.25 mm
Injection Pressure	202 bar
Number of Nozzle Hole	1
Revolution of Flywheel	Clockwise
Fuel Injection	Direct Injection
Sump Capacity of Lube Oil	1.2 L
Engine Weight	150-200 kg

Various biodiesels can be used as alternative fuels in compression-ignition engines without major adjustments. The investigations are performed under typical operating conditions, including a rotational speed of 1500 rpm, a compression ratio of 17.5, a fuel injection pressure of 202 bar, and a fuel injection timing of 23° BTDC. The load on a diesel engine was gradually varied using a rope-brake dynamometer. The engine initially consumed diesel fuel, and baseline performance and emissions data were recorded. Each prepared ternary fuel blend was then tested individually. After careful testing of each test blend, the engine was operated on diesel for ten minutes. To evaluate performance and emission data, assess repeatability, and ensure the reliability of results, all experiments are performed three times under similar conditions. The arrangement of all the components with the CI engine for testing is shown in Figure 6. Figure 7 shows the schematic diagram of the experimental setup, including engine connections.

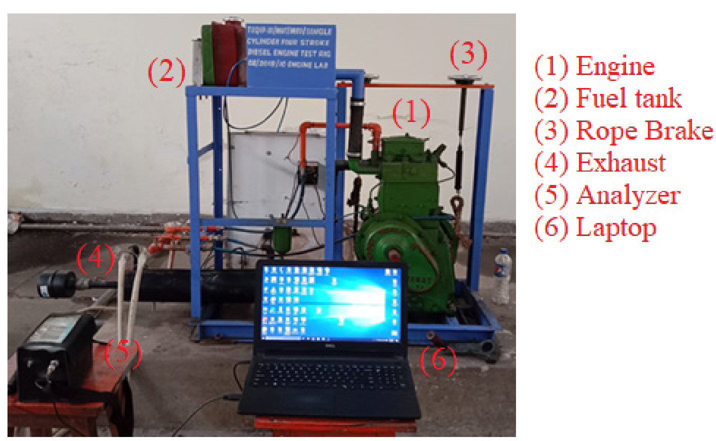

Figure 6. Experimental setup

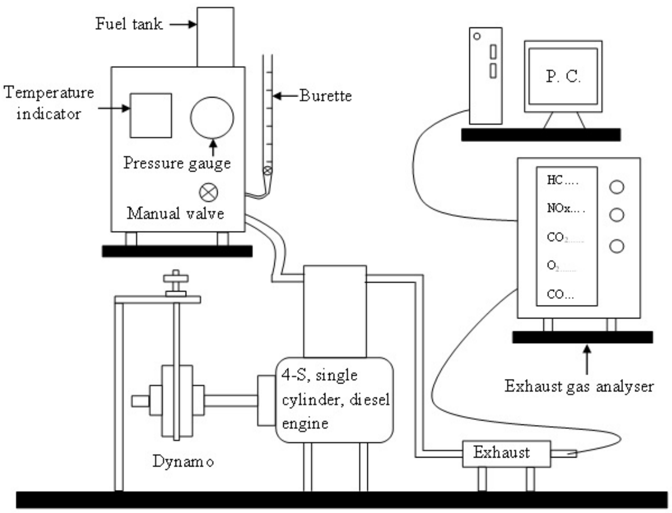

Figure 7. Experimental setup schematic diagram [23]

Brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are two distinct performance indicators that are evaluated individually as follows:

$$FC = \frac{V \times \rho \times 3600}{t \times 1000} \quad (2)$$

$$BP = \frac{2 \times \pi \times N \times T}{60000} \quad (3)$$

Where, N is the engine speed(rpm);T is the torque(N-m)which can be calculated as:

$$T = (W_1 - W_2) \times 9.81 \times 0.46 \quad (4)$$

Where, W is the load (kg); the distance from drum shaft centre to rope is 0.46 m.

$$BSFC = \frac{F.C.}{B.P.} \quad (5)$$

$$BTE = \frac{B.P. \times 3600}{m \times C.V.} \times 100 \quad (6)$$

3.1.Experimental uncertainty

To evaluate errors during the experiments, it is necessary to perform an uncertainty analysis. Malfunctioning measuring devices, inconsistent instrument calibration, workplace climatic conditions, and observational errors during readings are usually the main causes of errors in experiments. The percentage uncertainties of several parameters are shown in Table 3.

Table 3. The percentage of uncertainty in various parameters.

Instruments	Uncertainty (±) (%)
Tachometer (speed indicator in rpm)	± 1.0
Spring balance (Load in kg)	± 0.25
Burette (Fuel measuring in ml)	± 0.55
Temperature indicator (°C)	± 0.2
Stopwatch (time in sec)	± 0.1
Emission analyzer (ATS-206A):	
HC	± 0.25%
NOx	± 0.5%
CO_2	± 0.5%
CO	± 0.75%

By the help of square root method, the prediction of the overall % uncertainty (U_C) can be determined, as shown below:

$$U_c = \sqrt{\sum_{i=1}^{n} (U_i)^2} \quad (7)$$

Where U_i is the individual uncertainty of parameter.

Uncertainty found in overall experiment = Square root of [(uncertainty of tachometer)^2 + (uncertainty of spring balance)^2 + (uncertainty of burette)^2 + (uncertainty of temperature indicator)^2 + (uncertainty of stopwatch)^2 + (uncertainty of HC)^2 + (uncertainty of NOx)^2 + (uncertainty of CO_2)^2 + (uncertainty of CO)^2

$= [(1.0)^2 +(0.25)^2 +(0.55)^2 +(0.20)^2 +(0.1)^2+(0.25)^2+(0.5)^2+(0.5)^2+(0.75)^2]^{1/2}$

= ±1.594%

4. Results and discussion

This experimental investigation examines the effects of water hyacinth biodiesel–n-butanol–diesel fuel blends, designated as WHB20D80 (WHB 20% and diesel 80%), WHB20D75B5 (WHB 20%, diesel 75% and n-butanol 5%), and WHB20D70B10 (WHB 20%, diesel 70% and n-butanol 10%) on the performance and emission parameters of the diesel engine at variable engine loads (0-5 kg). The error bars in the graphs, representing standard deviations, indicate the reliability and precision of the results. These deviations encapsulate the range of variation and uncertainty associated with individual data points, providing valuable insights into the robustness and consistency of the results. A smaller error bar signifies less uncertainty and suggests greater reliability of measurements. In all plots of performance and emission parameters, corresponding errors are calculated as standard deviations and included. The performance and emission parameters of the prepared blends were analyzed and compared with those of diesel fuel.

4.1. Performance analysis

Various performance parameters, such as EGT, BSFC, and BTE, are evaluated for prepared blends of WHB, butanol, and diesel fuel and compared with diesel under variable engine loading conditions. The parameters mentioned above are discussed in detail below.

4.1.1. Brake-specific fuel consumption

Figure 8 illustrates the variation in BSFC for diesel and prepared fuel blends under variable engine loads. The term BSFC denotes the fuel consumption per unit of power produced. For a fuel to perform optimally, the BSFC should be as low as possible. The BSFC is significantly affected by several fuel characteristics, including density, heating value, viscosity, and cetane number. The results of the measurements show that, for a given load, BSFC increases with increasing concentration of butanol, while it decreases with increasing engine load, and that all the test fuels exhibit the same pattern. Diesel has the lowest BSFC because of its high heating value. Moreover, due to their lower and higher heating values, WHB20D80 and WHB20D75B5 have the higher and lower BSFC values, respectively. Additionally, as butanol concentration increases, a blend's heating value decreases, resulting in increased BSFC. At higher engine loading, the BSFC values for diesel, WHB20D75B5, WHB20D70B10, and WHB20D80 are 0.25 kg/kW hr, 0.27 kg/kW hr, 0.28 kg/kW hr, and 0.30 kg/kW hr, respectively. Finally, BSFC was observed to increase by 8%, 12%, and 20% for WHB20D75B5, WHB20D70B10, and WHB20D80, respectively, compared to diesel.

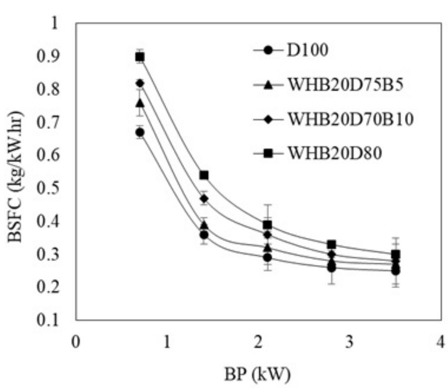

Figure 8. Plot of BSFC Vs Load

4.1.2. Brake-thermal efficiency

Figure 9 illustrates the variation in BTE for diesel and prepared fuel blends under varying engine loads. The brake thermal efficiency for each fuel is calculated to determine how effectively each fuel performs within the combustion zone to generate the required work output. Some of the fuel properties that affect BTE include kinematic viscosity, oxygen generation, cetane index, and calorific value. The fact that the BTE for WHB20D75B5 remains close to that of diesel fuel across the engine load range suggests that biodiesel blends have a better heating value owing to the blend's inherent oxygen content. BTE increases as load increases because increased load raises power output and reduces friction losses. Also, higher engine load increases the cylinder temperature, which promotes vaporization; thus, improved fuel–air mixing may lead to reduced ignition delay, resulting in higher BTE. As the butanol concentration in blends increases, BTE decreases because butanol has a high latent heat of vaporisation. For Diesel, WHB20D75B5, WHB20D70B10, and WHB20D80, the BTE values at the maximum load are 32.51%, 31.25%, 30.24%, and 28.69%, respectively. Finally, BTE was observed to decrease by 3.87%, 6.98%, and 11.75% for WHB20D75B5, WHB20D70B10, and WHB20D80, respectively compared to diesel.

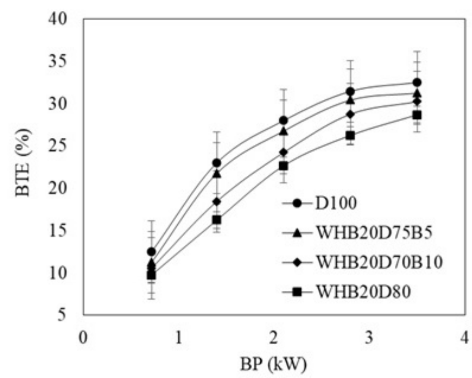

Figure 9. Plot of BTE Vs Load

4.1.3. Exhaust gas temperature

Figure 10 illustrates the variation in EGT for diesel and prepared fuel blends under varying engine loads. The quantity of heat released during combustion can be measured by EGT, which also affects pollutant generation. The engine performance, air/fuel ratio, and the heat released during the diffusion-combustion phase are clearly identifiable from EGT. WHB blends have higher EGT than diesel because biodiesel has a higher cetane number and higher oxygen concentration. EGT increases with engine load because more fuel is pumped into the cylinder. Exhaust gas temperatures for all biodiesel blends are slightly higher than those for diesel at maximum load. This is primarily caused by increased cetane numbers, higher internal oxygen content, and shorter ignition delays, which result in more complete combustion and higher exhaust gas temperatures. The EGTs at maximum load for Diesel, WHB20D75B5, WHB20D70B10, and WHB20D80 are 230 °C, 260 °C, 280 °C, and 295 °C, respectively. Finally, the EGT increased by 13.04%, 21.73%, and 28.26% for WHB20D75B5, WHB20D70B10, WHB20D80, respectively compared to diesel.

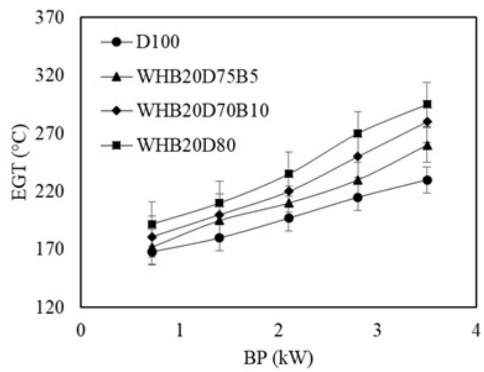

Figure 10. Plot of EGT Vs Load

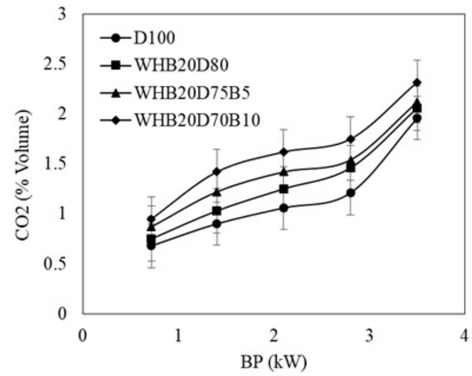

Figure 11. Plot of CO_2 Vs Load

4.2. Emission analysis

Emissions analysis was performed using an exhaust gas analyzer (EGA). It is coupled to the exhaust of the diesel engine with the help of a probe. Emissions from all fuel blends at variable loads (0-5 kg) have been recorded on the digital screen of the exhaust gas analyzer(ATS-206A model).The various emission parameters, such as HC, CO_2, NOx and CO are explored for the prepared WHB, butanol and diesel fuel blends and compared with the diesel at variable load. The above-mentioned emission parameters are explained in the sections below.

4.2.1. Carbon dioxide

Figure 11 illustrates the variation in carbon dioxide emissions for diesel and prepared fuel blends under varying engine loads. Air, fuel, and heat are used in the combustion process of the diesel engine to ignite the heterogeneous air-fuel mixture. The products of effective combustion are CO_2 and H_2O, but incomplete combustion produced CO, HC, NOx, and smoke. There is an imbalance between CO and CO_2 emissions, therefore the higher the emissions of CO_2, better the oxidation of fuel. WHB and diesel blends emit more carbon dioxide throughout the engine loading, indicates that there is sufficient oxygen to promote complete combustion. Additionally, it has been noted that D100 emits less CO_2 than other WHB fuel blends. Since butanol's high oxygen content promotes complete fuel combustion, the CO_2 release rate increases with increasing butanol percentage in blends. Diesel, WHB20D80, WHB20D75B5, and WHB20D70B10 release CO_2 emissions at maximum load are 1.96%, 2.06%, 2.12%, and 2.32% respectively. The CO_2 was observed to be increased by 5.10%, 8.16% and 18.36% for WHB20D80, WHB20D75B5, and WHB20D70B10 respectively in comparison to diesel. Compared with other fuel blends, WHB20D80 has values closer to those of diesel. The CO_2 emissions may be reduced by employing after-treatment system, carbon capture system and hydrogen injection with biodiesel.

4.2.2. Nitrogen oxides

Figure 12 illustrates the variation in NOx emissions from diesel and prepared fuel blends under varying engine loads. At the end of combustion, NOx tends to be released only when gas temperatures exceed 1500 °C. This is because NOx is generated when atmospheric O_2 and N_2 react with O_2 concentration in biodiesel. The abundance of O_2 molecules in a lean mixture creates an increase in NOx emissions, which raises the combustion temperature. It has been shown that when engine loads increase for biodiesel mixtures, NOx emissions increase because of the O_2 availability, enhanced combustion rate and total heat released during prior combustion's cycles. Higher fuel density resulting from higher injection pressures, which increases fuel consumption can cause higher emissions of oxides of nitrogen in WHB and diesel blends. Additionally, the WHB-diesel blend burns for a shorter period, influencing the cooling time via dilution and heat transfer, ultimately leading to increased NOx emissions. The butanol additive has good oxygen availability, which promotes better combustion and elevates in-cylinder temperature, resulting in increased NOx emissions. Meanwhile, the 78% nitrogen content of atmospheric air also promotes this. NOx emissions for D100, WHB20D80, WHB20D75B5, and WHB20D70B10 at maximum load (5 kg) were 309 ppm, 320 ppm, 330 ppm, and 345 ppm, respectively. The NO_X was observed to be increased by 3.55%, 6.79%, and 11.65% for WHB20D80, WHB20D75B5, and WHB20D70B10 respectively in comparison to diesel. NOx emissions may be controlled by well-known exhaust gas recirculation technique and injection timing adjustments [38].

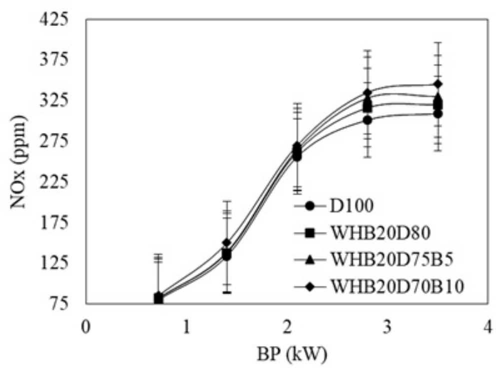

Figure 12. Plot of NOx Vs Load

4.2.3. Carbon monoxide

Figure 13 illustrates the variation in CO emissions for diesel and the prepared fuel blends under varying engine loads. Diesel engines generally emit less carbon monoxide because they operate effectively with a lean mixture, making carbon monoxide a minor contributor to pollution. However, the use of biodiesel modifies the oxygen level, oxidation rate, fuel spray properties, in-cylinder temperature, and ignition centres, all of which are crucial for generating CO. The deficiency of oxygen in diesel fuel leads the CO concentration to be significantly higher than that of WHB-diesel blends, despite the WHB-diesel blends inherent O_2 concentration. The rate of combustion is accelerated, and CO_2 is converted to CO more quickly when O_2 is present. In-cylinder temperature and pressure increase with load, facilitating effective combustion. Increasing engine loads result in reduced CO emissions. The CO for Diesel, WHB20D80, WHB20D75B5, and WHB20D70B10 was found to be 0.36% volume, 0.34% volume, 0.30% volume, and 0.27% volume, respectively. CO was observed to decrease by 5.5%, 16.6%, and 25% for WHB20D80, WHB20D75B5, and WHB20D70B10, respectively, compared with diesel.

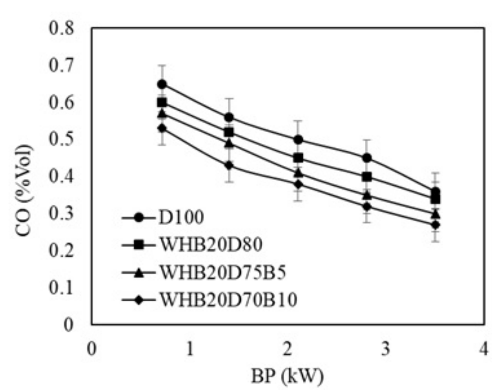

Figure 13. Plot of CO Vs Load

4.2.4. Hydrocarbon

Figure 14 illustrates the variation in HC for diesel and prepared fuel blends under varying engine loads. In CI engines, HC formation is extremely complex and depends on several factors, including fuel trapped in nozzles, voids, and cylinder-piston interfaces. Blends of WHB and diesel exhibit lower HC emissions across the engine load range because biodiesel contains oxygen, which increases combustion efficiency. As engine load increases, HC emissions decrease because improved combustion results from higher in-cylinder temperature and pressure. At maximum engine load, HC is highest for diesel fuel (34 ppm), followed by WHB20D80 (32 ppm), WHB20D75B5 (30 ppm), and WHB20D70B10 (28 ppm). Lowered emissions of HC for WHB-diesel blends can be attributed to improved mixing, a higher rate of vaporization, and greater availability of oxygen. Insufficient evaporation of the fuel–air mixture, locally over-rich or lean mixtures, and excessive spray impingement resulting from biodiesel combustion in a diesel engine make HC emissions more frequent. However, HC was observed to decrease by 5.80%, 11.76%, and 17.64% for WHB20D80, WHB20D75B5, and WHB20D70B10, respectively, compared with diesel.

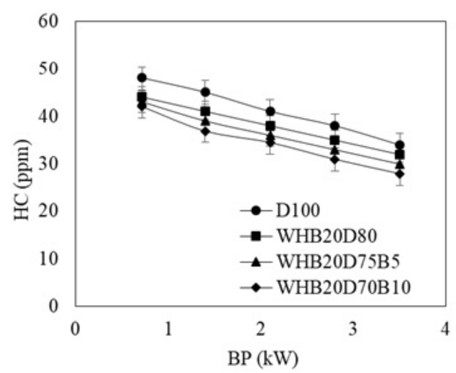

Figure 14. Plot of HC Vs Load

The current study reported the performance and emission parameters based on experimental evidence. In the future, these parameters may be optimized by adjusting the ternary blends and the operating conditions using methods such as Taguchi methodology [39-40], the artificial neural network technique [41-42], and response surface methodology [43-44]. These mathematical and statistical optimization techniques have been shown to achieve optimal outcomes. Also, the above optimization techniques save time and resources and minimize human labor compared with conventional methods. Table 4 presents a comparative analysis of the current work and recent significant studies. Biofuels extracted from various biomass sources (with or without additives), their different blending samples, and the optimum blends (enhanced performance, improved properties, and reduced emissions) reported in existing research are described and compared with the current work. This study found that the WHB20D75B5 blend is the optimum blend.

Table 4. Comparative analysis of current work with other existing works.

Biodiesel + Base Fuel	Additives	Prepared Blends	Most Effective Blend	References
Tamarind seed methyl ester (TSME) + D	none	D30P.I.-Cr18, D100M.I.-Cr18, 30TSME20P.I.-Cr18, 30TSME20M.I.-Cr18	30TSME20P.I.-Cr18	Prasad et. al [32]
Lemon peel Oil methyl easter (LPOME) + D	none	LPOME10D90, LPOME20D80, LPOME30D70	LPOME20D80	Kumari et al. [34]
Cyclohexanol + ULSD	none	CHX10, CHX20, CHX30	CHX30	Kumar et al. [45]
Lemongrass BD + D	none	BM5, BM10, BM15, BM20, BM25, BM30, BM40	BM20	Kumar et al. [46]
Eucalyptus biodiesel + D	n-Butanol	B100, B20, B20Bu5, B20Bu10, B20Bu15	B20Bu10	Singh et al. [21]
Calophyllum Inophyllum biodiesel	1-Pentanol, 1-Butanol	1B40-CB60, 1B50, CB50, 1B60-CB40, 1P40-CB60, 1P50-CB50, 1P60-CB40	1P40-CB60	Nanthagopal et al. [24]
Jatropha biodiesel + D	Pentanol	D50B50, DBOP10, DBOP20, DBOP30, DBOP40	DBOP40	Appavu et al. [31]
Mango seed biodiesel + D	Diethyl ether (DEE)	MSME20, MSME20DEE5, MSME20DEE10, MSME20DEE15	MSME20DEE5	Reddy et. al [33]
Jatropha biodiesel + D	Ethanol	B15D85E0, B15D80E5, B15D75E10, B15D70E15, B15D65E20	B15D75E10	Dhairiyasamy et al. [47]
Mahua biodiesel + D	1-hexanol	M10, M20, M30, M30D69.5H0.5, M30D69H1	M30D69H1	Raju et al. [35]
Sapota oil biodiesel + D	1-hexanol, 1-Butanol	B20D70Bu10, B20D60Bu20, B20D50Bu30, B20D870H10, B20D60H20, B20D50H30,	B20D870Bu10, B20D870H10	Mylavarapu et al. [48]
WHB + D	none	B10, B20, B30, B40, B100	B20	Alagu et al. [7]
Delonox regina	1- Butanol	DR100, D90DR05B05, D80DR08B12, D70DR16B14	D90DR05B05	Muniamuthu et al. [36]
WHB + D	n- Butanol	WHB20D80, WHB20D75B5, WHB20D70B10	WHB20D75B5	Current work

5. Conclusion

In current experimental investigation, the performance and emissions characteristics of the 4-S, single cylinder, water-cooled, compression ignition diesel engine working on water-hyacinth biodiesel (a problematic aquatic invasive weed for waste-to-energy) and butanol blends with the diesel fuel have been assessed. The following findings are described based on the experimental analysis:

- Brake specific fuel consumption was observed to increase by 8%, 12% and 20% for WHB20D75B5, WHB20D70B10 and WHB20D80 respectively compared to diesel.
- Brake thermal efficiency was observed to decrease by 3.87%, 6.98% and 11.75% for WHB20D75B5, WHB20D70B10 and WHB20D80 when compared with diesel.
- CO_2 was observed to increase by 5.10%, 8.16%, and 18.36% and the NO_X was observed to be increased by 3.55%, 6.79%, and 11.65%, for the WHB20D80, WHB20D75B5, and WHB20D70B10 respectively in comparison to diesel.
- CO was observed to be decreased by 5.5%, 16.6% and 25% and the HC was observed to be decreased by 5.80%, 11.76% and 17.64%, for WHB20D80, WHB20D75B5, and WHB20D70B10 respectively in comparison to diesel.
- The findings of the study suggest that, under the defined proportion, the combination of WHB-diesel-butanol (WHB20D75B5) can be effectively and safely utilized in the CI engines without any engine modifications and this WHB biodiesel holds a great possibility to get used as an effective fuel for future diesel engine applications.

This study is performed to check the oil extraction from water hyacinth biomass, its biodiesel and diesel/biodiesel/butanol blends and to compare the blend properties with fossil diesel for their potential utilization as fuel to run the diesel engine. The performance of prepared blend was found satisfactory and close to the diesel fuel. Whereas, optimization of the biodiesel yield, the prepared blends and the performance & emission parameters using optimization techniques may be part of future research requirements. Additionally, further investigation may involve blending ratio optimization, lifecycle or techno-economic analysis and the use of nano-additives in water hyacinth biofuel to improve performance and lower the emission levels from diesel engines. Also, Government subsidies and market demand for biodiesel may have an impact on its economic sustainability.

Conflict of interest

There is no conflict of interest.

Funding information

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Acknowledgements

Authors would like to thank "Chemical Engineering Department, Madan Mohan Malaviya University of Technology, Gorakhpur (Uttar Pradesh), India" for support and providing us facilities during biodiesel and blends preparation.

Ethics

There are no ethical issues with the publication of this manuscript.

Statement on the use of artificial intelligence

Artificial intelligence was not used in the preparation of the article.

Copyright and permission statement

The permission has been obtained from the copyright holder for all elements referred to as figures within the manuscript.

Abbreviations

D100	Diesel
WHO	Water hyacinth oil
WHB	Water hyacinth biodiesel
BD	Biodiesel
BP	Brake power
WHB20D80	20% WHB+80% Pure diesel
WHB20D75B5	20% WHB+75% Pure diesel+5% n-butanol
WHB20D70B10	20% WHB+70% Pure diesel+10% n-butanol
FC	Fuel consumption
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CI	Compression ignition
K.V.	Kinematic viscosity
C.V.	Calorific value
C. N.	Cetane number
EGT	Exhaust gas temperature
NOx	Nitrogen oxide
HC	Hydrocarbon
CO	Carbon monoxide

References

[1] Venu H, Venkataraman D, Purushothaman P, Vallapudi DR. Eichhornia crassipes biodiesel as a renewable green fuel for diesel engine applications: performance, combustion, and emission characteristics. Environ Sci Pollut Res 2019;26:18084–18097. doi.org/10.1007/s11356-019-04939-z

[2] Ganorkar PV, Jadeja G C, Parikh J K, Desai MA. Waste valorization of water hyacinth using biorefinery approach: a sustainable route. Catalysis for Clean Energy and Environmental Sustainability: Biomass Conversion and Green Chemistry 2021;1: 669-703. doi.org/10.1007/978-3-030-65017-9_20

[3] Kataki R, Kataki MD. Weeds as a renewable bioresource: prospects for bioconversion to biofuels and biomaterials through a cascade of approaches. Biofuels Bioenergy 2022;437-446. doi.org/10.1016/B978-0-323-85269-2.00021-6

[4] Bhargavi G, Rao PN, Renganathan S. Review on the extraction methods of crude oil from all generation biofules in last few decades. IOP Conf Ser Mater Sci Eng 2018;330:012024. doi:10.1088/1757-899X/330/1/012024

[5] Yadav GPK, Muvvala P, Reddy RM. Study of performance, emission characteristics, and parametric optimization of compression ignition engine using biofuels: A review. Biofuels 2024;15(9):1215–1232. doi.org/10.1080/17597269.2024.2340178.

[6] Gaurav GK, Mehmood T, Cheng L, Klemes JJ, Shrivastava DK. Water hyacinth as a biomass: A review. J Clean Prod 2020;277:122214. doi.org/10.1016/j.jclepro.2020.122214

[7] Alagu K, Venu H, Jayaramn J, Raju VD, Subramani L, Appavu P, Dhanasekar S. Novel water hyacinth biodiesel as a potential alternative fuel for existing unmodified diesel engine: Performance, combustion and emission characteristic. Energy 2019;179:295-305. doi.org/10.1016/j.energy.2019.04.207

[8] Khan O, Yadav AK, Khan ME, Parvez M. Characterization of bioethanol obtained from Eichhornia Crassipes plant; its emission and performance analysis on CI engine. Energy Sources A: Recovery Util Environ Eff 2021;43(14): 1793-1803. doi.org/10.1080/15567036.2019.1648600

[9] Mohammed HS, Mashkour MA. The effect of Eichhornia Crassipes biodiesel/LPG dual-fuel on performance and emissions in a single-cylinder compression ignition engine. Eng Technol J 2023;41(1):232-242. doi.org/10.30684/etj.2022.135176.1266

[10] Hoang AT, Sirohi R, Pandey A, Nizetic S, Lam SS, Chen W, Luque R, Thomas S, Arici M, Pham VV. Biofuel production from microalgae: challenges and chances. Phytochem Rev 2023;22(4):1089-1126. doi.org/10.1007/s11101-022-09819-y

[11] Mishra C, Saini P, Singh RK, Azharuddin, Rai N. Oil extraction from microalgae, its performance and emission analyses in diesel engine using different blending mixtures with fossil diesel. Singapore:Springer;2023. pp. 205-221. doi.org/10.1007/978-981-19-6945-4 15

[12] Kumar P, Saini P, Kumar D, Shankar R, Yadav G, Singh J. Experimental analysis on performance and emission characteristics of diesel engine using lemongrass biodiesel and TiO2 nano additives blends. NanoWorld J 2023;9(S1):S419-S424. doi.org/10.17756/nwj.2023-s1-081

[13] Saini P, Gupta C, Shankar R. Characterization of corn oil biodiesel and its application in diesel engine. Energy Sources A: Recovery Util Environ Eff 2023;45(3):9498-9512. doi.org/10.1080/15567036.2019.1679913

[14] Elumalai PV, Das SK, Parthasarathy M, Dhineshbabu NR, Balasubramanian D, Cao DN, Troung TH, Le AT, Hoang AT. Combustion and emission behaviors of dual-fuel premixed charge compression ignition engine powered with n-pentanol and blend of diesel/ waste tire oil included nanoparticles. Fuel 2022;324:124603. doi.org/10.1016/j.fuel.2022.124603.

[15] Yadav PKG, Bandhu D, Reddy JK, Reddy MR, Srinivasu C, Katam GB. Performance evaluation of a thermal barrier-coated ci engine using waste oil biodiesel blends. Renew Energy Res Appl 2024;5(2):181-193. doi:10.22044/rera.2023.12828.1206

[16] Ardebili SMS, Solmaz H, Calam A, Ipci D. "Modelling of performance, emission, and combustion of an HCCI engine fueled with fusel oil-diethylether fuel blends as a renewable fuel. Fuel 2021;290:120017. doi.org/10.1016/j.fuel.2020.120017

[17] Ramakrishnan P, Kasimani R, Peer MS. Optimization in the performance and emission parameters of a DI diesel engine fuelled with pentanol added Calophyllum inophyllum/diesel blends using response surface methodology. Environ Sci Pollut Res 2018;25:29115–29128. doi.org/10.1007/s11356-018-2867-4

[18] Aldhaidhawi M, Chiriac R, Badescu V. Ignition delay, combustion and emission characterstics of Diesel engine fueled with rapeseed biodiesel - A literature review. Renew Sustain Energy Rev 2017;73:178-186. doi.org/10.1016/j.rser.2017.01.129

[19] Trung T, Nguyen XP, Pham VV, Le VV, Le T, Bui VT. Effect of alcohol additives on diesel engine performance: a review. Energy Sources A: Recovery Util Environ Eff 2025;47(2):2011490. doi.org/10.1080/15567036.2021.2011490

[20] Yesilyurt MK, Eryilmaz T, Arslan M. A comparative analysis of the engine performance, exhaust emissions and combustion behaviors of a compression ignition engine fuelled with biodiesel/diesel/1-butanol (C4 alcohol) and biodiesel/diesel/n-pentanol (C5 alcohol) fuel blends. Energy 2018;165:1332-1351. doi.org/10.1016/j.energy.2018.10.100

[21] Singh R, Singh S, Kumar M. Impact of n-butanol as an additive with eucalyptus biodiesel-diesel blends on the performance and emission parameters of the diesel engine. Fuel 2020;277:118178. doi.org/10.1016/j.fuel.2020.118178

[22] Tipanluisa L, Fonseca N, Casanova J, Lopez JM. Effect of n-butanol/diesel blends on performance and emissions of a heavy-duty diesel engine tested under the world harmonised steady-state cycle. Fuel 2021;302:121204. doi.org/10.1016/j.fuel.2021.121204

[23] Ahmad K, Saini P. Effect of butanol additive with mango seed biodiesel and diesel ternary blends on performance and emission characteristics of diesel engine. Energy Sources A: Recovery Util Environ Eff 2022;44(4):9988–10005. doi.org/10.1080/15567036.2022.2143954

[24] Nanthagopal K, Ashok B, Saravanan B, Patel D, Sudarshan B, Ramasamy RA. An assessment on the effects of 1-pentanol and 1-butanol as additives with Calophyllum Inophyllum biodiesel. Energy Convers Manage 2018;158:70–80. doi.org/10.1016/j.enconman.2017.12.048

[25] Nour M, Attia AMA, Nada SA. Combustion, performance and emission analysis of diesel engine fuelled by higher alcohols (butanol, octanol and heptanol)/diesel blends. Energy Convers Manage 2019;185:313–329. doi.org/10.1016/j.enconman.2019.01.105

[26] Sharma P, Le MP, Chhillar A, Said Z, Deepanraj B, Cao DN, Bandh SA, Hoang AT. Using response surface methodology approach for optimizing performance and emission parameters of diesel engine powered with ternary blend of Solketal-biodiesel-diesel. Sustain Energy Technol Assess 2022;52:102343. doi.org/10.1016/j.seta.2022.102343

[27] Reddy ER, Keerthana BVS, Raju VD, Mahith S, Dhanush B. Mitigation of NOX emissions with application of exhaust gas recirculation on diesel engine fuelled with diesel-corn seed oil biodiesel blend. Int J Amb Energy 2020;43:1-34. doi:10.1080/01430750.2020.1745275

[28] Raja E, Premjeyakumar M. Potent effect of prosopis juliflora (biodiesel + isopropanol + diesel) fueled with diesel engine and egr alteration.Cclean Eng Technol 2021;4:100205. doi.org/10.1016/j.clet.2021.100205

[29] Rahman MA, Aziz MA. Biodiesel from water hyacinth biomass and its influence on CI engine performance, emission, combustion and heat loss characterstics with the induction of hydroxy. Energy 2021;224:120151. doi.org/10.1016/j.energy.2021.120151

[30] Wahhab HAA, Al-Kayiem HH. Environmental Risk Mitigation by Biodiesel Blending from Eichhornia crassipes: Performance and Emission Assessment. Sustainability 2021;13:8274. doi.org/10.3390/su13158274

[31] Appavu P, Ramanan MV, Venu H. Quaternary blends of diesel/biodiesel/vegetable oil/pentanol as a potential alternative feedstock for existing unmodified diesel engine: Performance, combustion and emission characteristics. Energy 2019;186:115856. doi.org/10.1016/j.energy.2019.115856

[32] Prasad KB, Meduri O, Raju VD, Azmeera AK, Venu H, Subramani L, Soudagar MEM. Effect of split fuel injection strategies on the diverse characteristics of CRDI diesel engine operated

with tamarind biodiesel. Energy Sources A: Recovery Util Environ Eff 2025;47(1): 3566-3584. doi.org/10.1080/15567036.2020.1856973

[33] Reddy SR, Murali G, Raju VD. Assessment of diethyl ether as fuel additive on the diverse characteristics of diesel engine powered with waste mango seed biodiesel blend. Int J Amb Energy 2022;43(1):3365-3376. doi:10.1080/01430750.2020.1824944

[34] Kumari AA, Sivaji G, Arifa S, Mahesh OS, Rao TR, Kalyan VS, Raju VD, Bhargava K, Reddy KL. Experimental assessment of performance, combustion, emission characteristics of diesel engine fuelled with lemon peel oil. Int J Amb Energy 2022;43(1): 3857-3867. doi:10.1080/01430750.2020.1861089

[35] Raju VD, Kirankumar K, Kishore PS. Engine performance and emission characteristics of a direct injection diesel engine fuelled with 1- hexanol as a fuel additive in mahua seed oil biodiesel blends. Int J Therm Environ Eng 2016;13(2):121-127. doi:10.5383/ijtee.13.02.007

[36] Muniamuthu S, Kumar KS, Deepa S, Elangovan M, Verma A, Sonekar MM. Investigation on Delonix regina biodiesel blends on diesel engine with 1-butanol-diesel blends to test engine performance, combustion and emission characteristics. J Therm Eng 2025;11(1):170-180. doi:10.14744/thermal.0000911

[37] Yamini K, Kishore PS, Raju VD. Effect of diethyl ether and Isobutanol as fuel additives on the diesel engine attributes fueled with subabul seed biodiesel. J Therm Eng 2025;11(1):215-225. doi:10.14744/thermal.0000914

[38] Rajendran R, Venkatachalapathy V, Velmurugan K, Elangovan M, Balu P. Study on exhaust gas recirculation diesel engine using karanja oil methyl ester with low heat rejection in direct injection. J Therm Eng 2024;10(2):396-403. doi:10.18186/thermal.1448677

[39] Yadav GPK, Bandhu D, Chatterjee S, Gangwar PK. Optimizing diesel engine performance and emissions with mahua biodiesel blends using taguchi methodology. PloS one, 2025;20(9):0332035. doi.org/10.1371/journal.pone.0332035

[40] Yadav G, Muvvala P, Reddy RM. Optimization of injection parameters and low-reactive fuel share in CRDI engines with biodiesel–diesel–isoamyl alcohol ternary blends. J Renew Sustain Energy 2025;17(4), 043101. doi:10.1063/5.0278062

[41] Natarajan K, Subramani S, Govindasamy R, Kumar PD. Optimization of biodiesel powered CI engine process parameters using AHP and Taguchi grey method–A hybrid approach. J Therm Eng 2025;11(3):753-764. doi:10.14744/thermal.0000944

[42] Yadav GPK, Muvvala P, Reddy RM. Multi-criteria optimization of common rail direct injection engine parameters with isoamyl alcohol blends using Taguchi-Grey relational analysis (GRA) and Artificial neural network (ANN). Therm Sci Eng Prog 2025;103719. doi.org/10.1016/j.tsep.2025.103719

[43] Yadav GPK, Muvvala P, Reddy RM. Optimization of injection parameters, and ethanol shares for cottonseed biodiesel fuel in diesel engine utilizing artificial neural network (ANN) and taguchi grey relation analysis (GRA). J Non-Equilib Thermodyn 2025. doi.org/10.1515/jnet-2024-0095

[44] Gupta MK, Srivastava AK. Harnessing response surface methodology for diesel engine optimization using titanium dioxide-enhanced rice bran biodiesel to improve emissions and efficiency. J Therm Eng 2025;11(5):1276-1292. doi:10.14744/thermal.0000996

[45] Kumar BR, Saravanan S, Kumar RN, Nishant B, Rana D, Nagendran A. Effect of lignin-derived cyclohexanol on combustion, performance and emissions of a direct-injection agricultural diesel engine under naturally aspirated and exhaust gas recirculation (EGR) modes. Fuel 2016;181:630–642. doi.org/10.1016/j.fuel.2016.05.052

[46] Kumar P, Kumar D, Shankar R, Kumar S, Saini P, Kumar N. Effect of synthesized lemongrass biodiesel on the performance and emission characteristics of a CI engine. Sustain Energy Technol Assess 2023;57:103221. doi.org/10.1016/j.seta.2023.103221

[47] Dhairiyasamy R, Varshney D, Singh S, Gabiriel D. Performance and emission analysis of diesel–biodiesel–ethanol blends in a turbocharged CI engine: ignition delay and emission optimization. Clean Techn Environ Policy 2025;276343–6364. doi.org/10.1007/s10098-025-03287-6

[48] Mylavarapu A, Manikandan R, Alwetaishi M, Elumalai PV. Impact of butanol and hexanol on RCCI engine efficiency and emission characteristics using sapota oil methyl ester and response surface methodology. Sci Rep 2025;15:34009. doi.org/10.1038/s41598-025-11243-z