



Experimental investigation on performance and emission analysis of the higher alcohol-blended water-emulsified waste cooking oil biodiesel in an IC engine

B. Maharajan¹, P. Madhu^{2*}, C. Sowmya Dhanalakshmi³ & R. Vijayakumar⁴

¹Department of Mechanical Engineering, RVS Polytechnic College, Coimbatore 641402, Tamil Nadu, India

²Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore 641032, Tamil Nadu, India

³Department of Mechanical Engineering, SNS College of Technology, Coimbatore 641035, Tamil Nadu, India

⁴Centre for Smart Energy Systems, Chennai Institute of Technology, Chennai 600069, Tamil Nadu, India

*E-mail: pnpmadhu@gmail.com

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This study investigated the impact of alcohol addition on various diesel engine parameters using emulsified biodiesel derived from waste cooking oil (WCO). The primary contribution of this study is the development of a new blended fuel consisting of 30% WCO biodiesel by volume mixed with regular diesel, which is then emulsified with 10% water. Additionally, 1-hexanol was incorporated into the water-emulsified biodiesel at a volumetric concentration of 10% and 20%. Therefore, four different fuels were developed and tested against those of biodiesel–diesel fuel in a single-cylinder, four-stroke diesel engine without any modifications. The study shows that 1-hexanol-blended, water-emulsified WCO biodiesel improves combustion efficiency and lowers emissions compared to regular diesel. Adding 20% 1-hexanol to the water-emulsified WCO biodiesel significantly reduced the emissions of carbon monoxide (CO), hydrocarbons (HC), and smoke by 42.8%, 18.2%, and 31.3%, respectively. Additionally, there was an 18.5% drop in brake specific fuel consumption (BSFC) and a 6.6% increase in brake thermal efficiency (BTE). There was a gradual rise in smoke observed as the 1-hexanol in the fuel increased from 10% to 20%. The study shows that adding higher alcohol to water-emulsified WCO biodiesel improves combustion efficiency and helps reduce engine emissions and fossil diesel use.

Keywords: 1-Hexanol, Diesel engine, Waste-to-energy, Waste cooking oil, Water emulsion

Introduction

Numerous factors contribute to environmental pollution, which has a serious negative influence on human health. The main causes of soil, water, and air pollution are agricultural practices, urbanization, and industrial activity¹. These contaminants have serious negative effects on health, including respiratory disorders. The increasing use of fossil fuels, inappropriate sewage disposal, and negligent utilization of agricultural pesticides are primary causes of environmental pollution². The negative consequences of using fossil fuels, such as pollution and greenhouse gas (GHG) emissions, have made the demand for clean energy. As the world's energy needs increase, switching to renewable energy sources is crucial for environmental preservation and sustainable growth. This shift includes a number of renewable energy-harvesting technologies and approaches³. Alternative fuel research shows great promises for reducing GHG emissions, especially in the transportation industry. Different technologies, such

as hydrogen fuel cells, electric cars, and biofuels, show differing levels of efficacy in reducing emissions⁴. As a sustainable way to lessen GHG emissions and dependency on fossil fuels, biodiesel is becoming more and more acknowledged as a competitive alternative fuel for the transportation industry. Biodiesel is made from a variety of feedstocks, such as vegetable and leftover cooking oils. It can be used straight or blended with regular diesel⁵. It is used in a variety of transportation sectors, including rail, maritime, automotive, and aviation industries. Biodiesel considerably lowers CO₂ emissions in worldwide measurements.

Overview of biodiesel blend for internal combustion (IC) engine operation

Due to their lower pollutant emissions and the heavy dependence on fossil fuels, biomass-based oxygenated fuels have emerged as a promising alternative to conventional fossil fuels. Recovering energy from waste is appealing as it addresses waste management challenges while meeting energy needs.

Biodiesel produced from different edible and non-edible seeds was blended with regular diesel and was tested by different authors and showed improved efficiency. But in most cases, the performance of the engine depends on the engine load and basic fuel properties. But the production of biodiesel from edible oils may result in food shortages. On the other hand, large-scale production is necessary for non-edible oil sources, which may need land resources intended for food crops. Utilization of renewable biodiesel blends improved BTE by up to 3.82% and reduced soot formation by 4.65% only at partial load. However, the value of BSFC and NO_x emissions increased with higher biodiesel blends⁶. Chen *et al.* estimate that the use of biodiesel blends could result in a reduction of up to 1.17 trillion yuan in China by 2030⁽⁵⁾. Additionally, Gebremariam claims that using biodiesel helps decarbonize different forms of transportation, addressing about 29% of the world's energy-related CO₂ emissions from the transportation sector⁷. Numerous studies have examined the performance and emission characteristics of biodiesel blends, identifying both advantages and disadvantages. Blends of biodiesel, especially those with different percentages of biodiesel, can improve engine performance and lower some pollutants at the same time⁸. However, they might result in higher fuel usage and nitrogen oxide (NO_x) emissions⁹.

Overview of WCO biodiesel for IC engine operation

India possesses a very high technical potential for producing biodiesel from WCO, yet only a small fraction of this potential is currently being utilized. The country consumes nearly 27 billion liters of edible oil every year, out of which approximately 1.4 billion liters of WCO can be recovered annually from bulk food operators alone¹⁰. Market assessments further indicate that the volume of the used cooking oil market was already in the range of about 3.2–3.4 million tonnes during 2022–2024 and is projected to grow steadily to nearly 4.4 million tonnes by 2033. This consistent growth trend highlights the increasing availability of WCO as a sustainable and promising feedstock for biodiesel production in India. IC engines running on biodiesel made from WCO have both benefits and drawbacks. The renewable nature of WCO biodiesel and its ability to lower emissions make it an attractive substitute for traditional diesel. However, its operating characteristics differ from conventional fuels, impacting engine efficiency and fuel consumption. When compared to traditional

diesel, WCO biodiesel often produces lower brake power (BP), brake torque (BT), and BTE. For example, a study found that using WCO biodiesel reduced BP, BT, and BTE by 1.68%, 1.7%, and 21%, respectively¹¹. In another study, WCO biodiesel was used in a multi-fuel engine, and the results showed better performance under a 30% blend. The 30% blended fuel showed an 8.5% increment in BTE and a 10% reduction in fuel consumption. The study also showed 35% reduced CO with 29.5% reduced CO₂. WCO with n-pentanol ternary blends offered promising opportunities for use as recyclable and bio-components to partially replace diesel fuel. Comparing the blends to diesel, the BSFC of D95-WCO5 (95% diesel and 5% WCO biodiesel blend), D65-WCO20-Pe15 (65% diesel, 20% WCO biodiesel, and 15% pentanol blend), and D60-WCO20-Pe20 improved by 0.32%, 0.49%, and 0.68%, respectively. D60-WCO20-Pe20 achieved a 39.6% increase in BTE. The particulate matter emissions were decreased by the addition of n-pentanol, suggesting that WCO with pentanol has the potential to be a sustainable fuel substitute¹². According to Nguyen, the test engine running on WCO oil synthetic diesel (WCOSD) had BP comparable to that of regular diesel, although there was a modest increase in fuel consumption under certain operating conditions. Moreover, WCOSD had higher emissions of NO_x under all loads, but regular diesel had lower HC emissions by an average of 26.3% and smoke by an average of 17%¹³. The combustion behaviour of the WCOSD showed a shorter ignition delay compared to diesel fuel, indicating an earlier ignition start. However, the blended fuel had a longer ignition delay at higher loads. Apart from WCO with regular diesel, the addition of diethyl ether (DEE) with WCO biodiesel was also tested by different authors and showed considerable changes in IC engine operating parameters. Jagotra *et al.* showed improved engine efficiency with the addition of 20% WCO biodiesel and 5% DEE with regular diesel under rated load. Additionally, BSFC decreased by 20.8% without DEE and showed no change with DEE, indicating better fuel efficiency¹⁴. From an emission point of view, compared to diesel fuel, DEE-blended WCO showed a considerable decrease in hazardous emissions.

Overview of alcohol blend for IC engine operation

Similar to biodiesel fuel, alcohol seems to be the most desirable biofuel for use in IC engines. The enhancement of combustion quality and emission

characteristics is an advantage of incorporating alcohol into biofuels. Oxygen is naturally present in the molecular structure of alcohols, which improves air-fuel mixing and encourages more thorough combustion. As a result, particulate matter, HC, and CO emissions are decreased. Additionally, because alcohol has a high latent heat of vaporization, it can lower in-cylinder temperatures and reduce NOx formation. Anaerobic fermentation of lignocellulosic biobased materials such as wood pulp, sawmill waste, paper mill residues, and agricultural residues can produce alcohol with minimal dependence on food sources¹⁵. In addition to that, elephant grass and switch grass are also used as raw materials for the production of alcohol. Therefore, alcohol availability would not be a significant problem. Usage of lower alcohols such as methanol and ethanol in IC engines has some obstacles due to its lower cetane number, higher latent heat of vaporization, and increased susceptibility to auto-ignition¹⁶. These restrictions on the application of alcohol as diesel engine fuel have been addressed by a number of methods, including the dual-fuel concept, alcohol-diesel blending, and alcohol-diesel emulsions¹⁷. Instead of lower alcohol, researchers are now interested in higher alcohols due to their hygroscopic nature. Compared to lower alcohol, higher alcohols have a greater energy value, higher cetane number, and superior blending ability¹⁸. Higher alcohol can improve engine performance and lower hazardous emissions when blended with biodiesel. According to research, these alcohols enhance combustion properties, which results in increased BTE and reduced fuel usage. The performance analysis of neat palm oil biodiesel blended with cyclooctanol showed improved BTE and reduced ignition delay compared to neat biodiesel at all loads. Particularly, a 30% blend of cyclooctanol exhibited the lowest CO and CO₂ emissions¹⁹. Harikrishna and Reddy showed that blending 75% diesel, 20% *Chlorella vulgaris* algae biodiesel, and 5% pentanol achieved a BTE of 31.7% with BSFC of 0.12 kg/kW-h. The authors compared the results with biodiesel-butanol blends and highlighted the use of biodiesel-pentanol blends for improved engine performance²⁰. A combination of 80% mango seed biodiesel, 5% 2-propanol, and 15% 1-hexanol was optimized by Reddy & Sarangi, resulting in a maximum BTE of 24.31% and a reduction in CO, CO₂, and NOx emissions at 76% load²¹. Using rapeseed biodiesel and n-butanol blends, Mickevicius *et al.* found that BSFC

is higher than that of regular biodiesel. Under full load conditions, the study emphasized performance gains in smoke opacity and NOx emissions, especially with the 20% butanol blend²².

Overview of alcohol-biodiesel emulsion for IC engine operation

Emulsification, the process of combining biodiesel with water, has the potential to enhance combustion properties and lower emissions. Adding water to the fuel improves the atomization process due to the micro-explosions behaviour of the fuel. The micro-explosion phenomenon of a fuel refers to the rapid breakup of a fuel droplet produced by the quick vaporization of volatiles inside the droplet, such as water in emulsified fuels. When the droplet is exposed to high combustion temperatures, the dispersed volatile part superheats and explosively vaporizes, leading to secondary atomization of the parent droplet into finer droplets. This phenomenon considerably increases the surface area available for evaporation and mixing with air, resulting in faster fuel vaporization, enriched air-fuel mixing, and more complete combustion. The effects of water-emulsified diesel/biodiesel on engine emission and performance vary greatly depending on the water concentration and nature of the fuel²³. It has been demonstrated that using alcohol-biodiesel emulsions in IC engines has a major impact on emissions and performance. By mixing biodiesel with alcohols, these emulsions seek to maximize engine performance while lowering hazardous emissions. Alcohols increase premixed combustion efficiency, prolong ignition delay, and improve fuel atomization, which boosts cylinder pressure and fuel conversion efficiency. In comparison to pure soybean biodiesel, the study found that adding 10% water to biodiesel increased BSFC and brake-specific energy consumption (BSEC) by 4% and 10.6%, respectively. It also found that under peak brake mean effective pressure (BMEP), emissions of NOx, HC, CO, and smoke decreased by 21.2%, 16.7%, 16.9%, and 11.8%, respectively²⁴. A stable emulsion consisting of 81% jatropha biodiesel and 15% wood pyrolytic oil with 4% surfactant exhibits better combustion and performance characteristics than regular diesel. According to the study conducted by Prakash *et al.* the use of emulsions made from pyrolytic oil and biodiesel improved the BTE of the engine up to 11.3% and the NO emission²⁵. According to Kannan and Marappan, blending DEE with *Thevetiaperuviana* biodiesel emulsion significantly reduced NOx

emissions. When compared to pure biodiesel, a 44% reduction was observed for 15% DEE blended emulsified biodiesel and a 48% reduction for 20% DEE blended emulsified biodiesel²⁶. Adding DEE improves combustion by lowering the temperature during combustion due to its high latent heat of vaporization. These results increased thermal efficiency and reduced emissions from the engine. From the results it can be understood that DEE-blended emulsified biodiesel outperformed other fuel combinations in terms of performance and emission reductions, indicating that biodiesel emulsions containing DEE could be a good substitute for traditional diesel fuels.

Novelty and objective of the work

Considering the significant advances in biofuel research, the present investigation aims to fill the gaps in the literature. In contrast to the thoroughly researched usage of ethanol and methanol as biofuel additives, the addition of 1-hexanol and its effect on the engine performance characteristics when combined with water-emulsified biodiesel are still not fully established. Moreover, there is an absence of complete studies that examine the combined effects of water emulsification and higher alcohol on a broad range of biodiesels, particularly in WCO. There is a lack of integrated research that systematically examines how varying proportions of 1-hexanol, water content, and WCO biodiesel blends interact to influence combustion performance and emission characteristics of the engine simultaneously. The study evaluates both the energy and environmental effects of mixing 10% and 20% volume of 1-hexanol with diesel fuel, water, and transesterification WCO biodiesel. The goal of this study is to shed light on how these biofuel blends might increase the combustion rate and lower pollutants, which would aid in the development of renewable and ecologically friendly energy sources.

Experimental Details

The detailed procedure for preparing and analyzing the test fuels is shown in Fig. 1.

Biodiesel production

Transesterification is a promising technique for producing biodiesel and developing sustainable fuel substitutes. This technique uses alcohol, usually methanol, along with a suitable catalyst to turn vegetable oils into biodiesel. The efficiency and

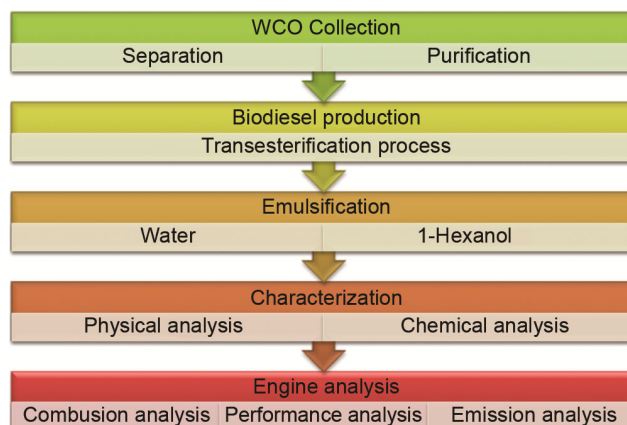


Fig. 1 — Experimental flowchart

sustainability of the production of biodiesel can be greatly impacted by the flexibility of the transesterification process, which permits the use of a variety of feedstocks and catalysts. The WCO used for frying purposes was gathered from a nearby restaurant certified by the local government at low cost. In order to avoid variations in fuel characteristics, the required amount of WCO was acquired as a single collection and utilized for the entire research. Unlike other kinds of vegetable oils, WCO has extremely high viscosity and density, which means that using it directly as fuel in engines may cause injection-related issues and negatively impact combustion. Therefore, the transesterification process was selected to turn used cooking oil into a viable diesel substitute.

In this process triglycerides are transformed into diglycerides, diglycerides into monoglycerides, and monoglycerides into glycerol in a series of three successive reversible processes²⁷. Two-step catalyzed transesterification was taken into consideration in this study since it has been shown to be successful in producing biodiesel from vegetable oils that contains a significant proportion of FFA²⁸. The initial step of the transesterification process started with the removal of impurities and other food sediment from the oil. In the two-step transesterification process, both basic and acidic catalysts are utilized independently. An acidic catalyst, such as ferric sulfate or sulfuric acid, was used in the first step, whereas a basic catalyst was used in the second step. For acid esterification, 175 mL of methanol and 5 mL of concentrated sulfuric acid were combined together in a round-bottomed flask. A further 500 mL of preheated WCO was blended with the mixture of methanol and sulfuric acid and stirred constantly at

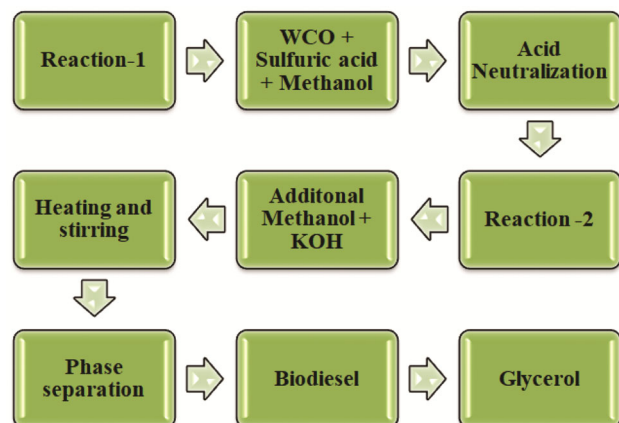


Fig. 2 — Biodiesel production process

500 rpm for one hour at 60°C. The mixture was then allowed to settle for 12 h. The bottom layer was identified as residues, and the top layer was composed of acid esterified oil. After removing the residue, the produced esterified oil was used for the base transesterification. In this stage, 3.5 g of potassium hydroxide (KOH) and 125 mL of methanol were added to acid-esterified oil. Further, the solution was set on a magnetic heater and constantly swirled at 500 rpm for one hour at 60°C. After ending the process, the solution was left to settle for 12 h. The produced glycerine identified at the bottom of the funnel was drained out, and the final biodiesel was separated by decantation. Fig. 2 shows the steps involved in the production of WCO biodiesel.

Water emulsified WCO biodiesel production

The emulsification process consists of adding a selected amount of water and surfactant to the prepared biodiesel blend. Prior to the emulsification process, a biodiesel blend was prepared by blending 30% WCO biodiesel with 70% regular diesel and named D70-WCOB30. The measured quantity of D70-WCOB30 was put into the vessel in order to produce 10% water in the blended biodiesel. The emulsification process can be developed instantly while every component is combined in the proper ratios²⁹. Additionally, the water content of biodiesel was restricted to 10% since diesel fuel with high water content has a longer ignition delay time and operates rougher³⁰. To prepare the emulsion, 10% volume of water was allowed to mix with the WCO biodiesel and stirred at a speed of 5000 rpm. To prevent layer separation during the stirring process, sorbitan monolaurate surfactant (1% volume) was also permitted to be added by drops with the

Table 1 — Tested fuel and its notation

Fuel	Notation
Diesel	D
70% diesel + 30% WCO biodiesel	D70-WCOB30
60% diesel + 30% WCO biodiesel + 10% water	D60-WCOB30-W10
50% diesel + 30% WCO biodiesel + 10% water + 10% hexanol	D50-WCOB30-W10-H10
50% diesel + 20% WCO biodiesel + 10% water + 20% hexanol	D50-WCOB20-W10-H20

emulsified fuel. The purpose of adding surfactants is to enhance the superficial contact area and to decrease superficial tension. The prepared solution was left to stir continuously for approximately 45 min to obtain emulsified fuel. Finally, the emulsified fuel was filtered and named as D60-WCOB30-W10. Further, the effect of the addition of a higher alcohol blend with emulsified biodiesel was tested by blending 10% and 20% 1-hexanol and named D50-WCOB30-W10-H10 and D50-WCOB20-W10-H20. Table 1 shows the prepared biodiesel blends used for the engine analysis.

Characterization study

The procedures outlined in the earlier study were followed in the determination of the elemental analysis of the prepared WCO biodiesel³¹. An Elementa Vario EL-III was used for the analysis of carbon, hydrogen, nitrogen, and sulphur content of the biodiesel. The elemental analysis is necessary for the determination of their fundamental chemical composition, which directly impacts fuel quality and combustion performance. This analysis helps in determining stoichiometric air–fuel ratios, which are essential for better performance. The analysis also enables calculation of emission potential. Moreover, elemental analysis is useful for comparing biodiesel with conventional diesel. The oxygen content of the biodiesel was found by subtracting other elements from 100. All the tests were performed according to ASTM standards. The different functional groups of the biodiesel were analyzed using FTIR spectroscopy (BRUKER Optik GmbH TENSOR 27). The spectra were obtained at a resolution of 4 cm⁻¹ and in the range between 400 and 4000 cm⁻¹. The density of the fuel sample was identified by weighing a known volume. The viscosity of the sample was identified using a BROOKFIELD LV-DV-II Pro viscometer. The calorific value of the fuel was found using a Parr-6772 calorimetric thermometer. The flash point of the biodiesel samples was assessed using the Pensky–

Martens closed-cup apparatus. All physical characteristics of the biodiesel samples were also analyzed according to the ASTM standard.

Engine setup

Engine design, fuel blending, and operating characteristics are some of the crucial factors to be taken into account while setting up engines for the use of biodiesel. According to research, biodiesel is a feasible substitute for fossil diesel because it can be used in conventional compression ignition (CI) engines with and without modifications. The present study was conducted on a single-cylinder, water-cooled, direct-injection diesel engine (Kirloskar TV1). Fig. 3 shows a schematic of the engine setup used for this work. The rated speed and rated power of the engine are 1500 rpm and 3.5 kW. The technical specification of the engine is given in Table 2.

The engine can be operated either in diesel or biodiesel mode by controlling the fuel outlet valve. In order to load the engine, the output shaft of the engine

is coupled with an eddy current dynamometer. The engine exhaust emissions, such as CO, HC, NOx, and smoke, were measured using an AVL Di gas analyzer and smoke meter. The engine analysis was carried out using different fuel samples under a rated speed of 1500 rpm, whereas the compression ratio, injection pressure, and injection timing were kept at 17.5:1, 200 bar, and 23° bTDC (occurring 23 degrees of crankshaft rotation before the piston reaches Top Dead Center (TDC) during the compression stroke), respectively. To achieve a steady-state condition, the engine was first operated with regular diesel for 15 minutes. Following that, the performance and emission characteristics were noted by changing the load from 0% to 100%. The same method was adopted for other tested fuels represented in Table 1. In order to ensure the repeatability, 5 readings were taken under the same operating conditions, and the average was taken for the account. The total uncertainty of the test results is computed as follows, and the uncertainty percentage of different parameters, including BP and BSFC, was determined using the root mean square method, shown in Eq. (1):

$$Overall\ uncertainty = \sqrt{\frac{uncertainty\ of\ (N^2 + W^2 + BSFC^2 + CO^2 + HC^2 + NOx^2 + Smoke^2)}{...}} \quad \dots(1)$$

The experimental findings have an overall uncertainty of 1.40%. Table 3 provides a list of the uncertainty percentages for each parameter.

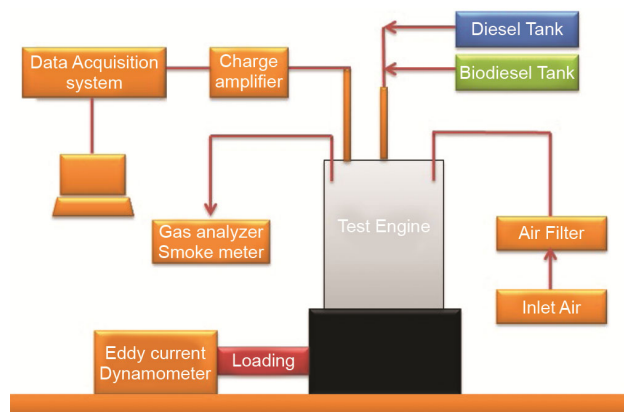


Fig. 3 — Schematic of the engine setup

Table 2 — Technical specification of the engine

Make and Model	Kirloskar
Model	TV1
Number of stroke	Four stroke
Number of cylinder	1
Ignition type	compression
Cooling type	Water
Compression ratio	17.5:1
Rated power	5.2 kW
Engine capacity	661 cc
Rated speed	1500 rpm
Bore	87.5 mm
Stroke	110 mm
Injection pressure	210 bar
Start of injection	23 °bTDC
Loading type	Eddy current dynamometer

Results and Discussion

Specifications of the test fuels

Physiochemical analysis

The physiochemical properties of the regular diesel, WCO, WCO biodiesel, and emulsified fuel were tested, compared, and listed in Table 4, and Table 5 represents elemental analysis of diesel, biodiesel, and biodiesel blends. The analysis of these

Table 3 — Accuracy and uncertainty of the equipment

Quantities	Accuracy	Uncertainty (%)
Engine speed (N)	± 10 rpm	± 0.1
Dynamometer load cell (W)	± 50 g	± 0.15
BP	-	± 0.9
BSFC	-	± 1.0
CO emission	± 0.01%	± 0.1
HC emission	± 15 ppm	± 0.25
NOx emission	±15 ppm	± 0.25
Smoke meter	± 1.0	± 0.1

Test fuel	Density kg/m ³	Viscosity cSt	Flash point °C	Cetane index -	HHV MJ/kg
Diesel	850	2.81	58	50.0	42.76
WCO	940	9.80	238	43.3	31.55
1-Hexanol	825	3.33	60	23.2	39.54
WCO biodiesel	900	3.98	90	55.2	36.81
D70-WCOB30	865	3.21	68	52.1	40.92
D60-WCOB30-W10	891	3.90	76	50.5	37.10
D50-WCOB30-W10-H10	874	3.62	71	49.0	36.85
D50-WCOB20-W10-H20	859	3.38	66	48.1	36.53
ASTM standard	D1298	D445	D92	D976	D240

Test fuel	Elements (wt%)				
	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
Diesel	86.6	13.0	0.04	0.35	-
WCO	68.5	8.9	0.06	0.01	22.53
WCO biodiesel	75.4	9.8	0.12	0.01	14.67
D70-WCOB30	83.2	12.0	0.06	0.24	4.50
ASTM Standard	D5373	D5373	D5373	by difference	D5373

parameters is important since they affect the performance behaviour of the engine. Compared to all types of blended fuels, regular diesel has a higher calorific value of 42.76 MJ/kg due to its higher carbon and hydrogen content. Compared to diesel, the density, viscosity, and flash point of the WCO are higher and recorded at 940 kg/m³, 9.80 cSt, and 238 °C respectively. The density and viscosity of the highly viscous raw oil were reduced to 900 kg/m³ and 3.98 cSt via the transesterification process. The table shows that adding 30% WCO biodiesel by volume to regular diesel changed the viscosity of the blended fuel to 3.21 cSt. The viscosity of fuel is significant for engine operation due to several reasons since it directly affects fuel atomization, injection, lubrication, and combustion efficiency. The value is further raised by emulsifying the blended fuel with a 10% water addition. The hydrodynamic attraction of the water particles in the fuel causes the coefficient of internal friction inside the emulsion, which increases the viscosity of the emulsified fuel³². The outcome of this analysis is also comparable with the previous literature^{33, 34}. Similar to viscosity, the density of the fuel also increased with the addition of water content in the fuel. However, the energy content of the emulsified fuel decreased compared to WCO biodiesel and D70-WCOB30. The increased oxygen molecules in fuel are consistent with this tendency.

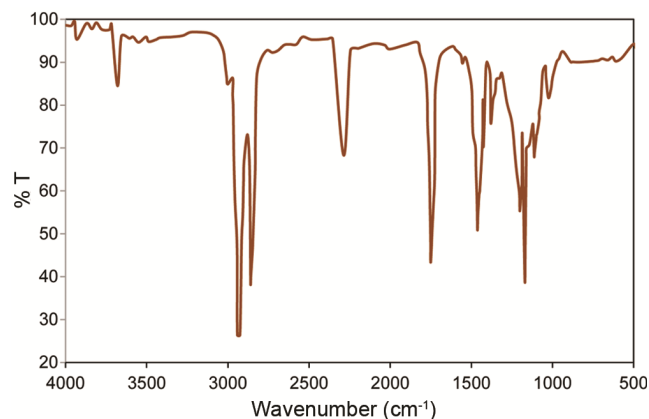


Fig. 4 — FTIR spectrum of WCO biodiesel

FTIR spectra of the WCO biodiesel

Fig. 4 shows the FTIR spectrum of WCO biodiesel, which examines the different functional groups present in the biodiesel. The spectra show several peaks related to fatty acid esters in the biodiesel. The presence of the O-H group in the biodiesel is identified by the peak that appears at 3679.5 cm⁻¹. The presence of an alkane group with a C-H stretch vibration is demonstrated by the peaks seen at 2920.43 and 2855.06 cm⁻¹. The appearance of C≡N stretch vibration at 2285.9 cm⁻¹ represents nitriles in the oil. The existence of a stretched carbonyl group is indicated by the appearance of the C=O bond type at 1752.33 cm⁻¹. At 1433.88, 1420.63, and 1372.19 cm⁻¹, the -C-H peaks indicate the presence of an alkane

group with bending vibration. The =C-O-C symmetric and asymmetric stretch vibration at 1200.95 cm^{-1} shows the existence of ethers in the oil. The existence of an alkane group with stretch vibration is indicated by the C-H band at 1193.95 , 1176.74 , and 1115.71 cm^{-1} . The presence of ester in the WCO biodiesel is indicated by the C-O band at 1015.30 cm^{-1} .

Performance analysis

IC engine performance analysis involves evaluating various operational parameters to optimize efficiency, reduce emissions, and enhance power output. This analysis encompasses a range of methodologies, including diagnostic tools and fuel performance evaluations, which collectively contribute to a comprehensive understanding of engine behavior under different operating conditions. In our study, the performance of the engine using different test fuels was evaluated under different load conditions.

Brake thermal efficiency

BTE of an engine is a measure of how efficiently an IC engine converts the chemical energy of the fuel into mechanical energy. In general, BTE of an engine is greatly affected by engine design, operational, and environmental factors. For each test fuel, the variations in BTE at five different engine loads, 20%, 40%, 60%, 80%, and 100%, are shown in Fig. 5. As shown in the figure, the BTE of the engine increases as load increases. The increased BTE with respect to engine load is due to reduced heat loss at higher load and an increase in BP. At lower and higher loads, the BTE of an engine operated with a biodiesel blend (D70-WCOB30) is lower compared to regular diesel. The lower BTE of the engine with biodiesel is due to

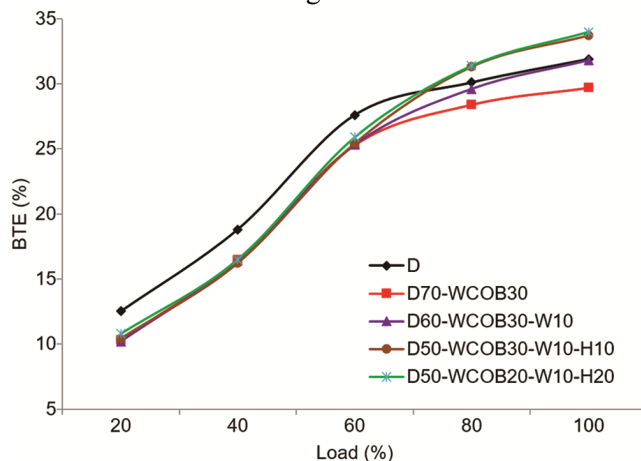


Fig. 5 — Performance behaviour of selected fuels under different engine loads

its inbound oxygen molecule. At 100% load, the BTE of the biodiesel blend engine is 6.9% lower compared to diesel fuel. The biodiesel has demonstrated reduced BTE due to its higher viscosity, which results in a poorer air-fuel mixture by generating larger fuel droplets during the fuel injection process³⁵. Diesel blended with biodiesel results in incomplete combustion because of its greater viscosity and poor volatility. The higher viscous fuel creates intermolecular friction and creates a non-uniform mixture³⁶. In comparison to regular diesel, engines with emulsified WCO biodiesel show significant improvements in BTE. Emulsified fuels can enhance engine operating characteristics by optimizing several interacting physical and chemical mechanisms³⁷. The existence of finely dispersed water droplets leads to the micro-explosion characteristics, where rapid evaporation of water molecules causes a secondary atomization process. These results can improve air-fuel mixing and a larger reactive surface area.

Additionally, the evaporated water molecules can absorb heat, which moderates peak in-cylinder temperatures and promotes controlled combustion and reduces knocking⁶⁸. Further, the process can reduce ignition delay and enhance flame propagation. At 100% load, the addition of 10% water with D70-WCOB30 showed higher performance, and its value is identical with regular diesel. Compared to higher loads, the impact of the water in D60-WCOB30-W10 on combustion efficiency is low at low loads. At rated load conditions, compared to D60-WCOB30, the BTE of the engine increased up to 7.07% with D60-WCOB30-W10. This is believed to be the result of a longer ignition delay with higher loads, which raises the premixed combustion proportion and accelerates the initial phases of combustion³⁹. The lower performance with lower load also relates to the higher latent heat of vaporization of water molecules. The efficiency is also increased with emulsified fuel by the micro-explosions that take place during the compression stroke, which increase the quantity and surface area of the fuel particles. Additionally, the increased fuel diffusion and improved air-fuel mixing carried on by the micro-explosions reduce the combustion duration⁴⁰. The BTE of the engines using emulsified biodiesel with higher alcohol shows considerable improvements compared to regular diesel. The D50-WCOB30-W10-H10 blend demonstrated a 5.6% improvement in BTE compared to diesel at 100% load conditions. In comparison to D60-WCOB30-W10, adding 1-hexanol improves

engine BTE under all engine loads. Compared to diesel fuel, utilizing D50-WCO230-W10-H20 for IC engines showed a 6.58% improved BTE. Compared to baseline fuels, 1-hexanol has a larger percentage of oxygen and encourages fuel burning; this extra oxygen boosts total combustion efficiency⁴¹. The result indicates that 1-hexanol with emulsified fuel effectively enhances engine performance. The BTE curve patterns for D50-WCOB30-W10-H10 and D50-WCO230-W10-H20 are nearly identical, indicating that injecting 20% 1-hexanol into the fuel did not significantly increase the engine's BTE.

Brake specific fuel consumption

The BSFC of an IC engine using various biodiesel blends varies significantly based on the type of biodiesel and its concentration. Fig. 6 displays the variations in BSFC with engine load for various test fuels. The BSFC is regarded as a significant phenomenon in determining an engine's ideal operating condition in relation to running costs. As the load increases, the BSFC of all blend ratios tends to decrease. This might be due to the fact that, as was mentioned in the previous subsection, complete combustion is brought on by a rise in the combustion chamber temperature as the load increases, which shortens the ignition delay. For all load conditions, a significant difference was noted in BSFC value when the engine was operated with diesel and biodiesel blends.

The higher consumption of fuel with biodiesel blend is due to lower energy value, higher viscosity, and poor spray characteristics⁴². At 100% load, the BSFC value of diesel and D70-WCOB30 is 0.27 kg/kW h and 0.31 kg/kW h, respectively, which is 14.8% more compared to diesel fuel. The BSFC of D70-WCOB30

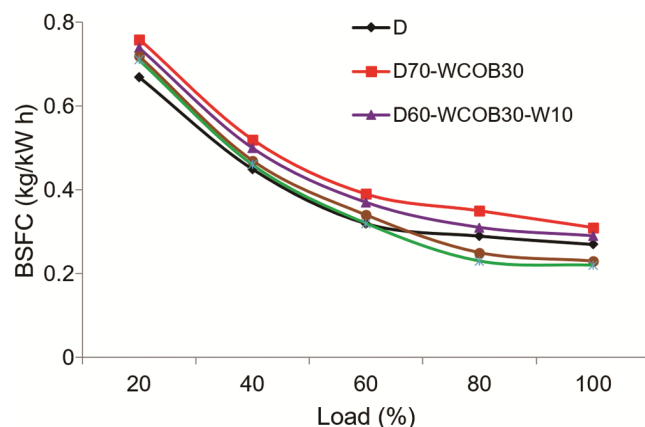


Fig. 6 — Fuel consumption of selected fuels under different engine loads

decreases when water is added. The addition of 10% water in a biodiesel blend has better micro-explosion behavior, which speeds up the combustion behaviour of the fuel⁴³. It also can be explained by another phenomenon: during combustion, water molecules in the diesel and biodiesel blends transform into superheated steam and generate more power⁴⁴. This outcome is consistent with many other literature that stated that engines running on a combination of biodiesel and water have lower BSFC^{45,46}. Fig. 6 validates the change of BSFC for 10% and 20% addition of 1-hexanol with emulsified fuel. The addition of 10% and 20% 1-hexanol to emulsified biodiesel fuel generally decreases the BSFC up to 0.23 kg/kW h and 0.22 kg/kW h, respectively. The addition of higher alcohol to engine fuel can reduce the viscosity and improve fuel injection behaviour leading to improved atomization. The increased volatility of the fuel also makes evaporation quicker with a better air-fuel mixing ratio.

Combustion analysis

In-cylinder pressure

Fig. 7 shows the differences in in-cylinder pressure for the diesel, D70-WCOB30, D60-WCOB30-W10, D50-WCOB30-W10-H10, and D50-WCOB20-W10-H20. From the figure, it can be noticed that the configurations of in-cylinder pressure for all the tested fuels are similar. Cylinder pressure data reveals how efficiently the engine is converting fuel into mechanical energy. These data aid in optimizing combustion behaviour and fuel delivery. The peak pressures for diesel, D70-WCOB30, D60-WCOB30-W10, D50-WCOB30-W10-H10, and D50-WCOB20-W10-H20 are 57.2 bar, 56.1 bar, 56.5 bar, 59.3 bar, and 59.5 bar, respectively. It is evident from this data that adding biodiesel to blends lowers the peak

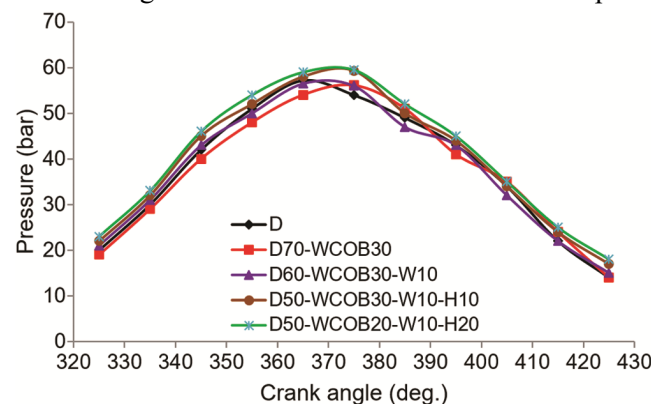


Fig. 7 — Cylinder pressure variation of the test fuels under maximum load

cylinder pressure. On the other hand, the combustion of the fuel consists of premixed and diffusion combustion phases. Since a large amount of heat is released closer to top dead centre, an average and well-controlled premixed phase increases thermal efficiency by improving the transformation of thermal energy into useful work. The premixed phase is followed by the diffusion combustion phase, which includes burning fuel as it is continually injected and combines with the surrounding air. This phase is slower and controlled mainly by the rate of fuel-air mixing.

The ignition delay duration and the spray pattern regulate the premixed combustion stage⁴⁷. The fuel's volatility and viscosity are therefore crucial for improving the air-fuel mixing rate and accelerating atomization. When water is added to blended fuel, the peak pressure is seen to rise noticeably because of its enhanced micro-explosion behaviour. The water molecule in D70-WCOB30 speeds up the combustion process⁴⁸. As a result, the combustion starts earlier, raising the peak pressure. This finding is consistent with numerous types of research that documented comparable pressure variations in diesel engines running on a blend of fuel, biodiesel, and water. In comparison to regular diesel, the emulsified biofuels with water content start burning later. The prolonged ignition delay caused the start of combustion to shift near the TDC due to their lower cetane number and higher viscosity. A larger percentage of the fuel burns in the premixed combustion phase since higher blended fuel can be vaporized and combined for a more thorough chemical process due to extended ignition delay. Jeong and Lee examined the impact of water proportion on combustion and found that, except for extended combustion duration, micro-explosion activities become more vital when water content is present in the fuel⁴⁹. When 10% 1-hexanol was added to the emulsified fuel, the peak cylinder pressure increased to 59.3 bar. But the addition of 20% higher alcohol showed a maximum in-cylinder pressure of 59.5 bar. The peak pressure for the blends was found to be greater as the percentage of hexanol in the blends rose to 20%. The increased volatility and decreased viscosity of hexanol, which allow for the mixing of a larger amount of fuel-air mixture in the premixed combustion stage during the ignition delay period, may be the cause of the increased pressure⁵⁰.

Heat release rate

The rate at which fuel's chemical energy is transformed into thermal energy during combustion is known as the HRR. The HRR is a crucial factor in engine design from an economic standpoint since it is directly related to fuel economy and operating costs. An optimized HRR confirms that combustion occurs close to the ideal crank angle, maximizing useful work output. HRR depends on the energy density of the fuel used for the analysis, combustion temperature, and other physiochemical properties of the fuel. Assuming an open system, HRR is derived from the first law of thermodynamics.

$$dQ_c = d_u + dQ_h \quad \dots(2)$$

Where,

$dQ_c \rightarrow$ heat release due to combustion of hydrocarbon fuel

$dQ_h \rightarrow$ heat transfer from combustion chamber to wall

$d_u \rightarrow$ internal energy

$w \rightarrow$ work output

$$\frac{dQ_c}{dt} = P \frac{dv}{dt} + mC_v \frac{dT}{dt} + \frac{dQ_h}{dt} \quad \dots(3)$$

$$\frac{dQ_c}{dt} = P \frac{dv}{dt} + mC_v \frac{d}{dt} \left[\frac{PV}{mR} \right] \quad \dots(4)$$

$$\frac{dQ_c}{dt} = P \frac{dv}{dt} + \frac{C_v}{R} \frac{d}{dt} \left[P \frac{dv}{dt} + V \frac{dp}{dt} \right] \quad \dots(5)$$

$$\frac{C_v}{R} = \frac{1}{\gamma - 1} \quad \dots(6)$$

Substitute the value of Eq. (5) in Eq. (6)

$$\frac{dQ_c}{dt} = \frac{\gamma}{\gamma - 1} P \frac{dv}{dt} + \frac{1}{\gamma - 1} V \frac{dp}{dt} \quad \dots(7)$$

The method of fuel burned in an engine is described by the heat release. The higher peak cylinder pressure is influenced by the HRR. Fig. 8 displays the HRR for diesel, D70-WCOB30, D60-WCOB30-W10, D50-WCOB30-W10-H10, and D50-WCOB20-W10-H20. The onset of vaporization during the ignition delay

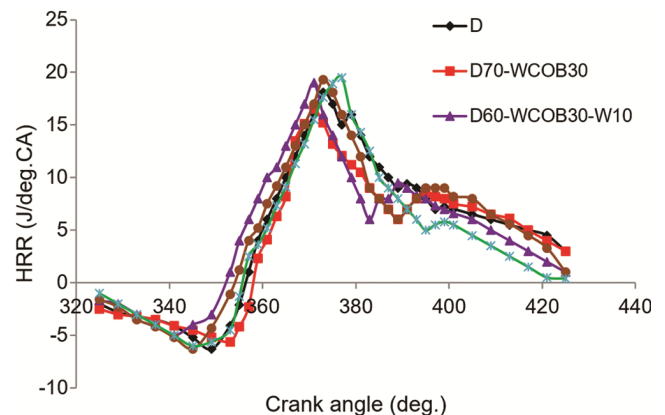


Fig. 8 — Variations in HRR of the test fuels under maximum load

caused a negative value of heat release during the first stage of combustion; however, once combustion began, the value changed to a positive one³⁵. Compared to blended fuel (D70-WCOB30), diesel may have a higher HRR because of its increased energy value. During burning, fuel with a higher energy value generates more heat. Adding biodiesel to pure diesel generally resulted in an earlier shift of combustion. It is also confirmed with the figure that with a 100% engine load, biodiesel blends begin to burn earlier than diesel fuel. This is most likely due to increased bulk modulus and viscosity. When 30% WCO biodiesel was added to ordinary diesel fuel, the peak HRR seen in blended fuel was dropped by about 8.9%. When 10% water was added to the chamber during emulsification, the peak HRR increased noticeably. This is because water particles have a higher surface area to volume ratio, which leads to better combustion and shorter delay time. Additionally, water in the blend causes vigorous micro-explosions and better air and fuel mixing, which speeds up combustion and releases more heat⁵¹. Inclusion of alcohol had dramatically raised the HRR, which may be ascribed to enhanced blend compatibility along with improved atomization qualities due to alcohol addition. This is in line with the findings of Jayapal and Radhakrishnan⁵² and Ramesh *et al.*⁵³, who found that the addition of propanol and hexanol increased HRR due to improved fuel atomization properties. It should be mentioned that high-temperature running conditions were caused by superior fuel atomization qualities of alcohol and comparatively larger oxygen concentration than other tested fuels. The work by Nour *et al.* showed a similar pattern, with greater HRR profiles⁵⁴.

Emission analysis

CO emission

Fuel composition, combustion conditions, and engine characteristics are some of the major elements that affect the CO emissions from biodiesel-powered engines. Emissions of CO have detrimental effects on both the environment and human health. It is a colourless and odourless poisonous gas that lowers blood's ability to carry oxygen, causing several health issues. Additionally, it deteriorates the quality of the air and helps create secondary pollutants. Despite not being a direct greenhouse gas, CO indirectly contributes to global warming by increasing the atmospheric lifetime of methane. The primary cause of the CO emissions is incomplete combustion of the fuels. In comparison to regular diesel, the biodiesel-

diesel blends in the engine always produce lower CO at all engine parameters due to higher combustion efficiency and temperature⁵⁵. More CO was reduced when the load of the engine was increased because it created an atmosphere with sufficient turbulence and high temperature. There are two methods for producing CO in the engine cylinder, namely via too rich or too lean air-fuel mixture. When the mixture is too lean, the flame cannot be continued, and CO is formed as an outcome of fuel pyrolysis with midway oxidation. For too rich a mixture, the air-fuel mixture is insufficient⁵⁰. The inability of O₂ to completely oxidize the fuel's CO content is the main reason for the formation of CO in rich air-fuel mixtures. The differences in CO emission between regular diesel and other blended fuels according to different engine loads are displayed in Fig. 9.

Compared to diesel, D70-WCOB30 had lower CO emissions at all operating conditions due to its complete combustion. The increased amount of O₂ in the blended fuel is the main reason for reduced CO. The CO emission for diesel and D70-WCOB30 under full load conditions is 0.07% and 0.06% volume. Additionally, it was found that emulsified fuel D60-WCOB30-W10 produced lower CO emissions than the corresponding values of regular diesel fuel at higher engine loads. However, emulsions produced more CO than diesel at lower engine loads. It was believed that increased CO emissions resulted from inefficient degradation of the suspended water molecules caused by the lower cylinder temperature at lower loads. The higher CO emissions are consistent with findings of rapeseed biodiesel-diesel-water emulsion fuels in the literature⁵⁶. At higher engine loads, the CO emission varies to 0.05% and 0.04%, respectively, when 10% and 20% higher alcohol is blended with emulsified biodiesel blends. Adding

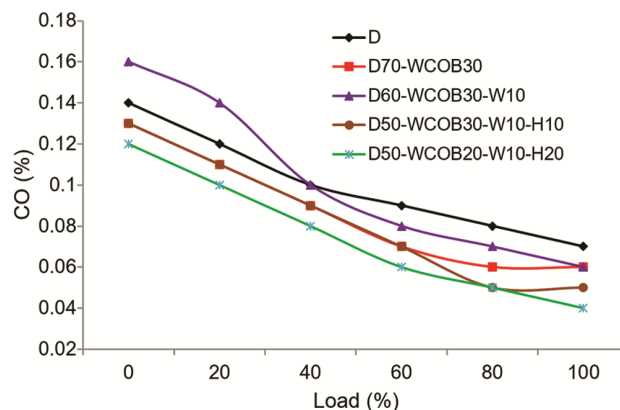


Fig. 9 — Change in CO emissions with engine load

alcohol to the fuel caused a considerable reduction in CO emissions, since alcohol is known to operate as an oxygen transporter, providing adequate oxygen during burning and facilitating the conversion of CO to CO₂^(57, 58). This outcome is also in line with the superior physical characteristics of the 1-hexanol, which enhanced the blend's mixing capabilities. It can be concluded that the outcomes of this study are consistent with the research done by Ashok *et al.* where they found lower CO emission by adding decanol and hexanol with *Calophyl luminophyllum* biodiesel/diesel blends⁵⁹.

HC emission

The main factor of HC emissions in diesel engines is fuel that becomes trapped in the chamber's crevice volumes. Other than this, inadequate fuel dissipation, a rich or lean air-fuel mix, and liquid wall films for excessive spray impingement are some other factors forming HC during combustion. Fig. 10 illustrates the variation in HC emissions in relation to engine loads. Compared to diesel fuel, the HC emissions for D70-WCOB30 dropped considerably. In comparison to diesel, the results indicated an average 14.3% decrease in HC emissions for D70-WCOB30. Due to a lack of oxygen in regular diesel, the production of HC increases with increasing load. On the other hand, the oxygenated character of the biodiesel demonstrated a significant decrease in HC emissions at all loading conditions³⁵.

At peak load conditions, improved air-fuel mixing and atomization are encouraged by adding optimistic water quality to the fuel. When compared to regular diesel at a peak load of 100%, the HC emission is thus reduced by 14.3% when using D60-WCOB30-W10 emulsion fuel. Increasing the proportion of 1-hexanol in emulsified fuel significantly reduced the generation of HC emissions, as seen in Fig. 10. At the rated speed and load, the average HC emission levels for D50-

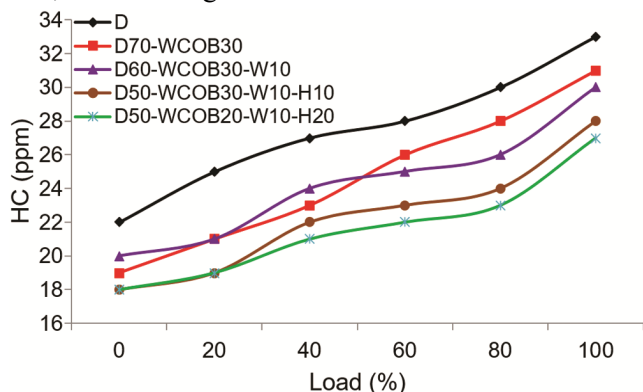


Fig. 10 — Change in HC emissions with engine load

WCOB20-W10-H20 decreased by a maximum of 42.9% when compared to diesel. This outcome was ascribed to the fact that more O₂ molecules were involved in the combustion process, which led to a more thorough burning of the fuel and consequently reduced HC emissions⁵⁰. Vellaiyan *et al.* also confirmed the aforementioned point in their trials, which used 10% 1-pentanol with a cottonseed oil biodiesel-water emulsion and showed a 4–14.3% decrease in HC emission⁶⁰.

NOx emission

The primary factors contributing to the rise in NOx concentration are the increased combustion temperature, higher oxygen availability, and spray properties. The interaction of nitrogen dioxide and nitric oxide produces NOx during combustion of the fuel. In general, NOx is more sensitive to in-cylinder temperature; it was discovered that the formation of NOx boosted drastically for all tested fuels as the load increased due to improved fuel-to-air ratio and higher gas temperature⁶¹. Fig. 11 illustrates the variation in NOx emissions in relation to engine loads. The NOx emission of regular diesel and D70-WCOB30 at 100% load condition is 585 ppm and 622 ppm, respectively. In comparison to regular diesel, the blended fuel D70-WCOB30 released NOx at concentrations that were roughly 6.32% higher at rated load. This was ascribed to the higher cetane number of the WCO biodiesel in the blended fuel, which led to greater combustion temperatures and, when combined with the higher oxygen content, increased the generation of NOx³⁴. There is a greater possibility of an interaction with nitrogen to produce NOx due to the larger oxygen level. It has also been determined that increased NOx emissions are correlated with the longer chain length and higher

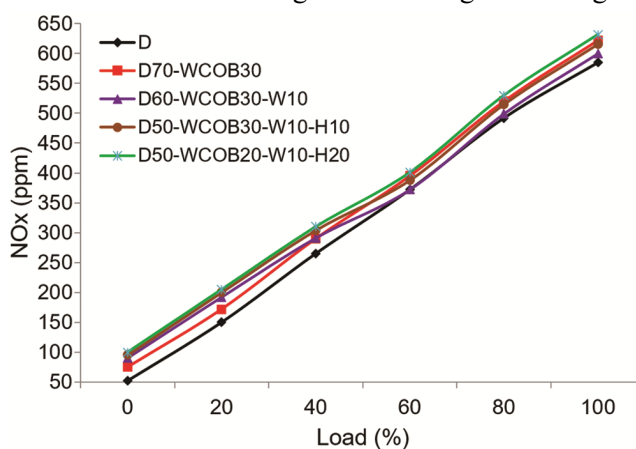


Fig. 11 — Change in NOx emissions with engine load

quantities of unsaturated fatty acids present in the biodiesel⁶².

The generation of NO_x is also favoured by adiabatic flame temperatures, which increase with the length of the biodiesel carbon chain. The graph depicting the D60-WCOB30-W10 tested fuel demonstrates a significant reduction in NO_x emissions across all operating conditions. This reduction is attributed to the presence of finely dispersed water particles within the emulsion, which lead to a phenomenon known as the heat sink effect. Through this effect, the water absorbs part of the emulsion's heat energy, thereby lowering the adiabatic flame temperature and subsequently limiting NO_x formation⁶³. The heat generated inside the engine cylinder is dissipated through water evaporation occurring during micro-explosion events, effectively suppressing the formation of NO_x emissions. Based on Zeldovich's mechanism, the heat absorption by water droplets is likely to hinder the chemical reaction between N₂ and O₂, thereby preventing the formation of NO_x. When compared to diesel, D60-WCOB30-W10 decreased NO_x emissions by up to 9.1%. The addition of 1-hexanol to emulsified fuel led to an increase in NO_x formation. This rise became more noticeable as the alcohol proportion increased and the cetane number decreased. The NO_x emission of D50-WCOB30-W10-H10 and D50-WCOB20-W10-H20 at 100% load condition is 616 ppm and 622 ppm, respectively. The most plausible explanation for the increased NO production was the higher oxygen content in the blended fuel. The lower viscosity and high volatility of the alcohol in the blend enhance the controlled combustion, which enhances higher NO_x production. The injection time for this fuel during the ignition delay period tends to be longer due to its lower cetane number compared to regular diesel. As a result, more fuel is burned during the premixed combustion phase, leading to increased temperature and pressure during the diffusion combustion phase. Moreover, the rise in in-cylinder temperature and pressure with increasing engine load leads to higher NO_x emissions⁵⁰.

Other alcohols, like butanol or pentanol, can be added in controlled amounts to reduce NO_x emissions while also moderating combustion temperature and preserving good atomization and combustion stability. In order to encourage uniform burning and shift peak heat release away from top dead centre, a slight delay in injection timing and an increase in injection

pressure help reduce concentrated high-temperature zones that cause NO_x generation.

Smoke emission

Fig. 12 displays the variance in smoke opacity of test fuels under various load circumstances. The main sources of smoke emissions are the incomplete combustion of hydrocarbons and the limited reactivity of carbon atoms. The quality of the air-fuel mixture, volatility, and viscosity also contribute to the smoke generation. Due to the lean mixture, all fuels generate lower smoke emissions at reduced engine load. However, as load increases, more fuel is injected, leading to a richer mixture that causes incomplete combustion and, consequently, higher smoke production⁴². In some cases, blending biodiesel with regular diesel increased the formation of smoke^{35, 64}. But in this study, smoke emissions from D70-WCOB30 are lower than those from regular diesel. The in-built oxygen present in biodiesel promotes more efficient combustion, resulting in reduced smoke emissions. The reduced carbon content in biodiesel fuel is also a contributing factor to its lower smoke emissions. At peak load conditions, D70-WCOB30 shows a 12.5% decrease in smoke opacity compared to diesel. Smoke opacity is further decreased by adding 10% water with a biodiesel blend. The improved air-fuel mixing and enhanced atomization, resulting from the micro-explosion phenomenon of water particles in D60-WCOB30-W10 emulsion fuel, lead to more complete combustion of hydrocarbons and carbon particles, thereby reducing smoke opacity⁶⁵.

Adding 1-hexanol with emulsified fuel also helps to reduce the smoke emission from the engine due to its higher volatility and ability to promote more complete combustion. The higher alcohols naturally

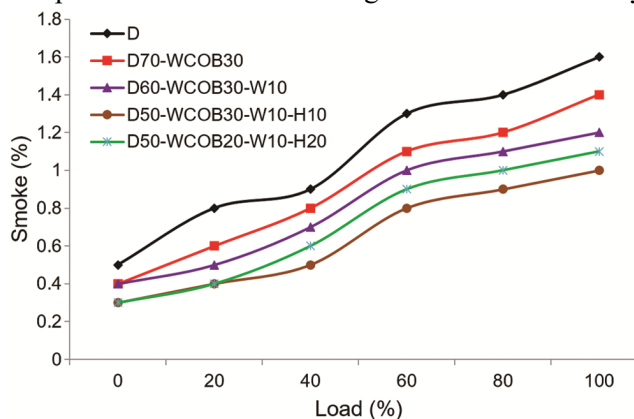


Fig. 12 — Change in smoke emissions with engine load

Table 6 — Comparative summary of the test results

Characteristic		Order (lower to higher)
Performance	BTE	D70-WCOB30 < D60-WCOB30-W10 < D < D50-WCOB30-W10-H10 < D50-WCOB20-W10-H20
	BSFC	D50-WCOB20-W10-H20 < D50-WCOB30-W10-H10 < D < D60-WCOB30-W10 < D70-WCOB30
Combustion	Pressure	D70-WCOB30 < D60-WCOB30-W10 < D < D50-WCOB30-W10-H10 < D50-WCOB20-W10-H20
	HRR	D70-WCOB30 < D < D60-WCOB30-W10 < D50-WCOB30-W10-H10 < D50-WCOB20-W10-H20
Emission	CO	D50-WCOB20-W10-H20 < D50-WCOB30-W10-H10 < D60-WCOB30-W10 < D70-WCOB30 < D
	HC	D50-WCOB20-W10-H20 < D50-WCOB30-W10-H10 < D60-WCOB30-W10 < D70-WCOB30 < D
	NOx	D < D60-WCOB30-W10 < D50-WCOB30-W10-H10 < D70-WCOB30 < D50-WCOB20-W10-H20
	Smoke	D50-WCOB30-W10-H10 < D50-WCOB20-W10-H20 < D60-WCOB30-W10 < D70-WCOB30 < D

increase oxygen content and reduce the carbon-to-hydrogen ratio, which aids in improved fuel mixing. When 1-hexanol and water emulsion blend together, the amount of smoke in the exhaust gas is decreased. Comparing the fuel blends examined in this work, D50-WCOB30-W10-H10 has the lowest smoke emissions. The smoke emission from the engine for D50-WCOB30-W10-H10 and D50-WCOB20-W10-H20 under 100% load conditions is 1.0% and 1.1%, respectively, and compared to regular diesel, D50-WCOB30-W10-H10 emits 37.5% less smoke. A progressive increase in smoke emissions is observed when the 1-hexanol content in the fuel is raised from 10% to 20%. This occurs because the higher volatility and lower energy value of the fuel lead to less effective fuel dispersion within the combustion chamber⁶⁶. Table 6 provides a comparison based on the average combustion and emission properties of all evaluated fuels at higher load conditions.

Limitations and social benefit of the study

The study on the performance of an IC engine has some limitations. The experimental results are typically conducted on a single-cylinder, diesel engine, which may not fully represent the performance of multi-cylinder engines under real driving circumstances. The stability of the fuel over long periods is not fully evaluated, and the phase separation may impact repeatability and practical applicability. The analysis is limited to particular blend ratios, engine loads, and injection parameters, without optimizing other operating parameters. On the other side, cold-start behaviour, long-term running durability, fouling, and lubricating oil performance are also not analyzed. Furthermore, only measured emissions are considered, while unregulated emissions such as aldehydes and nanoparticle concentrations are neglected. These limitations highlight potential research gaps and provide opportunities for researchers to extend the investigation. The performance analysis of these blended biodiesels in an IC engine

offers significant social benefits. Utilization of WCO supports effective waste management and decreases environmental pollution instigated by improper disposal. The use of locally available feedstocks decreases dependence on fossil fuels, contributing to national energy security and rural economic development. Reduced emissions, such as CO and HC, lead to better air quality. The adoption of cleaner fuels supports sustainable development goals and fosters social awareness toward environmentally responsible energy practices.

Conclusion

The substantial benefits of adding higher alcohol blends to water-emulsified WCO biodiesel for use in CI engines are demonstrated by this study. A two-stage transesterification process successfully transformed waste cooking oil used for frying purposes into biodiesel, which showed desirable elemental and chemical characteristics. The results of a comprehensive analysis of engine combustion, performance, and emission characteristics using WCO biodiesel, its 10% water emulsions, and alcohol blends with 10% and 20% 1-hexanol are compared to those of conventional diesel fuel. The combustion analysis showed that a 4.0% increase in peak pressure was observed when 30% WCO biodiesel was blended with diesel, emulsified with 10% water, and enhanced with 20% 1-hexanol. With the addition of 10% water in 30% biodiesel blended fuel, BSFC increased by 14.8%, but when 10% and 20% alcohol additions decreased the value by 14.8% and 18.5%, respectively. Additionally, the water-emulsified blend decreased BTE by 0.31%, and the addition of 10% and 20% alcohol increased it by an additional 5.6% and 6.6%, respectively. Increasing the amount of alcohol in the emulsified biodiesel blend reduced CO and HC emissions when compared to diesel fuel; nevertheless, a larger percentage of alcohol in the fuel was shown to increase smoke emissions. With the addition of 20%

1-hexanol, the emissions of CO, HC, and smoke were greatly decreased by 42.8%, 18.2%, and 31.3%, respectively. Compared to the biodiesel blend, adding 10% water significantly reduced NO_x emissions; however, the inclusion of higher alcohols led to an increase in NO_x levels. From these results, it can be concluded that blending higher alcohols like 1-hexanol with water-emulsified biodiesel derived from WCO significantly lowers hazardous emissions while simultaneously increasing combustion efficiency. This method has the potential to be a practical way to decrease fossil fuel reliance, this approach also helps to improve environmental sustainability and energy security.

Conflict of Interest

The authors declare no conflict of interest.

References

- Chitragar P R, Shivaprasad K V, Ichchangi M, Ravi R, Yadav M S & Kumar G N, Influence of water-methanol injection and turbocharging on the performance of a hydrogen-fueled spark ignition engine, *Environ Qual Manag*, 33 (2024) 543.
- Saravanakumar K, Robinson Y, Madhu P & Manoj M, Selection of oil and best bio-diesel blend based on performance and emission characteristics of IC engine: An integrated CRITIC-TOPSIS approach, *J Sci Ind Res*, 81 (2022) 1342.
- Kumar P M, Uvaraja V C & Madhu P, Effect of Al₂O₃/PSZ and Al₂O₃/YSZ ceramic coating in CI engine fueled with ternary blends of castor seed oil and jatropha oil biodiesel dosed with diesel, *J Ceram Process Res*, 23 (2022) 647.
- Thirumalaikumaran A, Senthilkumar G & Dhanalakshmi C S, Experimental investigation on thermophysical and tribological characteristics of conventional and biolubricating oil blended with nanoparticles, *Indian J Chem Technol*, 32 (2025) 441.
- Anand K, Bhardwaj A, Vinod D, Ashwinbhai P K, John K V & Dhanalakshmi C S, Utilization of triple blend biodiesel towards performance and emission characteristics of diesel engine, *AIP Conf Proc*, 2800 (2023) 020141.
- Chen Y, Zhang J, Zhang Z, Zhong W, Zhao Z & Hu J, Utilization of renewable biodiesel blends with different proportions for the improvements of performance and emission characteristics of a diesel engine, *Heliyon*, 9 (2023) e19196.
- Gebremariam S N, Biodiesel as a transport fuel, advantages and disadvantages, *Biofuel Bioprod Biorefin*, 17 (2023) 1445.
- Elango M, Dhanalakshmi C S, Madhu P & Muni T V, Improving the suitability of triple blend biodiesel in a low heat rejection diesel engine with the addition of nanoparticle through performance and emission characteristics analysis, *Indian J Chem Technol*, 32 (2025) 211.
- Raj R S, Madhu P, Dhanalakshmi C S & Prakash M A, Application of CuO nanoparticles on performance and emission characteristics of ternary blends of diesel, waste cooking oil and pumpkin seed oil biodiesel in an IC engine, *Indian J Chem Technol*, 32 (2025) 33.
- <https://earthjournalism.net/stories/used-cooking-oil-in-india-diverted-to-food-chain-public-health-and-biodiesel-sectors-suffer>
- Saputro E A, Saputro W & Saputro B W, An investigation of engine performance and exhaust gas emissions under load variations using biodiesel fuel from waste cooking oil and B30 blend, *Evergreen*, 10 (2023) 2255.
- Solangi F A, Memon L A, Samo S R, Luhur M R, Bhutto A A & Ansari A M, Investigation of performance and emission characteristics of CI engine using diesel and waste cooking oil blends, *Energies*, 15 (2022) 7211.
- Nguyen T V, Nguyen K D, Ho N X & Nguyen V D, Engine performance and combustion characteristics of a direct injection compression ignition engine fueled waste cooking oil synthetic diesel, *Int J Coal Sci Technol*, 7 (2020) 560.
- Jagotra A, Singh D K, Sandhu S S, Kango S & Bhadauria S S, Experimental investigation on performance and emission characteristics of single cylinder CI engine using waste cooking oil (WCO) with diethyl ether (DEE), *J Phys Conf Ser*, 1240 (2019) 012074.
- Kumar B R & Saravanan S, Use of higher alcohol biofuels in diesel engines: A review, *Renew Sustain Energy Rev*, 60 (2016) 84.
- Karabektas M & Hosoz M, Performance and emission characteristics of a diesel engine using isobutanol-diesel fuel blends, *Renew Energy*, 34 (2009) 1554.
- Ozsezen A N, Turkcan A, Sayin C & Canakci M, Comparison of performance and combustion parameters in a heavy-duty diesel engine fueled with iso-butanol/diesel fuel blends, *Energy Explor Exploit*, 29 (2011) 525.
- Koivisto E, Ladommatos N & Gold M, Systematic study of the effect of the hydroxyl functional group in alcohol molecules on compression ignition and exhaust gas emissions, *Fuel*, 153 (2015) 650.
- Devarajan Y, Munuswamy D B, Mahalingam A & Nagappan B, Performance, combustion, and emission analysis of neat palm oil biodiesel and higher alcohol blends in a diesel engine, *Energy Fuels*, 31 (2017) 13796.
- Harikrishna A & Reddy B C M, Effect of diesel-B20-pentanol and diesel-B20-butanol blends on diesel engine performance, emission, and combustion characteristics, *J Mech*, 40 (2024) 586.
- Reddy S R & Sarangi S K, Optimization of biodiesel/2-propanol/1-hexanol blends based on diesel engine performance using combined mixture-process design, *Biofuels*, 14 (2023) 835.
- Mickevicius T, Labeckas G & Slavinskas S, Experimental investigation of biodiesel-n-butanol fuel blends on performance and emissions in a diesel engine, *Combust Engines*, 188 (2022) 90.
- Yaser H S, Abdul Wahhab H A & Dhahad H A, Influence of water-in-fuel (diesel and biodiesel) emulsions on the performance and emission characteristics of a single-cylinder diesel engine, *Adv Mater Sci Eng*, (2022) 71.
- Vellaiyan S, Subbiah A & Chockalingam P, Combustion, performance, and emission analysis of diesel engine fueled with water-biodiesel emulsion fuel and nanoadditive, *Environ Sci Pollut Res*, 25 (2018) 33478.

- 25 Prakash R, Singh R K & Murugan S, Experimental studies on combustion, performance and emission characteristics of diesel engine using different biodiesel bio-oil emulsions, *J Energy Inst*, 88 (2015) 64.
- 26 Kannan T K & Marappan R, Study of performance and emission characteristics of diesel engine fueled with diethyl ether blended *Thevetiaperuviana* biodiesel emulsion, *J Energy Inst*, 85 (2012) 183.
- 27 Sharma Y C & Singh B, Development of biodiesel from karanja, a tree found in rural India, *Fuel*, 87 (2008) 1740.
- 28 Charoenchaitrakool M & Thienmethangkoon J, Statistical optimization for biodiesel production from waste frying oil through two-step catalyzed process, *Fuel Process Technol*, 92 (2011) 112.
- 29 Qi D H, Chen H, Matthews R D & Bian Y Z, Combustion and emission characteristics of ethanol-biodiesel-water micro-emulsions used in a direct injection compression ignition engine, *Fuel*, 89 (2010) 958.
- 30 Vellaiyan S & Amirthagadeswaran K S, Emission characteristics of water-emulsified diesel fuel at optimized engine operating condition, *Pet Sci Technol*, 35 (2017) 1355.
- 31 Raguraman D, Kumar A, Yadav S P R, Patil P Y, Isaac J S, Dhanalakshmi C S, Madhu P & Lalvani J I J R, Performance and emission characteristics of pyrolysis oil obtained from neem de-oiled cake and waste polystyrene in a compression ignition engine, *Adv Mater Sci Eng*, 2021 (2021) 3728852.
- 32 Attia A M & Kulchitskiy A R, Influence of the structure of water-in-fuel emulsion on diesel engine performance, *Fuel*, 116 (2014) 703.
- 33 Alahmer A, Influence of using emulsified diesel fuel on the performance and pollutants emitted from diesel engine, *Energy Convers Manag*, 73 (2013) 361.
- 34 Maawa W N, Mamat R, Najafi G & Goey L P H D, Performance, combustion, and emission characteristics of a CI engine fueled with emulsified diesel-biodiesel blends at different water contents, *Fuel*, 267 (2020) 117265.
- 35 Perumal V & Ilangkumaran M, Experimental analysis of engine performance, combustion and emission using *Pongamia* biodiesel as fuel in CI engine, *Energy*, 129 (2017) 228.
- 36 Panneerselvam N, Ramesh M, Murugesan A, Vijayakumar C, Subramaniam D & Kumaravel A, Effect on direct injection naturally aspirated diesel engine characteristics fuelled by pine oil, *Ceiba pentandra* methyl ester compared with diesel, *Transp Res Part D Transp Environ*, 48 (2016) 225.
- 37 Parthasarathi R, Gowri S & Saravanan C G, Effects of ethanol-diesel emulsions on the performance, combustion and emission characteristics of DI diesel engine, *Am J Appl Sci*, 11 (2014) 592.
- 38 Wang Z, Shi S, Huang S, Tang J, Du T, Cheng X & Chen J Y, Effects of water content on evaporation and combustion characteristics of water emulsified diesel spray, *Appl Energy*, 226 (2018) 397.
- 39 Baskar P & Kumar A S, Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air, *Alex Eng J*, 56 (2017) 137.
- 40 Antonov D V, Fedorenko R M & Strizhak P A, Micro-explosion phenomenon: conditions and benefits, *Energies*, 15 (2022) 7670.
- 41 Konjević L, Racar M, Ilinčić P & Faraguna F, A comprehensive study on application properties of diesel blends with propanol, butanol, isobutanol, pentanol, hexanol, octanol and dodecanol, *Energy*, 262 (2023) 125430.
- 42 Radhakrishnan S, Munuswamy D B, Devarajan Y & Mahalingam A, Performance, emission and combustion study on neat biodiesel and water blends fuelled research diesel engine, *Heat Mass Transfer*, 55 (2019) 1229.
- 43 Rathinam S, Baby S J A & Devarajan Y, Influence of water on exhaust emissions on unmodified diesel engine propelled with biodiesel, *Energy Sources Part A*, 40 (2018) 2511.
- 44 Dhas A A G, Devarajan Y & Nagappan B, Analysis of emission reduction in ethyne-biodiesel-aspirated diesel engine, *Int J Green Energy*, 15 (2018) 436.
- 45 Yogish H, Chandarshekar K & Kumar M R P, A study of performance and emission characteristics of computerized CI engine with composite biodiesel blends as fuel at various injection pressures, *Heat Mass Transf*, 49 (2013) 1345.
- 46 Senthil R, Silambarasan R & Pranesh G, Antioxidant (α -tocopherol acetate) effect on oxidation stability and NO_x emission reduction in methyl ester of Annona oil operated diesel engine, *Heat Mass Transf*, 53 (2017) 1797.
- 47 Buyukkaya E, Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics, *Fuel*, 89 (2010) 3099.
- 48 Ramanan M V & Yuvarajan D, Performance study of preheated mustard oil methyl ester on naturally aspirated CI engine, *Appl Mech Mater*, 787 (2015) 761.
- 49 Jeong I C & Lee K H, Auto-ignition and micro-explosion behaviors of droplet arrays of water-in-fuel emulsion, *Int J Automot Technol*, 9 (2008) 735.
- 50 Imdadul H K, Masjuki H H, Kalam M A, Zulkifli N W M, Alabdulkarem A, Rashed M M, Teoh Y H & How H G, Higher alcohol-biodiesel-diesel blends: An approach for improving the performance, emission, and combustion of a light-duty diesel engine, *Energy Convers Manag*, 111 (2016) 174.
- 51 Han Y, Tian Z, Xu J, Liang Q, Dai Z & Wang F, Study on the micro-explosion mechanism and influencing factors of oil water mixed fuel, *Energy*, 313 (2024) 133784.
- 52 Jayapal M & Radhakrishnan K G, A comparative assessment on the effect of 1-propanol and 1-hexanol as oxygenated additive with diesel/biodiesel blends on single cylinder diesel engine characteristics, *Energy Environ*, 33 (2022) 85.
- 53 Ramesh A, Ashok B, Nanthagopal K, Pathy M R, Tambare A, Mali P, Phuke P, Patil S & Subbarao R, Influence of hexanol as additive with *Calophyllum Inophyllum* biodiesel for CI engine applications, *Fuel*, 249 (2019) 472.
- 54 Nour M, Attia A M & Nada S A, Combustion, performance and emission analysis of diesel engine fuelled by higher alcohols (butanol, octanol and heptanol)/diesel blends, *Energy Convers Manag*, 185 (2019) 313.
- 55 Livingston T S, Madhu P, Dhanalakshmi C S & Kumar R V, An experimental investigation on performance, emission and combustion characteristics of IC engine using liquid fuel produced through catalytic co-pyrolysis of pressed oil cake and mixed plastics with the addition of nanoparticles, *Fuel*, 379 (2025) 133092.
- 56 Hossain A K, Refahtalab P, Omran A, Smith D I & Davies P A, An experimental study on performance and emission characteristics of an IDI diesel engine operating

- with neat oil-diesel blend emulsion, *Renew Energy*, 146 (2020) 1041.
- 57 Nemitallah M A, Abdelhafez A A, Ali A, Mansir I & Habib M A, Frontiers in combustion techniques and burner designs for emissions control and CO₂ capture: A review, *Int J Energy Res*, 43 (2019) 7790.
- 58 Tan Y, Douglas M A & Thambimuthu K V, CO₂ capture using oxygen enhanced combustion strategies for natural gas power plants, *Fuel*, 81 (2002) 1007.
- 59 Ashok B, Nanthagopal K, Darla S, Chyuan O H, Ramesh A, Jacob A, Sahil G, Thiyagarajan S & Geo V E, Comparative assessment of hexanol and decanol as oxygenated additives with *Calophyllum Inophyllum* biodiesel, *Energy*, 173 (2019) 494.
- 60 Vellaiyan S, Experimental study on energy and environmental impacts of alcohol-blended water emulsified cottonseed oil biodiesel in diesel engines, *Results Eng*, 24 (2024) 102873.
- 61 Mehanathan S, Madhu P, Dhanalakshmi C S & Vijayakumar R, Synergistic recovery of renewable hydrocarbon resources via co-pyrolysis of non-edible linseed and waste polypropylene: A study on influence of plastic on oil production and their utilization as a fuel for IC engine, *J Energy Inst*, 118 (2025) 101905.
- 62 Ghazali W N M W, Mamat R, Masjuki H H & Najafi G, Effects of biodiesel from different feedstocks on engine performance and emissions: A review, *Renew Sustain Energy Rev*, 51 (2015) 585.
- 63 Pourhoseini S H & Esmaeeli R, Effect of nanosilver/water-in-kerosene emulsion on NO_x reduction and enhancement of thermal characteristics of a liquid fuel burner, *Energy Fuels*, 31 (2017) 14288.
- 64 Elsanusi O A, Roy M M & Sidhu M S, Experimental investigation on a diesel engine fueled by diesel-biodiesel blends and their emulsions at various engine operating conditions, *Appl Energy*, 203 (2017) 582.
- 65 Ithnin A M, Noge H, Kadir H A & Jazair W, An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study, *J Energy Inst*, 87 (2014) 273.
- 66 Dinesha P, Kumar S & Rosen M A, Combined effects of water emulsion and diethyl ether additive on combustion performance and emissions of a compression ignition engine using biodiesel blends, *Energy*, 179 (2019) 928.