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Effect of Diethyl Ether on the Performance and Emission Characteristics of a Diesel Engine Fueled with a Light Fraction of Waste Cooking Oil

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Abstract: In this study, a diesel engine was used to operate with blends of light fraction waste cooking oil (LFWCO) with diethyl ether (DEE). DEE was blended as an additive in the 5% to 20% ratio in steps of 5% each. The test indicates that LFWCO+15-DEE produced optimum results regarding performance and emission. The BSFC for LFWCO+15-DEE was found to be higher by about 28.9%, and the BTE was lower by about 7.6%, in contrast to diesel, at 100% operating load, respectively. For LFWCO+15-DEE the EGT was lower by about 11.9%, in contrast to neat diesel, at 100% operating load. The various emissions such as carbon monoxide (CO), nitrous oxide (NO), and smoke opacity for LFWCO+15-DEE were found to be lower by about 32.9%, 25%, and 29.4%, but the NO release was more than other blends and it was about 36%, in contrast to diesel at 100% operating load, respectively.

Keywords: light fraction waste cooking oil (LFWCO); diethyl ether (DEE); diesel engine; performance characteristics; emission rate

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1. Introduction

In recent decades, the search for alternate fuel resources has become more essential due to the diminution of fossil-based energy resources. Since the availability of petroleum-based fuel reservoirs would not be enough to meet growing fuel demands [1]. The search for substitute fuels not only includes the solution for the shortage of fossil fuels, but also provides a solution that will reduce the greenhouse gas emission from the combustion process. Among many alternative resources, biomass-based resources are available in plenty at a very low price. All types of biomass-based waste can be transformed into valuable energy by thermos-chemical, biological, and chemical conversion methods [2–6]. The thermochemical method is considered to be an efficient method to yield high quantities and quality of fuel from both solid and liquid-based biomass wastes [7–13]. It is believed that liquid biomass waste oil can yield higher quality and quantity of biofuel during the thermochemical conversion process due to its high volatility and thermal degradation at low temperatures [14–17]. Liquid biomass-based waste cooking oil (WCO) is plenty available In food processing industries, the domestic sector, and commercial eateries. This WCO can be a potential feedstock for the extraction of light fraction waste cooking oil (LFWCO) economically followed by pyrolysis and distillation. LFWCO has a low density and auto-ignition temperature in comparison to WCO and can be used in a diesel engine efficiently. LFWCO has an inferior cetane index. Hence, it experiences a longer delay period, which leads to an elevation of pressure and high uncontrolled incineration in the diffusion combustion phase [18,19]. The ignition delay for the LFWCO-fueled engine can reduce by adding high-cetane fuels. DEE is an encouraging opinion, which has a cetane index of about 125 [20–22].

Many researchers have tried to produce biomass-based pyro-oil from WCO [16,17,17,23–28]. Some researchers have also tried to use WCO in diesel engines, either blended with diesel or biodiesel [19,29–44]. But, according to the authors' knowledge, none of the researchers have tried to use LFWCO in diesel engines blended with DEE. Gopal et al. [29] explored the benefits of the methyl ester extracted from waste cooking oil, in a 1-cylinder CI diesel engine. Their observation revealed that biodiesel reduced the emission of unburnt HC, smoke opacity, and CO. The oxides of nitrogen (NO_x) and brake-specific energy consumption (BSEC) were identified to be more than that of neat diesel at 100% engine load. Can [30] conducted a study in a 1-cylinder, DI diesel engine for varying engine load conditions. They investigated the engine characteristics with two dissimilar bases of WCO in varying blend ratios with diesel. They noticed that for a standard speed of the engine as 1500 RPM, the delay period was longer with the increase in WCO blend. This occurred with the reduction in the cetane number of the WCO. The BSFC increased with a drip in the BTE. The NO_x emission amplified with the increase in the fraction of WCO in the blend. Whereas the HC emission was inferior for every load case. Wei et al. [31] in their experimental study in a DI diesel engine with WCO. They detected that with the accumulation of WCO in diesel the BSFC augmented and the BTE was almost near to plain diesel. The PM (particulate matter) emission of the engine was in a decreasing trend with an increase in the emission of NO_x. Prabhu et al. [32] conducted an experimental investigation in a diesel engine fueled with butylated hydroxytoluene and n-butanol mixed with WCO. The test result indicated that the diesel-WCO30 blend was superior in comparison to diesel regarding performance and emission. Further, they investigated the diesel-WCO30 blend with the accumulation of butanol. The accumulation of butanol with diesel-WCO30 showed a rise in the BSFC and a diminution in BTE owing to the minor heating value of butanol. CO emission decreased drastically by about 37.5%. But the emission of NO_x was augmented by about 9% due to the accumulation of butanol in the diesel-WCO30 blend.

Another study by Necati et al. [19] on the application of canola oil and waste palm oil methyl esters (WPOME) as fuel in diesel engines with a rated power of 81 kW. They noticed the usage of the canola oil-WPOME mixture resulted in a reduction in BP (brake power) by about 5% and an increase in BSFC by about 10%. The CO, HC, and CO_2 emissions were decreased by about 67%, 26%, and 6%, respectively, in contrast to plain diesel fuel at 100% loading condition. But the emission of NO_x increased by 22%. Bari et al. [33] did an experimental study in a CI engine working with the WCO. They related the performance and discharge of harmful gases of WCO with neat diesel. They identified there were opposing effects in the injection of fuel and ignition owing to the highly viscous nature of the WCO. They also presented that there was a surge in the CO, and NO discharges from engines fueled with WCO in comparison to diesel. Lin et al. [34] experimentally examined the usage of various blend ratios of ULSD (ultra-low sulfur diesel) and WCO biodiesel in an engine working with neat diesel. Their investigation showed that the CO and HC discharge diminished by about 13% and 36% for the ULSD-WCOB blend when compared to ULSD. Senthil et al. [35] led an experimental study using WCO-emulsified biodiesel in an engine working with neat diesel. Their test results demonstrated that the BTE augmented with the WCO emulsion with a rise in the load on the engine and also there was a substantial reduction in the emission characteristics with WCO emulsion. An et al. [36] considered the application of WCO in diesel engines with a power rating of a 75-kilo watt at 3600 rpm. They reported that the use of WCO increased the in-cylinder pressure, reduced the delay in ignition and time taken for fuel combustion, and decreased the net heat release rate. They also noticed that BSFC increased and BTE had no significant changes in all test modes. Ali et al. [37] performed experimentation in a single-cylinder plunger-type injection neat diesel engine with a power rating of 5.8 kilo watts at 1500 rpm with WCO biodiesel blended in neat diesel. Their investigation revealed the performance of the engine with blending ratios ranging from 30% to 50% had 10% higher BSFC, the emissions of CO, HC, and NO_x

lowered by 25%, 20%, and 6%, respectively, and the smoke opacity increased by about 20% in disparity with diesel. Geng et al. [38] examined the emission of NO_x while using WCO mixed with neat diesel in a water-cooled diesel engine. They showed that the NO_x emission diminished with a rise in the biodiesel ratio. But it started growing with a rise in the engine torque with a decrease in the NO_2 (nitrogen dioxide) emission. The ratio of NO_2 to NO decreased by an increase with the engine load owing to a rise in the cylinder temperature.

The use of DEE with waste tire oil (WTO) was carried out by Hariharan et al. [39]. They examined the consequence of DEE on the engine physiognomy of the single cylinder water cooled diesel engine, fueled with blends of DEE-WTO. Their investigation exhibited that the engine performance was good enough when DEE was injected at 170 g/h in the intake manifold. Devaraj et al. [40] led an experimental study in a diesel engine with WPP (waste plastic pyrolysis) oil blended with di-ethyl ether. Their experiments exposed that there was a decrease in the emission rate and a rise in the BTE with WPPO-DEE blend when associated to WPPO and diesel. Dimitrios et al. [41] made an experimental investigation using diesel-DEE blend in a diesel engine. Their tests revealed that there was no effect of DEE on the BTE, but that BSFC was higher with increasing DEE in the blend. The exhaust gas temperature (EGT) was augmented suggestively with the addition of DEE. The emissions of HC, CO and smoke opacity reduced with the increase in the DEE mixture whereas the NO_x release increased. Lobo et al. [45] evaluated the use of biodiesel in a diesel engine, as well as its effect on performance and combustion-related metrics. To compensate for these disadvantages, additives are added to the biodiesel blend to improve its quality. The addition of additives enhanced both brake thermal efficiency and brake-specific fuel consumption by about 7%, according to the study. Chaudhari et al. [46] studied the effect of various fuel blends comprising regular diesel fuel and waste cooking oil methyl ester on the performance of diesel engines. The study determined that biodiesel (methyl ester) is one of the fuel options that can be used in a standard diesel engine with no design changes. Padmanabhan et al. [47] studied the effects of varied concentrations of diethyl ether (DEE) additives and waste cooking oil biodiesel on diesel engine efficiency and emissions. Emission metrics were compared to those of pure diesel, and results were optimized for various load circumstances and oxygenated additive mixes. According to the study, employing oxygenated fuels looks to be a viable technique for reducing engine emissions.

In the present investigation, WCO obtained from various sources (Food processing industries, domestic sectors, and restaurants) was distilled in a borosilicate round bottom flask. After distillation, light fraction waste cooking oil (LFWCO) was obtained from raw WCO. Further, various properties of LFWCO were investigated for its suitable application. LFWCO was further blended with DEE in a ratio of 0 to 20% in step of 5. The LFWCO-DEE blends were tried in a 1-cylinder DI diesel engine, and the performance of engine and emission release characteristics were analyzed and related to neat diesel characteristics.

2. Materials and Methods

2.1. Fuel Preparation

Initially, the WCO was collected from the food processing industries and commercial restaurants located near the Karpagam Academy of Higher Education, India. Then, WCO was filtered to remove any suspended particles. The elementary properties of WCO were characterized and related to diesel and given in Table 1. In comparison to diesel, WCO has a higher density. This is due to the fact that WCO is a fuel made from vegetable oil, which has a substantially larger molecular weight and greater viscosity than diesel made from minerals. Compared to WCO, diesel has a higher calorific value. This suggests that diesel has a higher energy content per mass, which may improve engine performance and efficiency. Both fuels have a similar temperature range for auto-ignition. The fuel-air mixture can spontaneously ignite within this range of temperatures without the need for an outside spark, demonstrating that both fuels have ignition properties suited for diesel engines. WCO has a substantially higher flashpoint than diesel. This means that WCO is less volatile and safer to handle than diesel since it needs a higher temperature to release enough vapors to create an ignitable combination. The fire point of WCO is higher than that of diesel, similar to the flashpoint. Given that WCO has a higher fire point than diesel, it may be less likely to catch fire than the latter. The fire point is the temperature at which sustained combustion takes place. Compared to WCO, diesel has a greater cetane number. Better ignition quality, quicker combustion, and smoother engine operation are all indicated by higher cetane numbers. The ignition and combustion properties of WCO may be a little bit slower due to its lower cetane number. Due to its origin in vegetable oil, WCO has a high oxygen content. This oxygen level may impact the combustion process, emissions, and deposits in the combustion chamber. Minimal oxygen content is found in diesel.

Table 1. Physiochemical properties of Diesel [32] and WCO.

Properties	ASTM	Diesel	WCO
Density, kg/m^3	D 4052	830	876
Calorific values, kJ/kg	D 4809	43,800	39,767
Auto-ignition temperature, °C	E 659	210–350 °C	250–380 °C
Flashpoint, °C	D 93	50 °C	160 °C
Fire point, °C	D 93	56	164
Cetane number	D 613	50	42
Oxygen, wt.%	E 385	Nil	20

2.2. Production of LFWCO

The WCO density is found to be more than that of diesel, and the calorific value and Cetane number (CN) of WCO were also lower in comparison to diesel. Hence, for a suitable application of WCO, fractional distillation was carried out in a round bottom glass, borosilicate flask furnished with a heater and temperature controller. The distillation reaction temperature was maintained constant using a PID (proportional integral and differential) controller. The distillation process was carried out at a 250–450 °C temperature range using a bench-made borosilicate glass flask. The investigational setup is shown in Figure 1.

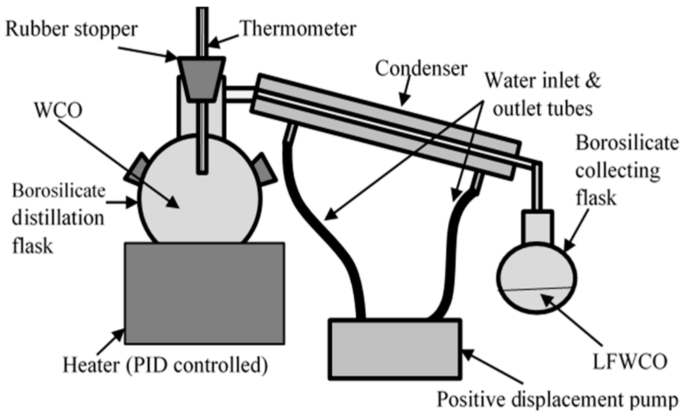


Figure 1. Distillation setup.

Initially, a measured quantity of WCO (3 L) was kept in the round bottom borosilicate flask, and it was sealed with a rubber stopper along with mercury in a glass thermometer (the range is 100–800 °C), a glass condenser was connected at another end of the borosilicate round bottom flask. The condenser was a counter-flow type condenser in which water was used as a condensing fluid, and WCO vapor was the condensate. The condensed vapor collected in the collecting flask was termed the light fraction of WCO (LFWCO). The water flow to the condenser was regulated by a positive displacement pump (0.5 HP–Aqua prime) and a water flow control valve (Airmax–6.35 mm RMFCV). The heating mantle was used to heat the WCO to a temperature of 320 °C to the vaporization temperature of volatile compounds. Initially, low boiling point volatile liquid evaporated and condensed while passing through the glass condenser and collected in the flask. The picture of the distillation unit is depicted in Figure 2.

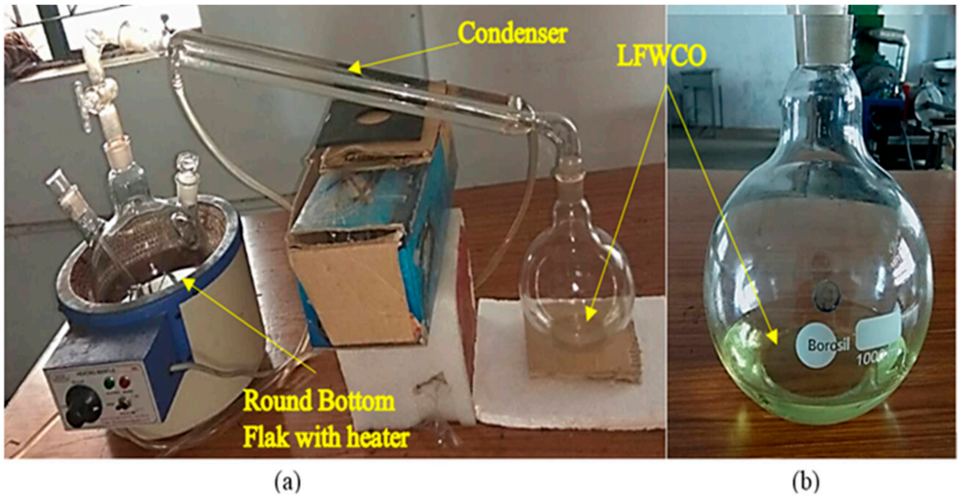


Figure 2. Picture of distillation unit (**a**) distillation unit (**b**) LFWCO.

The condensed oil (i.e., LFWCO) collected in the borosilicate round bottom collection flask was further characterized to know the properties. The properties of LFWCO are specified in Table 2.

Table 2. Physiochemical properties of LFWCO.

Properties	Test Method, ASTM	LFWCO
Density, kg/m^3	D 4052	812
Calorific value, kJ/kg	D 4809	41,670
Auto Ignition temperature, °C	E 659	230–320
Flashpoint, °C	D 93	110
Fire point, °C	D 93	130
Cetane number	D 613	43
Octane number	D909	66
Carbon, %	-	70.8
Hydrogen, %	-	6.1
Nitrogen, %	-	1.099
Sulphur, %	-	0.001
Oxygen, wt.%	-	22

2.3. Test Fuels

In this study, LFWCO blended with DEE varying from 0 to 20% in increments of 5%. The properties of LFWCO-DEE blends were characterized and given in Table 3. With an increase in DEE content, density drops. This is probably due to the fact that DEE has a lower density than LFWCO. A linear relationship between blend mix and density is implied by the progressive reduction. As DEE content rises, calorie values decrease. This is explained by the fact that DEE has less energy than LFWCO. The higher DEE proportion is inversely correlated with the reduction in calorific value. As DEE content rises, auto-ignition temperature ranges become more restricted. This implies that the presence of DEE results in a more distinct and reliable igniting behavior. A smaller range suggests enhanced igniting properties with higher DEE concentrations. As DEE content rises, flashpoint also increases. This increase is influenced by DEE's lower flashpoint and decreased volatility. The combination is less likely to ignite vapor since the trend fits with DEE's properties.

Similar to the flashpoint, the fire point increases with more DEE content. Due to its greater ignition point, fuel has improved safety at larger DEE proportions. As DEE content grows, likewise the Cetane number. Due to DEE's high Cetane rating, the blend's ignition quality is enhanced, resulting in a smoother and more effective combustion. The increasing trend reveals the beneficial effect of DEE on ignition properties. Higher DEE level results in a modest rise in oxygen content. This increase is a result of DEE's oxygen-rich structure, which may have an impact on combustion effectiveness and emissions regulation.

Table 3. Physiochemical properties of LFWCO-DEE blends.

Properties	Test Method, ASTM	LFWCO	DEE	LFWCO+5-DEE	LFWCO+10-DEE	LFWCO+15-DEE	LFWCO+20-DEE
Density, kg/m^3	D 4052	812	713	807.05	802.1	797.15	792.2
Calorific values, kJ/kg	D 4809	41,670	33,900	41,281.5	40,893	40,504.5	40,116
Auto-ignition temperature, °C	E 659	230–320	150–160	180–215	168–184	160–181	159–178
Flashpoint, °C	D 93	110	−40	102.5	95	87.5	80
Fire point, °C	D 93	130	44	125.7	121.4	117.1	112.8
Cetane number	D 613	43	125	47.1	51.2	55.3	59.4
Oxygen, wt.%	E 385	22	28.2	22.31	22.62	22.93	23.24

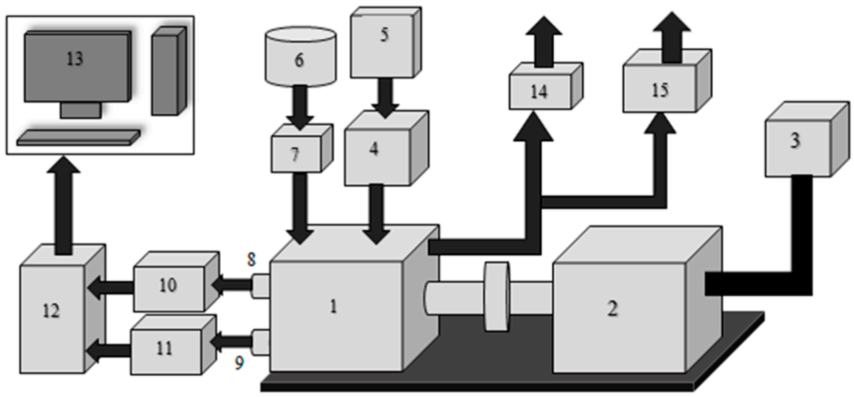
2.4. Experimental Setup

In the present investigation, a single cylinder 4-stroke, water-cooled diesel engine with direct injection of fuel is used. The power of the engine is 3.7 kilowatts at a constant speed of 1500 rpm and it is operated with LFWCO-DEE blends. The fuel supply system used in the engine is a mechanical fuel injection type. The fuel injector used is a plunger type and it is governed by the governor mechanism available in the engine test setup. The injection pressure is 200 bar. The engine is naturally aspirated. A detailed description of the engine used for testing is given in Table 4. The test unit layout and the engine setup are shown in Figures 3 and 4.

Table 4. Detailed description of the test engine.

Parameters	Description
Engine type	1 cylinder, 4-stroke, H_2O cooled
Power	3.7 kilowatt
Speed	1500 rpm
Compression ratio	18 (standard)
Cylinder bore diameter	87.5 mm
Stroke length	110 mm
Ignition type	Compression
Dynamometer type	Eddy current dynamometer
Injector type	Plunger type
Injection pressure, bar	200
Injector nozzle holes	3 nos.
Injection type	Direct
Injection angle, bTDC	23°
Temperature sensor	K-type

The fuel intake capacity of the engine was calculated by the use of burette built-in optical sensors. Using the data collected from the burette, the fuel consumption of the engine is calculated based on the change in fuel volume over a specific period, typically represented in liters per hour (L/h). The consumption of air by the engine was quantified by an airflow meter. An air box was linked to the intake manifold of the engine to control the damped pulses produced by the engine. An eddy current dynamometer coupled to the engine shaft was set to apply load for the engine. The Eddy Current Dynamometer Model TME-10 by Technomech, India was used in this experiment. It works by electromagnetic induction and applies a regulated braking force to the output shaft of the engine. Through induced eddy currents in a revolving disc system within a stator's magnetic field, it gauges torque and power production. A non-contact type speed sensor was allied to the engine flywheel to measure the speed. A crank angle encoder was connected to the crankshaft to measure the position of TDC in the engine. The burnt flue gas and cooling water temperature of the engine were calculated with thermocouples (K-type). The emission of CO, HC, and NO was quantified with a gas-analyzer (Model: AVL 444). These analyzers use a flame ionization detector to measure the HC, a Non-Dispersive Infrared (NDIR) Analyzer to measure the concentration of CO, and a Chemiluminescence analyzer to measure the NO emission level and the gas analyzer provides real-time measurement. The smoke opacity from the engine was found with a DSM (diesel smoke meter) (Model: AVL 437C). These meters use a light source and a photodetector to measure the opacity of the exhaust gas. The detailed experimental procedure is explained in the subsequent sections.



1 Engine; 2 Dynamometer; 3 Dynamometer control panel; 4 Air box; 5 Air flow meter; 6 Burette; 7 Fuel injector; 8 Pressure sensor; 9 Position sensor for TDC; 10 Amplifier; 11 amplifier circuits of TDC; 12 (AD) Analog to digital conversion unit; 13 (PC)Computer; 14 EG(Exhaust gas) analyzer; 15 Smoke meter.

Figure 3. Test engine setup layout.

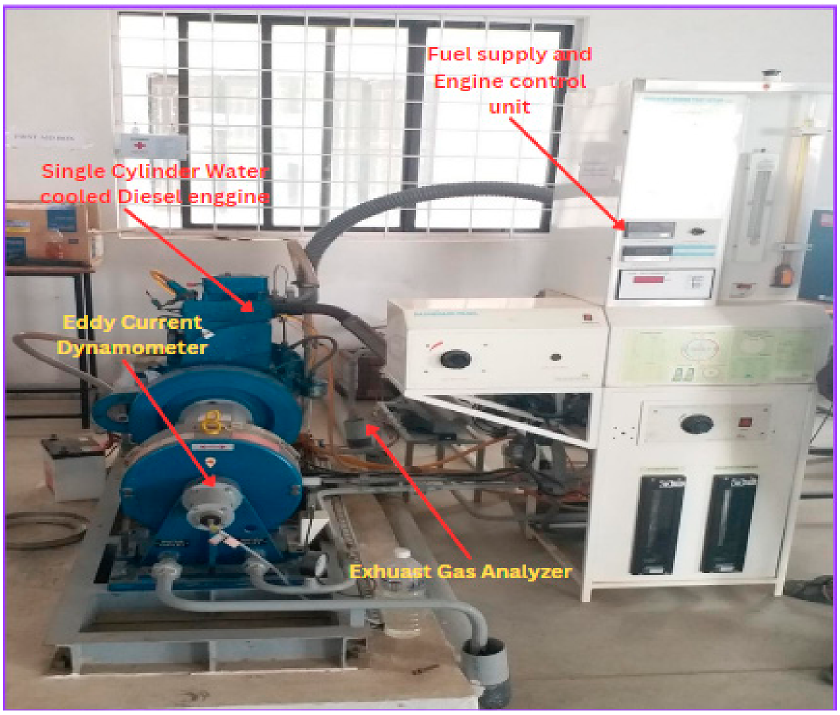


Figure 4. Engine Test Setup.

2.5. Design of Experiment

At first, the engine was permitted to run with neat diesel up to a steady state condition for collecting the baseline data for diesel. The engine was operated on LFWCO with variation in the load from 0 to 100% in step of 25. In each loading condition, the engine parameters which showcase the performance of the engine and emission rate fueled with LFWCO were recorded, 5%, 10%, 15%, and 20% of DEE was blended with LFWCO, and the engine run with LFWCO-DEE blends. The investigational outcomes of LFWCO-DEE blends were related to diesel and plain LFWCO and presented in this article. During the experiment, the atmospheric temperature was 27 °C. The engine test condition and the acronyms used are specified in Table 5.

Table 5. Test conditions.

Fuel	Acronyms Used	Compression Ratio	Injection Time, °CA bTDC
Diesel	Diesel	18	23
LFWCO (100%)	LFWCO	18	23
LFWCO (95%) + DEE (5%)	LFWCO+5-DEE	18	23
LFWCO (90%) + DEE (5%)	LFWCO+10-DEE	18	23
LFWCO (85%) + DEE (5%)	LFWCO+15-DEE	18	23
LFWCO (80%) + DEE (5%)	LFWCO+20-DEE	18	23

2.6. Error Analysis

To ensure the correctness of the data acquired during the experiment, uncertainty or propagation of error analysis was carried out. The unknown uncertainties of a known physical quantity can be evaluated using the general equation given below [42,48].

$$\frac{U_z}{Z} = \sqrt{\left[\sum_{i=1}^{n}\left(\frac{1}{Z}\frac{\partial Z}{\partial x_i}\right)^2\right]} \tag{1}$$

In this equation, Z represents the physical parameters that depend on the parameters x_i. U_z denotes the uncertainty of the variable Z. The uncertainties of the tools used are listed in Table 6. The overall error level of the collected data was found to be ±1.708%.

Table 6. Instruments used and their unreliability's.

Instruments	Parameters Measured	Range	Accuracy	Unreliability, %
Gas analyzer	Exhaust emissions	NO 0–5000 ppm	±10 ppm	±0.2
		CO 0–10%	±0.02%	±0.15
		HC 0–10,000 ppm	±20 ppm	±0.2
		CO2 0–20%	±0.03%	±0.2
Dynamometer	Brake power	0–100 Nm	±0.1 Nm	±0.2
Crank angle encoder	Crank position	0–720°	±0.2 °CA	±0.2
Speed sensor	Engine speed	0–10,000 rpm	±10 rpm	±0.1
Smoke meter	Smoke opacity	0–100%	±0.1	±1
Burette	Fuel consumption	0–100 mL	±0.1 cc	±1
Pressure transducer	In-cylinder pressure	0–100 bar	±0.1 bar	±0.15

3. Results and Discussion

3.1. Performance Factors

3.1.1. Brake-Specific Fuel Consumption (BSFC)

Figure 5 illustrates the values of the BSFC for varying loading conditions, for the neat diesel, LFWCO, and LFWCO-DEE blends. For diesel, LFWCO, and LFWCO-DEE blends the BSFC reduced with an increase in engine loading. An et al. [36] and Yang et al. [43] reported a similar trend in their research work. This is a result of a reduction in fuel usage with an increase in the engine load. The BSFC is higher for LFWCO-DEE blends when related to diesel. This might be owing to the low HV of LFWCO-DEE blends in comparison to diesel. It is noted that the BSFC for LFWCO+20-DEE is much higher than those of LFWCO+5-DEE, LFWCO+10-DEE, and LFWCO+15-DEE for all loading conditions. The HV of LFWCO+20-DEE is reducing with an increasing percentage of DEE since the HV of the DEE is much less than the LFWCO [22]. The BSFC for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE blends are found to be 14.7%, 24.3%, 28.9%, and 39.2% more than diesel at 100% loading condition respectively.

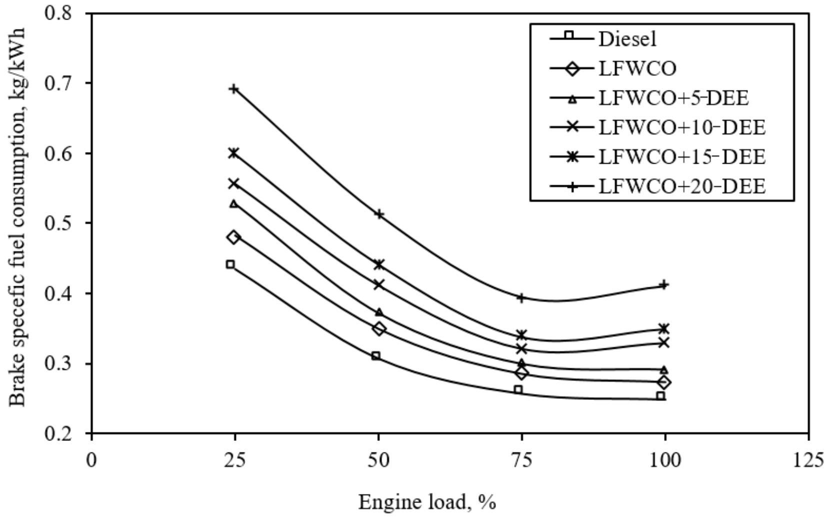


Figure 5. BSFC versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

3.1.2. Brake Thermal Efficiency (BTE)

Figure 6 illustrates the change in BTE for diesel, LFWCO, and LFWCO-DEE blends.

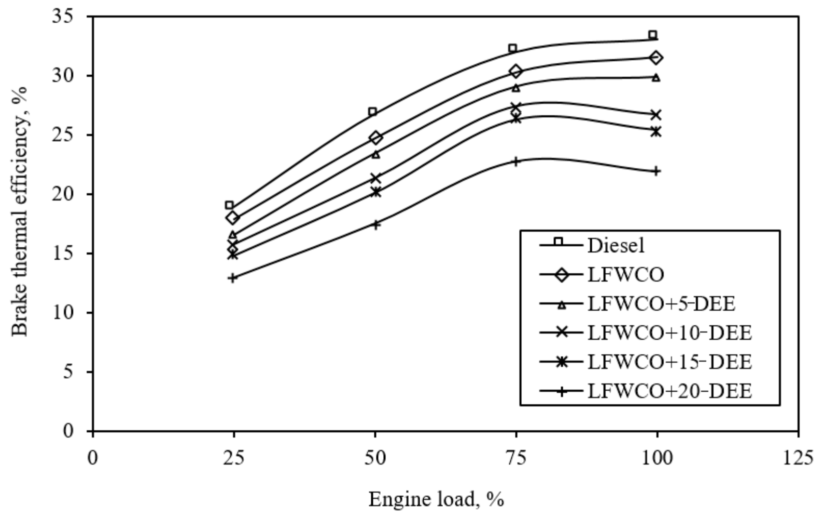


Figure 6. BTE versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

BTE increases with increasing load due to the increasing in-cylinder temperature for increasing load on the engine. For LFWCO, BTE was found to be 2% lower than diesel fuel, since the CV of LFWCO is lower than that of diesel and the viscosity of LFWCO is also higher than that of diesel. The same trend was reported by Senthil et al. [32] and Yang et al. [43] in their research work. The BTE for blends of LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE are identified to be about 3%, 6.3%, 7.6%, and 11.1% less than that of neat diesel at 100% load, respectively. The increasing percentage level of DEE results in a lower calorific value of the blends. It can be clearly noticed that in the case of LFWCO+20-DEE, the BTE dropped drastically in comparison with LFWCO+15-DEE. This may be due to the very high CN of LFWCO+20-DEE which results in knocking at the higher load of the engine. Can et al. [30] and Wei et al. [31] reported a similar trend in their research work. Hence the investigation was limited to a 20% DEE blend.

3.1.3. Exhaust Gas Temperature (EGT)

The EGT for plain diesel, LFWCO, and LFWCO-DEE blends are shown in Figure 7. The EGT is higher for diesel when compared to LFWCO and LFWCO-DEE blends. This is owing to the rapid combustion of diesel. The EGT indicates the thermal energy conversion rate into useful work, and it also indicates the duration of fuel combustion. Kumar et al. [35] and Senthil et al. [49] reported such a pattern of the EGT in their investigation. The EGT for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE are found to be 6.5%, 9.8%, 11.9%, and 13.7% lower than that of diesel at 100% loading condition, respectively. The early combustion caused by increased CN and dissolved oxygen in the fuel is the cause of the significant reduction in EGT for the LFWCO-DEE blends.

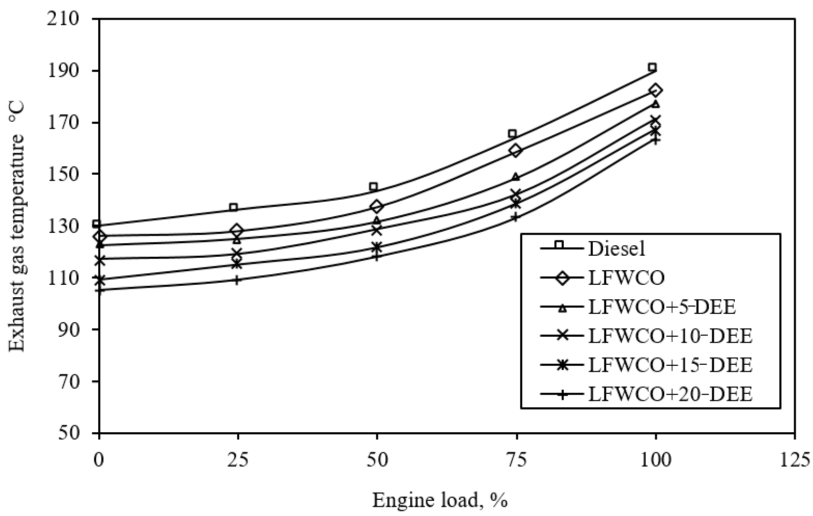


Figure 7. EGT versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

3.2. Emission Factors

3.2.1. CO

Figure 8 illustrates the change in the emission of CO for diesel, LFWCO, and LFWCO-DEE blends. The CO emission rate decreased with increasing engine load for all fuel blends. It is obvious, owing to improved combustion energy at a higher operating load. LFWCO gives lower CO emissions than plain diesel for all over the load range. This is owing to the existence of dissolved oxygen, which promotes complete combustion of the fuel. Van et al. [36] and Tudu et al. [50] in their research work, reported that the presence of dissolved oxygen in the blends due to the addition of DEE resulted in the complete combustion of the fuel. The CO emission for LFWCO-DEE blends is noted to be significantly lower than that of the plain diesel and LFWCO. This might be due to the higher ignition rate, and supplementary oxygen present in DEE resulting in smoother combustion of fuel and reducing the emission rate of CO. Prabu et.al. [32] and Yang et al. [43] in their study identified a similar pattern of reducing CO for the different blends of fuel with WCO. The emission of CO for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE is noted to be less than the neat diesel by 5.9%, 8.8%, 20.5%, 32.9%, and 36.8% at 100% load, respectively.

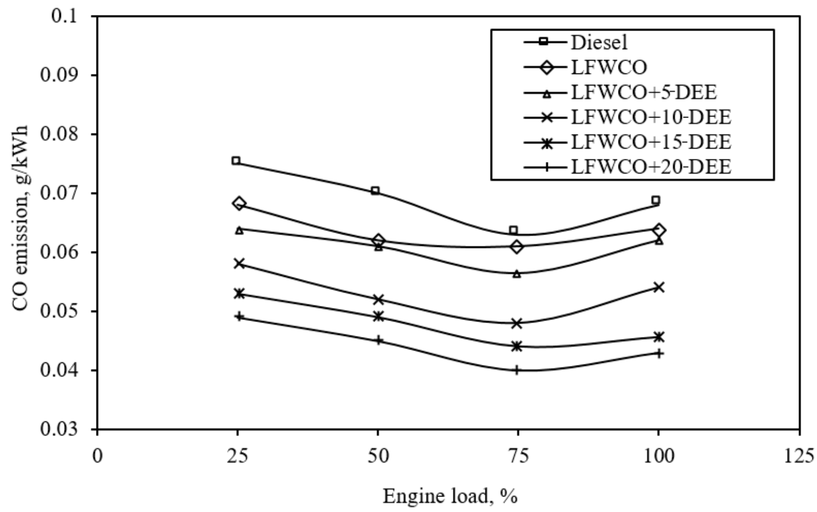


Figure 8. CO emission versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

3.2.2. NO

Figure 9 illustrates the NO emission rate for plain diesel, LFWCO, and LFWCO-DEE blends. The NO emission depends on the in-cylinder combustion temperature, the presence of oxygen, and the retention time for reaction. The NO emission increases with an increase in engine load, for plain diesel, LFWCO, and LFWCO-DEE blends due to the elevated gas temperature in the cylinder at maximum loading conditions. However, the brake-specific NO emission shows a declining trend with an increase in load due to an increase in brake power. An et al. [36] and Tudu et al. [50] showcased a very similar trend of increasing NO emission for different fuel blends under varying load conditions. The emission of NO for LFWCO is 30.7% more than that of neat diesel at 100% load. This might be owing to the dissolved oxygen in LFWCO which reacts with nitrogen at high temperature and results in NO emission. It is also observed that with the increase in the proportion of DEE in the mixture, the NO emission increases progressively. This may be owing to the early start of combustion of LFWCO-DEE blends which gives the high combustion temperature. Hariharan et al. [39] and Devaraj et al. [40] reported the usage of DEE in the fuel blends increased the NO emission due to the complete combustion and presence of excess oxygen in the fuel blends. The NO emission for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE is found to be higher by about 30.6%, 27%, 36%, and 41% related to LFWCO, at 100% load, respectively.

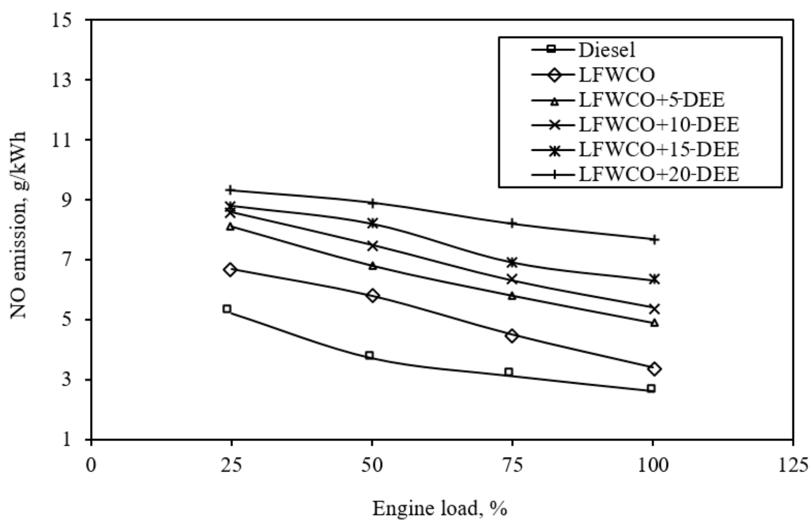


Figure 9. NO emission versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

3.2.3. HC

The HC emission for diesel, LFWCO, and LFWCO-DEE blends for varying engine loads is shown in Figure 10. The hydrocarbon (HC) emission from diesel fuel was found to be higher in this study than in the other fuels evaluated. The difference in HC emissions can be related to the fact that diesel is a mineral-based fuel that doesn't contain dissolved oxygen. As a result, partial combustion of diesel fuel happens throughout the combustion process in the engine, resulting in greater HC emissions [51]. The HC emission for LFWCO is 10.8% lower related to diesel, at 100% operating load. The drop in HC emission for LFWCO is due to the presence of dissolved oxygen content, the early start of the fuel combustion, and adequate time for the combustion of fuel inside the cylinder. Gopal et al. [29] and Tudu et al. [50] in their investigation reported a drop in HC emission for various fuel blends due to the presence of the additional oxygen content in the mixture leading to complete combustion at elevated temperatures. The HC emission for LFWCO-DEE blends gradually decreases with the increasing ratio of DEE. This might be due to the initial start of ignition caused by the higher value of CN of DEE which enhances the combustion quality. The HC emission for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE is found to be lower by 16.6%, 20.4%, 25%, and 28.3% related to diesel, at 100% load, respectively. Can et al. [30] and Yu et al. [33] reported a similar pattern of HC emission for various fuel blends in addition to DEE.

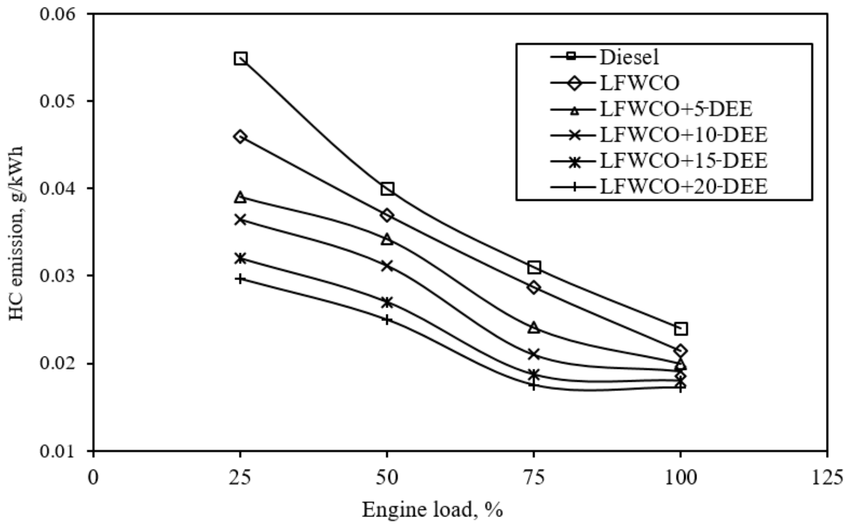


Figure 10. Role of HC emission versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

3.2.4. Smoke Opacity

The smoke opacity for plain diesel, LFWCO, and LFWCO-DEE blends are shown in Figure 11. The smoke opacity reduces with an increasing ratio of DEE in the LFWCO-DEE blend. The smoke opacity is higher for diesel when compared to LFWCO. This is owing to the presence of aromatic compounds in diesel. Qi et al. [22] and Barik et al. [52] reported a similar pattern of smoke opacity for various fuel blends and stated that it is due to the presence of aromatic compounds in the diesel and fuel blends. The smoke opacity for LFWCO-DEE blends reduces with an increasing DEE ratio. This may be owing to the breakdown of long-chain HC in the fuel. Prabu et al. [32], Lin et al. [34], Kumar et al. [35], An et al. [36], and Ali et al. [37] in their investigation of waste cooking oil with diesel blends showed that the smoke opacity for diesel fuel is much higher than the other fuel blends and it happened due to the breaking down of the long chain HC presence in the fuel blends, and another possible reason can add to this is due to the renewable nature of LFWCO and DEE the fuel combustion undergoes in a heterogeneous situation at a higher temperature and suppresses the smoke opacity. The smoke opacity for LFWCO+5-DEE, LFWCO+10-DEE, LFWCO+15-DEE, and LFWCO+20-DEE is found to be lower by about 13.1%, 21.7%, 29.4%, and 30.6% than diesel, at 100% load, respectively.

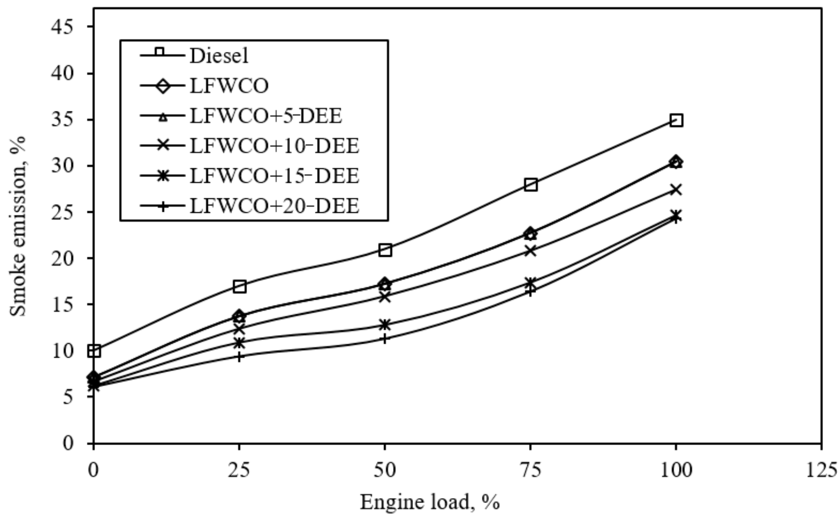


Figure 11. Smoke opacity versus load for plain diesel, LFWCO, and LFWCO-DEE blends.

4. Conclusions

The inferences of the current investigation are listed below:

- LFWCO can be used as a potential biomass-based renewable fuel in a CI DI diesel engine for heat and power production.
- The mixing of DEE with LFWCO increased the CN of the fuel and decreased its viscosity near diesel.
- LFWCO+15-DEE was found to give optimum results regarding performance and emission characteristics. When compared to neat diesel and other LFWCO DEE blends, the LFWCO+15-DEE blend performed better in terms of higher BTE and lower BSFC and EGT. It also had lower emissions of HC, CO, and Smoke Opacity, demonstrating its potential as an alternative fuel option. Overall, LFWCO+15-DEE has the potential to improve engine performance while reducing environmental effects.
- The BSFC for LFWCO+15-DEE was found to be higher by about 28.9%, and the BTE was identified to be lower by about 7.56% on par with diesel at 100% load correspondingly.
- For LFWCO+15-DEE the exhaust temperature of gas was identified to be less by about 11.9% on par with plain diesel at 100% load.
- The HC, CO, and smoke opacity for LFWCO+15-DEE seemed to be inferior by 32.9%, 25%, and 29.4% on par with diesel at 100% load.
- The NO production for LFWCO+15-DEE seemed to be larger by about 36% in contrast with neat diesel at 100% load.

The adoption of this waste to energy technologies will reduce the mineral-based non-renewable fuel use in the automotive and power sectors. The soil and water pollution caused due to the improper disposal of WCO can also be minimized. This technique can be used in stationary diesel engines used in food processing industries which can save annual diesel consumption for running various mechanical components efficiently.

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Nomenclature

WCO	Waste cooking oil
LFWCO	Light Fraction waste cooking oil
DEE	Diethyl ether
BTE	Brake thermal efficiency
BSFC	Brake-specific fuel consumption
EGT	Exhaust gas temperature
HC	Hydrocarbon
CO	Carbon monoxide
NO	Nitrous oxide
CR	Compression ratio
CI DI	Compression-Ignition Direct injection
IT	Injection time
CA	Crank Angle
CN	Cetane number
CV	Calorific Value
HV	Heating Value

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