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Experimental probe into an automative engine run on waste cooking oil biodiesel blend at varying engine speeds

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ABSTRACT

The present work attempts to evaluate the performance of an automotive diesel engine run on waste cooking oil biodiesel (WCO) blend at variable engine speeds. The composition of the blend (B40) used in the study is 40% WCO and 60% diesel by volume and the engine used for the experimentation is a naturally aspirated, water-cooled and direct injection type having a compression ratio of 18:1. The engine settings used in the study are an injection timing (IT) of 15^0bTDC and a fuel injection pressure (IP) of 500 bar. The performance and emissions characteristics of the automotive engine are studied at various loads of 20%, 40%, 60%, 80% and 100% and at different engine speeds of 1500, 1800 and 2400 rpm. The first two rotational speeds are chosen to study the stationary power generation capabilities of the blend, while the feasibility of blend for automotive applications has been evaluated at 2400 rpm. Experiments have also been conducted on the engine run on mineral diesel fuel in order to make a comparative analysis. At full load, the maximum brake thermal efficiency (BTE) is found to be 21.51%, 25.48% and 23.56% for the blend at 1500, 1800 and 2400 rpm, respectively. At 2400 rpm and at 20% and 40% loads, the blend shows an absolute improvement in BTE of 0.17% and 0.03%, respectively over diesel fuel. On an average, there is a decrease of carbon monoxide (CO) emissions by 87.5%, 22.22% and 14.28% at 1500, 1800 and 2400 rpm as compared to diesel fuel. At 1500 and 2400 rpm, there is an average absolute increase in hydrocarbon (HC) emissions by 1.6 ppm and 9.6 ppm, respectively; while at 1800 rpm, an average decrease in HC emissions by 4 ppm is observed vis-a-vis diesel fuel. While emissions of oxides of nitrogen (NOx) as compared to diesel fuel increased on an average by 19.43%, 26.09% and 1.01% at 1500, 1800 and 2400 rpm, respectively.

1. Introduction

Reducing dependence on fossil fuel is the need of the hour and the quest for alternate sources of energy is of paramount importance to fuel the energy needs of the ever developing world. Further, CO_2 emissions have drastically increased due to use of fossil based fuels leading to climate change and its devastating effect. Globally, the energy-related CO_2 emissions have almost doubled from 18.0 bn tonnes in 1978 to 33.7 bn tonnes in 2018 [1]. Increased emissions of greenhouses gases have slowly raised the average global temperature and pose a serious threat to the existence of mankind. The major challenge lies in limiting this increase in the average global temperature to well below 2 °C above pre-industrial levels and taking further steps to limit this increase to 1.5 °C above pre-industrial levels, thereby significantly mitigating the risks and impacts of climate change [2]. Biodiesel use in compression ignition (CI) engines reduces GHG emissions and its renewable availability and the advantages offered by biodiesel can help automobile diesel engines manufacturers earn good profits in the automobile market and has potential to revolutionize the future of liquid fuel and automobile vehicles [3].

Internal combustion (IC) engines operating on fossil fuel oil provide about 25% of the world's power which amounts to roughly about 3000 out of 13,000 million tons oil equivalent per year producing about 10%

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Nomenclature

BP	Brake power [kW]
BSFC	Brake specific fuel consumption [g/kWh]
B40	40 % blend of WCO with diesel –
aTDC	After top dead center –
bTDC	Before top dead center –
BTE	Brake thermal efficiency –
CA	Crank angle [^{o}]
CI	Compression ignition –
CO	Carbon monoxide –
CO_2	Carbon dioxide –
CR	Compression ratio –
FFA	Free fatty acid –
GHG	Greenhouse gas –
HC	Hydrocarbon –
HRR	Heat release rate [J/^{o}CA]
IC	Internal combustion –
IP	Injection pressure [bar]
IT	Injection timing [^{o}]
NA	Naturally aspirated –
NO_x	Oxides of nitrogen –
RPM	Revolution per minute [rpm]
WCO	Waste cooking oil –
η_m	Mechanical efficiency –

of the world's greenhouse gas (GHG) emissions [4]. Depleting conventional fossil fuels have forced us to turn to tight oil and other unconventional sources which are difficult and expensive to extract [5]. Hence alternative to fossil fuels need to be evaluated and biodiesel which is transesterified vegetable oil can be a viable alternative to diesel fuel in CI engines. GHG emissions can be curbed by the increased usage of biofuel in diesel engines can and the dependency on imported fossil diesel also shall be reduced, dual fuel mode in CI engines can use biogas and producer gas as secondary fuel and further reduce the diesel consumption in engines [6].

Studies on using neat vegetable oil in CI engine have also been done which showed that neat vegetable oil can been used in the engine though the maintenance needs of the fuel injection system of the engine are found to be higher aroused out of higher viscous nature of the oil although, pretreatments like preheating and blending of vegetable oil gives better engine performance [7]. Neat Mesua ferrea Linn vegetable oil blended upto 30% v/v with diesel was used in a stationary CI engine; all blends reported a reduction in BTE and increase in BSFC Further higher blends showed an increase in the emissions of CO and HC and a decrease in NO_x emission [8].

Waste cooking oils (WCO) contain high free fatty acids (FFA) which is troublesome in for the process of transesterification. Hence, acid esterification using acid catalysts like H_2SO_4 followed by transesterification using alkali catalyst like KOH is usually employed for such high FFA oils [9]. A single cylinder constant speed 1500 RPM CI engine gives satisfactory performance on WCO biodiesel and its blends with the diesel fuel without any engine modifications [10]. Further WCO biodiesel blends upto 30% with diesel on volume basis reported lower Brake thermal efficiencies and emissions of HC and CO of blends as compared to diesel fuel and higher specific fuel consumptions [11]. A 40% WCO biodiesel blend with diesel reported the engine performance as compared with the conventional standard diesel at compression ratio (CR) of 21 with a slight increase in NO_x emissions [12].

Biodiesel can be a viable alternative to mineral diesel in CI engines. A biodiesel blend upto 40% with diesel can suitably be used in a constant speed diesel engine for stationary power applications [10]. This substitution of diesel with biodiesel can go a long way in reducing the fuel import bills of our country.

The WCO has high viscosity, high pour point, and low volatility and they give high NOx level in CI engine. Gasoline emulsion with WCO biodiesel improves the properties of WCO and leads to reduction in NO_x emission [13]. 25% blend of WCO biodiesel with diesel when run in a 33KW diesel generator, at full load, showed reduction in CO_2 and NO_x emissions by 19.27%, and 41.54% respectively while CO emissions increased by 52.40% compared to diesel [14]. Biodiesel blends were tested in an auxiliary marine engine with WCO biodiesel-diesel blends and it was reported that higher percentage of WCO biodiesel in the blend increase the cylinder pressure slightly and reduces the ignition delay with decrease in NO_x emission [15]. WCO biodiesel reported a longer injection delay, lower equivalence ratio and higher peak of injection rate due to its higher fuel viscosity and density and inherent oxygen present in WCO biodiesel [16]. At low loads, WCO biodiesel blend fueled IDI engine reported a higher BTE and lower BSFC as compared to diesel also lower emissions expect that of NOx were also reported by the biodiesel blends which showed comparable combustion characteristics with diesel [17]. The B25 WCO biodiesel-diesel blend fueled turbocharged CI engine was run at a speed of 1750 RPM and different load conditions with hydrogen added to the intake air at different flow rates, tests showed hydrogen addition at 30 L per minute as the optimal flow rate, hydrogen addition increased BSFC in all the test cases while the NOx and HC emissions decreased with hydrogen addition upto 30 lpm at low and moderate engine loads; further CO_2 emissions decreased with the hydrogen addition and the smoke emissions increased [18].

Thus,we see that from relevant literatures that biodiesel can be a viable alternative to mineral diesel in various CI engines, but the experimental testing of WCO biodiesel in an automotive diesel engine has not been reported in literature. A series of experimental investigations have been reported in literature using biodiesel in stationary engines, however, not much work has been carried out with biodiesel in a variable speed CI engine. The performance and emission evaluation of WCO oil biodiesel blends in an automotive engine has not been done and the suitability of WCO biodiesel to be used in automotive engines for automotive applications as well as stationary power generation needs to be studied in detail.

In this work, WCO biodiesel (methyl esters of WCO) and its 40% blend with diesel (B40) is taken as the fuel in a single cylinder, 625 cc, naturally aspirated (NA), CRDI, Mahindra Jeeto Engine automotive engine. The B40 blend is prepared and the following studies are performed in the engine.

(a) The B40 blend is tested at 1500 and 1800 RPM to evaluate the blend's suitability for stationary power generation and the automotive utility of the blend is evaluated at an RPM of 2400. The results obtained are compared with that of diesel fuel.
(b) Tests are carried out at an injection timing (IT) of 15^0 before top dead center (bTDC) and an injection pressure (IP) of 500 bar. The engine loads used in testing the fuels are 5 Nm to 25 Nmin steps of 5 that correspond to 20% to 100% load.
(c) The performance and emission parameters evaluated for the B40 blend and the diesel fuel arebrakepower (BP), bake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions of NO_x, CO, CO_2, and unburnt HC.
(d) For comparison of a particular performance and emission parameter of the fuels at different engine speeds, average value of the parameter was considered considering its average at all the load points.

(e) The combustion parameters such as variation of cylinder pressure, maximum rate of pressure rise and heat release rate are discussed with reference to the crank angle for the tested fuels.

2. Materials and methods

2.1. Biodiesel blend preparation

Waste cooking oil methyl ester is procured from SVM Agro Processor, Nagpur, Maharashtra and its B40 blend with diesel having 40% WCO biodiesel and 60% diesel by volume is prepared by using a mechanical stirrer at 5000 RPM for 5 min. The diesel used in the blending as well as in the engine testing has been procured from NRL petrol pump, Dibrugarh, Assam. The fuel properties viz. density, calorific value and flash point was measured for the three fuels viz., biodiesel, diesel and B40 blend as shown in Table 1 [19].

2.2. Engine test rig

The diesel engine used for testing was a 625 cc, NA, single cylinder, multi-speed engine of Mahindra and Mahindra make engine having a peak power of 9HP @ 3000RPM. The technical specifications of the engine are specified in Table 2. The engine is coupled with a water cooled eddy current dynamometer of make Technomech for measurement of engine load.

The intake airflow is measured with a HFM Type T-MAF sensor of make Bosch. Thermocouple probes of PT-200 types are used for temperature measurements at different locations in the experimental set up such as intake air manifold and exhaust gas. The engine is provided with a combustion pressure sensor of make PCB and a rotary crank angle encoder of make autonics. Two fuel tanks of 14.5 L and 4 L capacity are mounted on the panel to fuel the engine with diesel and biodiesel fuels respectively. One burette with stopcock and two-way valves is mounted for fuel flow measurements and selecting between both diesel and biodiesel fuels. A five-gas analyzer of make AVL and model DiGAS 444 Analyzer is used for the measurements of exhaust gas concentrations (CO, HC, CO_2, O_2 and NO_x). The experiments have been carried out by varying the engine load from 5 Nm to 25 Nm with an incremental step of 5 Nm at three different engine speeds of 1500, 1800 and 2400 RPM. The average values of the performance and emission data at a particular engine speed are taken considering the average of the values at all the tested loads. The schematic of the engine test rig is illustrated in Fig. 1.

Also the pictorial view of the engine test rig are shown in Figs. 2 and 3.

3. Results and discussion

3.1. Comparison of BSFC and BTE

The variation of average BSFC and BTE for diesel and the B40 at different engine speeds of 1500 RPM, 1800 RPM and 2400 RPM is shown is Fig. 4. BSFC of B40 is found to be higher than diesel at all tested RPMs [20,21]. The diesel fuel gives its best performance at 1800 RPM with an average BTE of 23.89% and BSFC value of 388.50 g/kWh. For the same fuel,performance at 1500 RPM is found to be satisfactory without much deviation from the 1800 RPM values (22.07% BTE and 413.79 g/KWh BSFC), while the engine performance at 2400 RPM for diesel fuel deteriorates as it gives lower BTE and appreciably higher BSFC. For B40 fuel alsoalso similar trend is observed with a maximum BTE and BSFC of 19.45% and 497.35 g/kWh respectively at 1800 RPM and poorresults at 1500 and 2400 RPM, however, the values are closer to one another for B40 fuel for all the three tested RPMs. On comparison between 1500 RPM and 2400 RPM for diesel, BSFC increases by 21.58% and BTE reduces by 15.54% while for B40, the BSFC decreases as speed increases from 1500 to 2400 rpm by 3.75% and BTE increases by 2.9% [23]. This may be to the fact that as the engine speed increases, the turbulence increases inside the cylinder which increases the heat transfer but deceases the time available for heat transferfurther, for B40 higher oxygen content in the biodiesel results better combustion and increase in the combustion chamber temperature [22,24].

Table 1
Fuel properties of WCO biodiesel and its B40 blend as compared with diesel using ASTM standards.

Properties	Testing method	Diesel	WCO biodiesel	B40
Density at 18 °C, (kg/m^3)	ASTM D-4052	828.2	910.3	860.9
Flash Point, (^{0}C)	ASTM D-92	71	175	90
Calorific Value, (MJ/Kg)	ASTM D-224	42.5	39.3	40.9

Table 2
Specification of diesel engine used for experimentation.

General Details	4 S CRDi, single cylinder, NA, water cooled diesel engine
Engine capacity	625 CC
Rated Power	9 HP @ 3000 RPM
Compression Ratio	18:1 (fixed)
Bore	93 mm
Stroke	92 mm
Max Torque	30 Nm @ 1800 RPM
Engine speed	1000–3000 RPM
Loading	Strain Gauge load cell
Engine controls	ECU controlled

It is observed that the average BTE and BSFC for B40 fuel at 2400 RPM are 1.13% lower and4.87% higher relativeto diesel fuel respectively. At 1500 RPMhowver, B40 reported 18.85% higher BTEand 24.26% lower BSFC compared to diesel respectively. These differences at 1800 RPM are similar to the values observed at 1500RPMand are 18.58% lower and 28.02% highercompared to diesel respectively. This shows that at higher engine speed of 2400RPM, B40 fuel and diesel fuelhave similar performance characteristics with regards to BTE and BSFC. The variation of BTE and BFSC with engine load at 1500, 1800and 2400RPM for B40 and diesel is shown in Figs. 5through 7, respectively.

It is seen that at 1500 RPM, the BTE for diesel is found to be higher than B40 at all loads, while the BSFC for diesel is lower as compared to the blend at all loads stheB40 blend values match closely with the diesel at 20 Nm load. At an RPM of 1800, the diesel fuel again performs better than the B40 blend at all the tested loads. With increase in load, the BSFC decreases and BTE increases for diesel at all tested engine speeds, B40 fuel also gives similar trend with exceptions at some of the tested loads at 1500 and 1800 RPM [25]. The least deviation in the values of the fuels is observed at a load of 10Nm for an engine RPM of 1800. The B40 blend gives the best results at 2400 RPM with BTE comparable to that of the diesel fuel at all the tested loads. It even exceeds the BTE of diesel at a load of 5Nm and 20 Nm with a very little increase in BSFC as compared to diesel.

3.2. Comparison of BP and mechanical efficiency (η_m)

In this work, the B40 blend is tested at 1500 and 1800 RPM to evaluate the blend's suitability for stationary power generation and at 2400 RPM to find its utility in automotive applications. In Fig. 8, the variation with average BP and average η_m at different engine speeds for the tested fuels is shown.

On comparison with diesel, it is observed that at 1500 and 1800 RPM, there is a relative decrease of 5.05% and 15.96% in the mechanical efficiencyof B40 fuel. At 2400 RPM though the mechanical efficiency of B40 is higher relative to diesel by 2.43% The average BP values for both the fuels are roughly equal for all the tested RPMs with no statistically significant deviation.

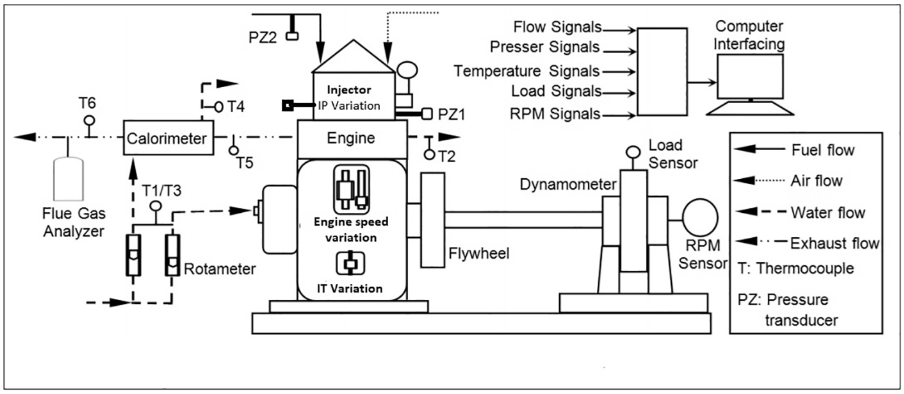

Fig. 1. Schematic of Engine Test Rig.

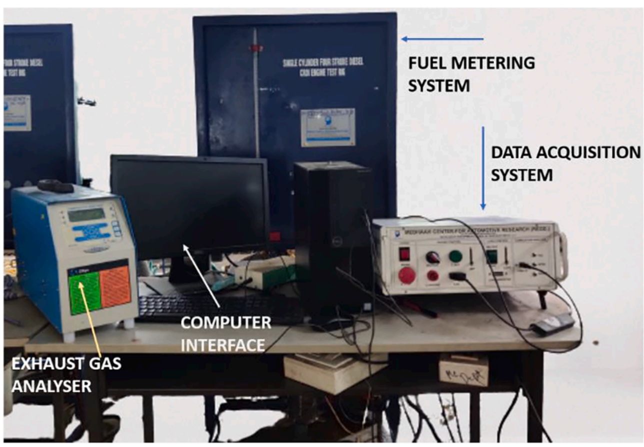

Fig. 2. Schematic of Engine Front View.

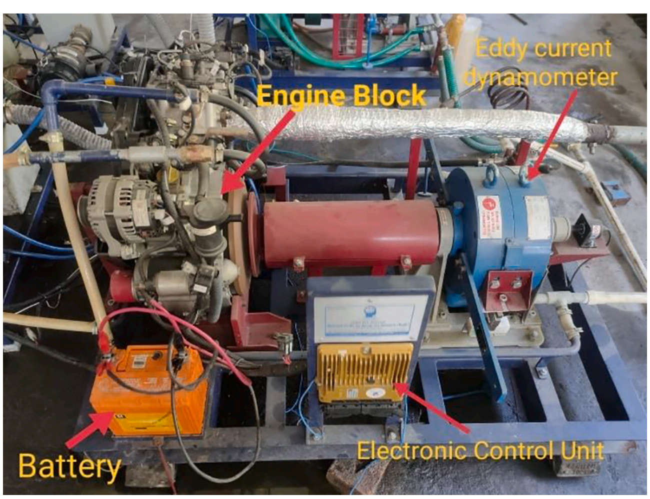

Fig. 3. Schematic of Engine Side View.

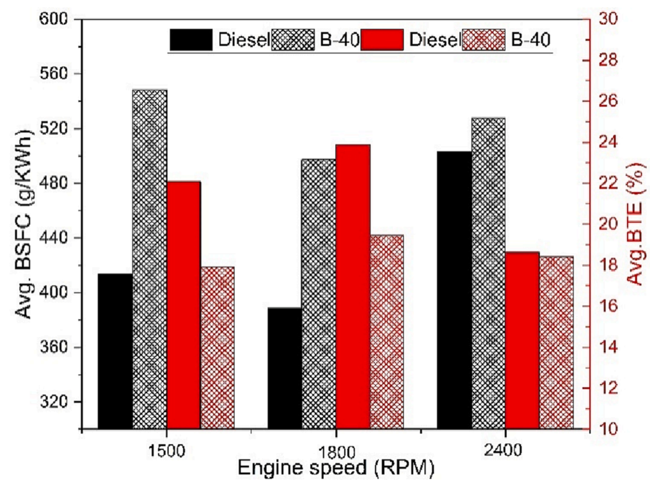

Fig. 4. Variation of BTE and BFSC with engine speed.

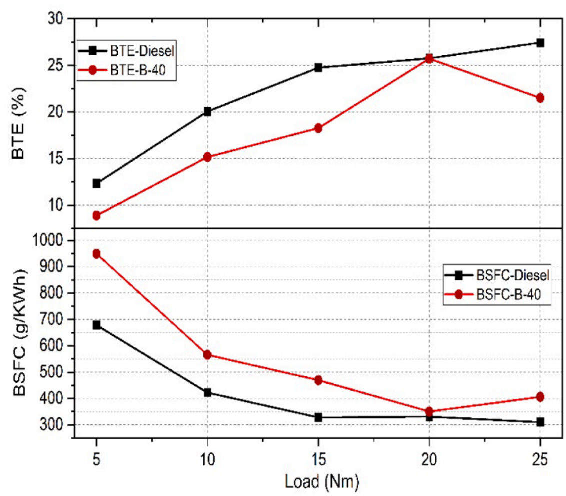

Fig. 5. Variation of BTE and BFSC with load at 1500 RPM.

3.3. Emissionssanalysis

In the present investigation, a DiGAS 444 model, AVL portable gas analyzer is used for measuring the exhaust gas emissions. The probe of the analyzer is inserted into the exhaustpipe of the engine before taking the measurements. After the engine has stabilized in working condition, the exhaust emissions have been measured. By using this analyzer,carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NOx), carbon dioxide (CO_2) and oxygen (O_2) are measured for the B40 blend and diesel fuel at different engine speeds. The various Indian standards used for emission analysis are given in Table 3 [26].

The average exhaust gas emissions of Avg NO_x, CO, CO_2 and HC

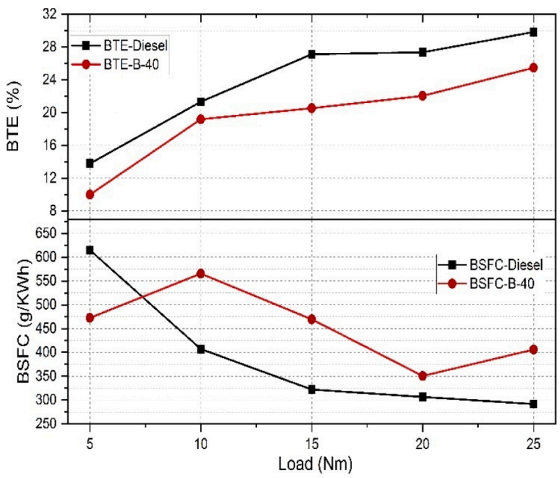

Fig. 6. Variation of BTE and BFSC with load at 1800 RPM.

forB40 and diesel fuels are shown in Fig. 9. It is observed that CO emissions are lower for B40 at 1500 and 1800 RPM compared to diesel fuel by 58.92% and 33.33%, respectively [27]. Higher oxygen availability in the fuel is believed to be the possible cause for lower CO emission in the lower B40 blend [28]. While at 2400 RPM, the emissions of CO are approximately equal for both the fuels [29]. With increase in engine speeds CO emission reduces similar trends were reported by [37,38]. The CO_2 emissions are higher for the B40 blend as compared to diesel at 1500 and 1800 RPM, while at 2400RPM, the CO_2 emission for B40 reduces by 3.66% relative to diesel fuel. Emissions of NOx are found to be higher for the B40 blend at all the tested RPMs as compared to diesel fuel [30,31], however, the increase in NO_x emission for B40 is the least at 2400 RPM which is only 1.01% more relative to diesel this may be due to the fact that NOx emissions increase with increased mass percent of oxygen in the biofuel and increased engine speeds [35,36]. While NOxemissions for B40 at 1500 and 1800 RPM are found to be 19.44% and 45% higher relative to diesel. The HC emissions are higher for B40 as compared to diesel fuel at 1500 and 2400 RPM by 1.6 ppm and 6.6 ppm volume, while at 1800 RPM, B40 gives lower HC emissions by 3.4 ppm vis-a-vis diesel fuel.

3.4. Combustion analysis

3.4.1. Combustion pressure

The variation of combustion pressure with respect to crank angle for diesel and the B40 blend for different engine speeds are shown in Fig. 10. The cylinder pressure is plotted against the crank angle for a crank angle from 40^0 before top dead center (bTDC) to 60^0 after top dead center (aTDC). Both the fuels show similar pattern for in cylinder pressure at all the tested RPMs [32]. At 1500 RPM, the peak pressures for diesel and B40 are found to be 68.18 bar at 6^0 aTDC and 70.26 bar at 5^0aTDC, respectively.

While at 1800 RPM, the corresponding values for both the fuels are 66.71 bar at 5^0aTDC and 68.60 bar at 5^0aTDC, respectively; and at 2400 RPM, they are 74.91 bar at 7^0aTDC and 74.22 bar at 6^0aTDC, respectively. It is observed that the peak pressure for the blend B40 is found to be higher than that of diesel fuel at 1500 and 1800 RPM, while at 2400 RPM, the peak pressures are found to be approximately similar for both the test fuels. This is due to the longer ignition delay (ID) of WCO biodiesel as compared to diesel. This longer ID is not much pronounced at higher engine RPMs. The in-cylinder pressures at 2400 RPM are appreciably higher for both the fuels as compared to their corresponding values at 1500RPM and 1800 RPM [34].

3.4.2. Heat release rate (HRR)

The variation of HRR with respect to crank angle for diesel and the B40 blend at different engine speeds are shown in Fig. 11. The cylinder pressure is plotted against crank angle for a crank angle from20^0bTDC to 40^0aTDC. It is seen that the HRR of B40 is slightly higher than diesel for 1500 and 1800 RPM, while for 2400 RPM, it is slightly lower. Also, the HRR decreases with the increase in engine speed due to the lesser time availability for the combustion process. The similar nature of the HRR for B40 and diesel is due to the fact that the B40 blend and diesel have the comparable spray formation characteristics however, the slight increase in the HRR for B40 at all engine speeds is due to higher oxygen fraction in B40 [33,34].

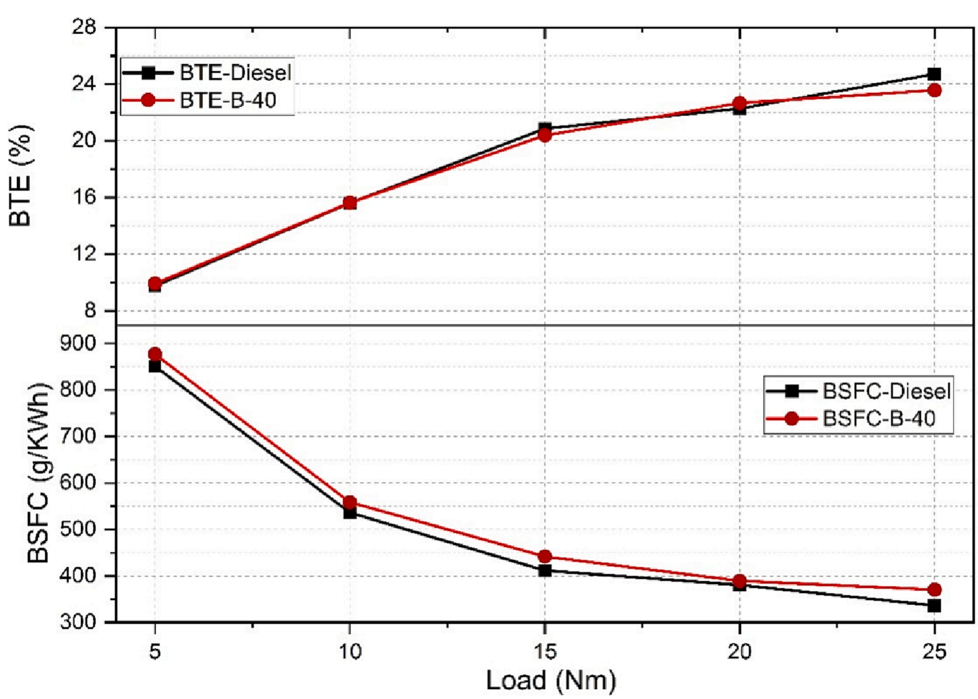

Fig. 7. Variation of BTE and BFSC with load at 2400 RPM.

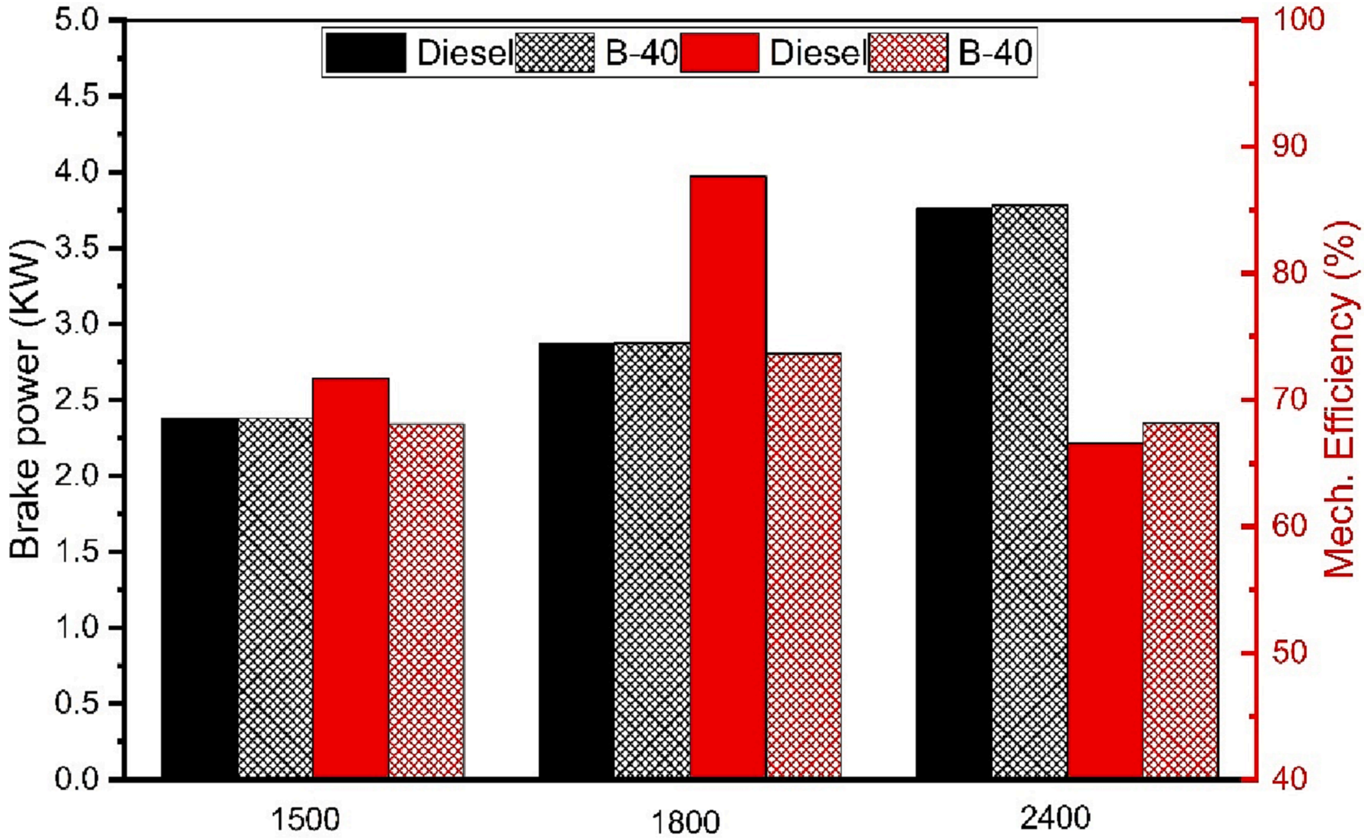

Fig. 8. Variation of average BP and average η_m with engine speed for diesel and B40.

Table 3
Indian standards used in emission measurement.

Gas Emission	Testing method
Carbon di-oxide	IS 13270:1992
Carbon mono-oxide	IS 11293:1992
Oxides of Nitrogen	IS 11255
Hydrocarbon	–

4. Conclusions

The performance, emissions and combustion characteristics of a single cylinder variable speed automotive engine fueled with WCO biodiesel blend B40 have been investigated at various engine speeds and the results obtained are compared with that of mineral diesel. The engine behaves differently at lower RPMs of 1500 and 1800 which is the stationary power generation speeds for India and China respectively and at higher RPM of 2400. The following conclusions can be drawn from the present study:

- At 2400 RPM, the automotive engine fueled with B40 blend gives identical performance as compared to diesel on various parameters. The BSFC is found to comparable to that of diesel at all load conditions. The average BP and η_m both are found to be higher as compared with diesel, while the average BTE is just 0.21% lower than diesel on absolute terms.
- At 2400 RPM, the diesel alike performance of B40 justifies the replacement of upto 40% diesel with WCO biodiesel for automotive applications in a commercial CI engine.
- When used for stationary power generation at 1500 RPM, the automotive engine run on B40 gives identical performance as that of diesel fuel at 80% load (20Nm). The BTE and BFSC values for B40 are (25.72% and 350.62 g/KWh)while that for diesel are (25.76% and 330.94 g/KWh). Further, at 1500 RPM, for B40 fuel, the average emissions of CO are found to be lower as compared to diesel with almost similar levels of HC, CO_2 and NO_xemissions vis a vis diesel fuel.
- At 2400 RPM, B40 gives lower CO_2emissions as compared to diesel (5.26 % vol and 5.46 % vol respectively), and almost diesel fuel like emission values of CO and NO_x while emissions of HC increased with respect to diesel fuel.

The above observations justify the usage of B40 blend in automotive engine for both stationary power generation (1500RPM) and automotive applications (2400RPM). However, the automotive application of B40 appears to be more promising as this gives similar BTE and BSFC at all the tested loads which is on an average 1.13% relative decrease in BTE and 4.87% relative increase in BSFC as compared with diesel fuel. Further,at 2400 RPM, the tested B40 fuel shows average decrease in CO_2 emission by 4.8% relative to diesel. The test results provethat upto 40% replacement of diesel with WCO biodiesel can be suitably done for commercial usage in automotive CRDi engines especially at higher RPMs.

CRediT authorship contribution statement

Keshab Biswakarma: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Pranjal Sarmah:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Prabhu Paramasivam:** Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Seshathiri Dhanasekaran:**

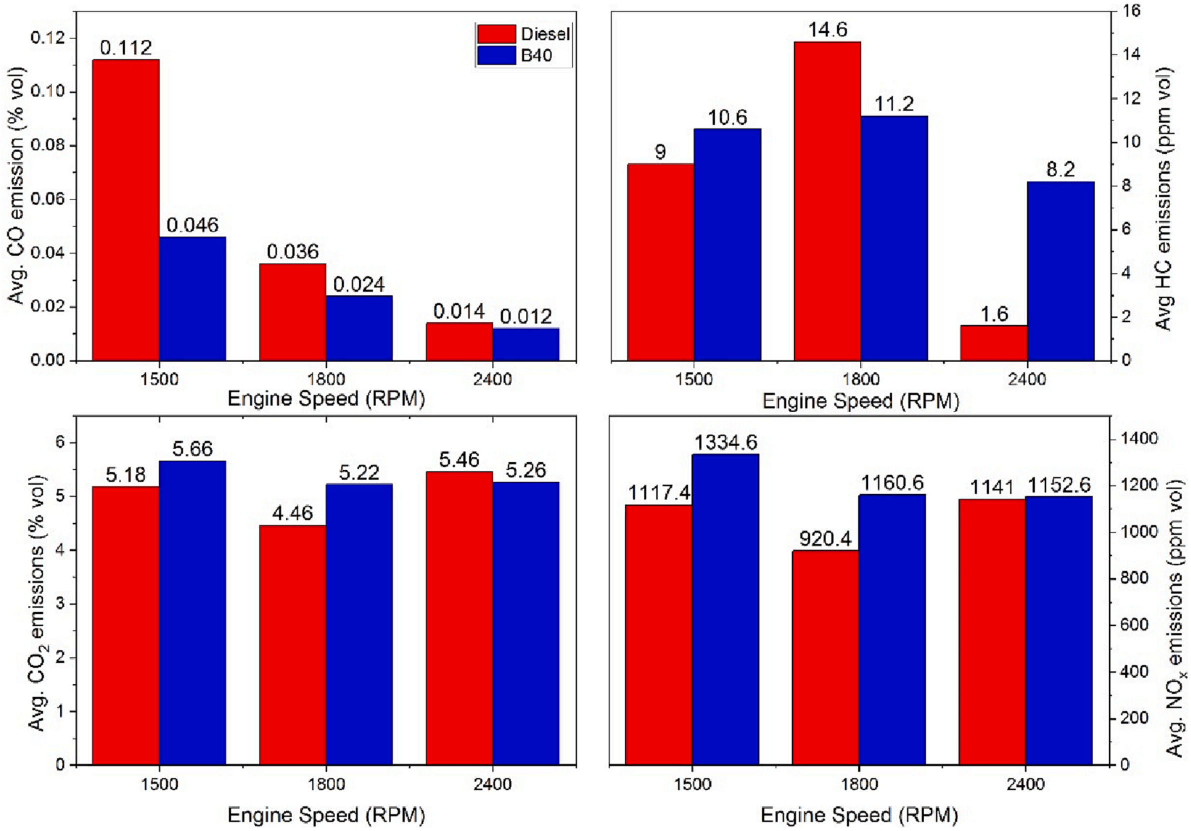

Fig. 9. Average exhaust gas emissions of B40 and diesel at different engine speeds.

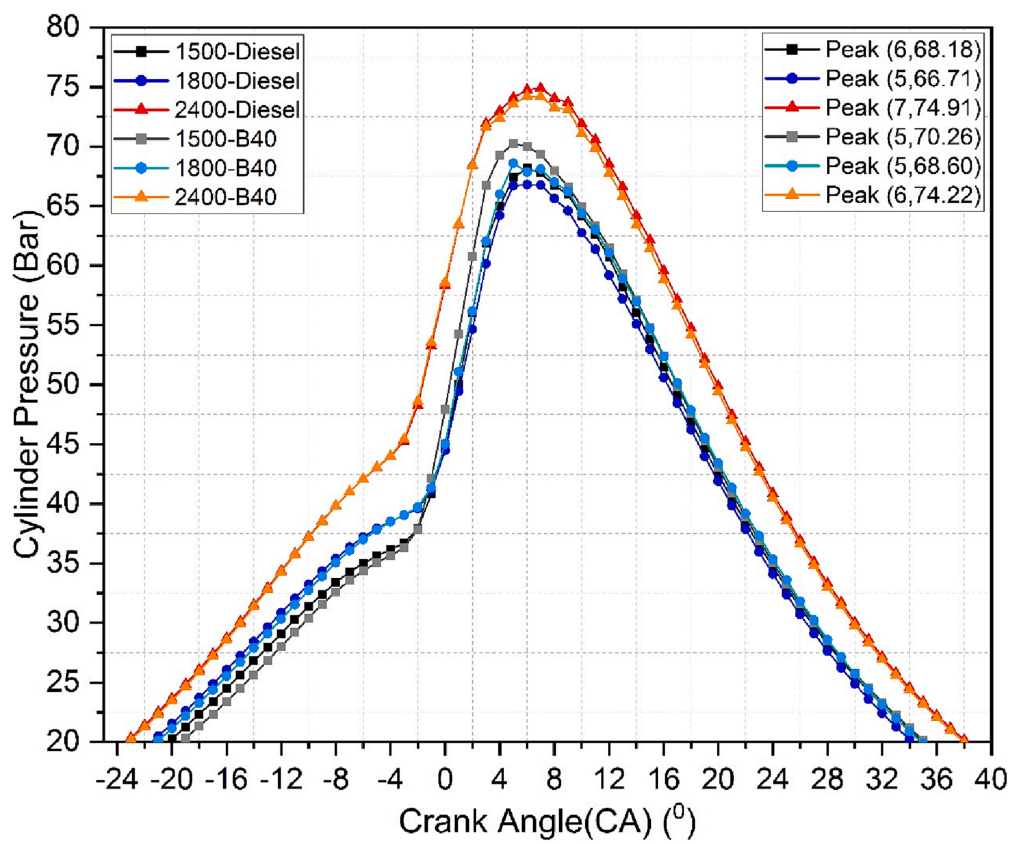

Fig. 10. Variation of average cylinder pressure with crank angle at different engine speeds for B40 and diesel.

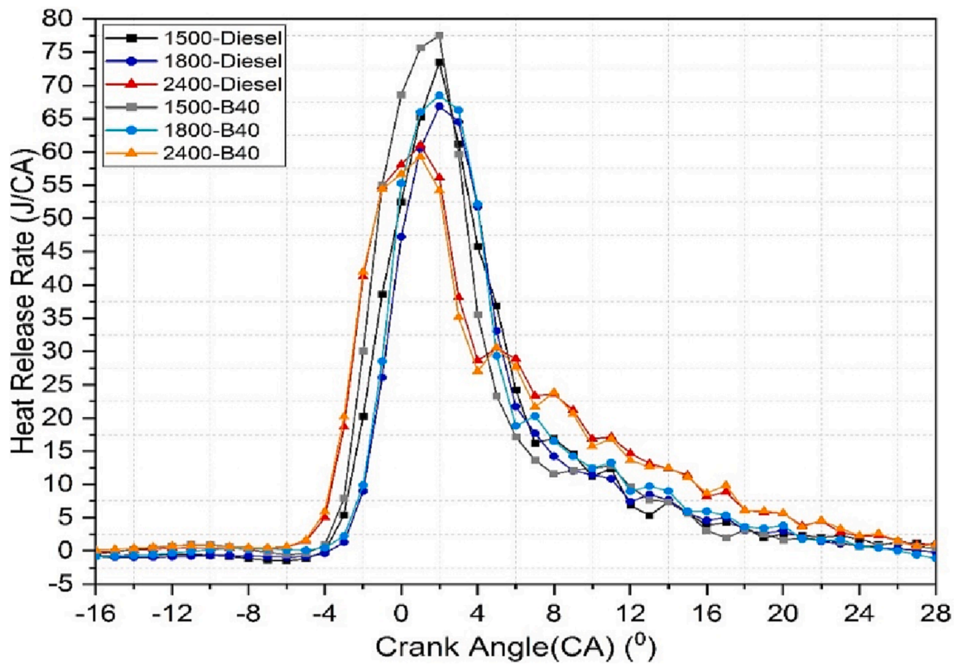

Fig. 11. Variation of average HRR with crank angle at different engine speeds for B40 and diesel.

Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Surendra Kumar Yadav:** Software, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Virendra Kumar:** Software, Resources, Data curation, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Kober T, Schiffer H-W, Densing M, Panos E. Global energy perspectives to 2060 – WEC's World Energy Scenarios 2019. Energy Strat Rev 2020:31. https://doi.org/10.1016/j.esr.2020.100523.
[2] Skytt T, Nielsen SN, Jonsson BG. Global warming potential and absolute global temperature change potential from carbon dioxide and methane fluxes as indicators of regional sustainability – A case study of Jämtland, Sweden. Ecol Indic 2020;110. https://doi.org/10.1016/j.ecolind.2019.105831.
[3] Ogunkunle O, Ahmed NA. A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines. Energy Rep 2019;5:1560–79. https://doi.org/10.1016/j.egyr.2019.10.028.
[4] Reitz RD, et al. IJER editorial: The future of the internal combustion engine. Int J Engine Res 2019;21(1):3–10. https://doi.org/10.1177/1468087419877990.
[5] Kreps BH. The Rising Costs of Fossil-Fuel Extraction: An Energy Crisis That Will Not Go Away. Am J Econ Sociol 2020;79(3):695–717. https://doi.org/10.1111/ajes.12336.
[6] Sarkar A, Dabi M, Saha UK. Supplementing the Energy Need of Diesel Engines in Indian Transport and Power Sectors. Sustain Energy Transp 2017:61–86. https://doi.org/10.1007/978-981-10-7509-4_5.
[7] Dabi M, Saha UK. Application potential of vegetable oils as alternative to diesel fuels in compression ignition engines: A review. J Energy Inst 2019;92(6):1710–26. https://doi.org/10.1177/1468087419877990.
[8] Dabi M, Saha UK. Implications of blended Mesua ferrea Linn oil on performance, combustion and emissions of compression ignition diesel engines. Therm Sci Eng Prog 2020:19. https://doi.org/10.1016/j.tsep.2020.100579.
[9] Sadaf SS, Iqbal J, Ullah I, Bhatti HN, Nouren S, Rehman H, Nisar J, Iqbal M. Biodiesel production from waste cooking oil: An efficient technique to convert waste into biodiesel. Sustain Cities Soc 2018;41:220–6. https://doi.org/10.1016/j.scs.2018.05.037.
[10] Gopal KN, Pal A, Sharma S, Samanchi C, Sathyanarayanan K, Elango T. Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends. Alex Eng J 2014;53(2):281–7. https://doi.org/10.1016/j.aej.2014.02.003.
[11] Abed KA, El Morsi AK, Sayed MM, El Shaib AA, Gad MS. Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. Egypt J Pet 2018;27(4):985–9. https://doi.org/10.1016/j.ejpe.2018.02.008.
[12] Muralidharanand K, Vasudevan D. Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. Appl Energy 2011;88(11):3959–68. https://doi.org/10.1016/j.apenergy.2011.04.014.
[13] Gad MS, Ahmed I, Seesy EL, Ali R, Zhixia H. Enhancing the combustion and emission parameters of a diesel engine fueled by waste cooking oil biodiesel and gasoline additives. Fuel 2020;269. https://doi.org/10.1016/j.fuel.2020.117466.
[14] Viornery-Portillo EA, Bravo-Díaz B, Mena-Cervantes VY. Life cycle assessment and emission analysis of waste cooking oil biodieselblend and fossil diesel used in apowergenerator. Fuel 2020;281. https://doi.org/10.1016/j.fuel.2020.118739.
[15] Geng P, Mao H, Zhang Y, Wei L, You K, Ju J. Combustion characteristics and NOx emissions of a waste cooking oil biodiesel blend in a marine auxiliary diesel engine. Appl Therm Eng 2017;115:947–54. https://doi.org/10.1016/j.applthermaleng.2016.12.113.
[16] Hwang J, Bae C, Gupta T. Application of waste cooking oil (WCO) biodiesel in a compression ignition engine. Fuel 2016;176:20–31. https://doi.org/10.1016/j.fuel.2016.02.058.
[17] Mazumdar B, Agarwal AK. Performance, Emission and Combustion Characteristics of Biodiesel (Waste Cooking Oil Methyl Ester) Fueled IDI Engine. SAE 2008:1384. https://doi.org/10.4271/2008-01-1384.
[18] Akcay M, Yilmaz IT, Feyzioglu A. Effect of hydrogen addition on performance and emission characteristics of a common-rail CI engine fueled with diesel/waste cooking oil biodiesel blends. Energy 2020:212. https://doi.org/10.1016/j.energy.2020.118538.
[19] Sania S, Kaisanb MU, Kullab DM, Obib AI, Jibrinc A, Ashok B. Determination of physico chemical properties of biodiesel from Citrullus lanatus seeds oil and diesel blends. Ind Crop Prod 2018;122:702–8. https://doi.org/10.1016/j.indcrop.2018.06.002.
[20] Di Yage CS, Huang ZH. Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil. Sci Total Environ 2009;407:835–46. https://doi.org/10.1016/j.scitotenv.2008.09.023.
[21] Lertsathapornsuk V, Pairintra R, Aryusuk K, Krisnangkura K. Microwave assisted in continuous biodiesel production from waste frying palm oil and its performance in a 100 kW diesel generator. Fuel Process Technol 2008;89:1330–2136. https://doi.org/10.1016/j.fuproc.2008.05.024.
[22] Subramaniyam S, Ganesan V, Rao PS. Turbulent flow inside the cylinder of a Diesel engine - an experimental investigation using hot wire anemometer. Exp Fluids 1990;9:167–74. https://doi.org/10.1007/BF00187418.
[23] Amir K, Azim M, Jaat M, Norrizal M, Manshoor B, Mas F, et al. Effects of Biodiesel Derived By Waste Cooking Oil on Fuel Consumption and Performance of Diesel

Engine. Appl Mech Mater 2014;554:520–5. https://doi.org/10.4028/www.scientific.net/AMM.554.520.
[24] Ekrem B. Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 2010;89(10):3099–105. https://doi.org/10.1016/j.fuel.2010.05.034.
[25] Jain S, Sharma MP, Rajvanshi S. Evaluation of engine performance on biodiesel from waste cooking oil. World multi-conference on systemics, Cybernetics & Informatics under Energy, Informatics & Cybernetics. Orlando, Florida, USA; June 29–July 2. 2008.
[26] Orhan A, Recep Y, Zeki A. Experimental investigation of the effects of diesel – like fuel obtained from waste lubrication oil on engine performance and exhaust emission. Fuel Process Technol 2010;91:1241–9. https://doi.org/10.1016/j.fuproc.2010.04.004.
[27] Haseeb Y, Yew HT, Sher F, Umer MF, Jamil MA, Kausar Z, Sabah NU, Faizan MS, Hafiz ZUR, Atiq UR. Potential of Waste Cooking Oil Biodiesel as Renewable Fuel in Combustion Engines: A Review. Energies 2021;14(9). https://doi.org/10.3390/en14092565.
[28] Bajpai S, Sahoo PK, Das LM. Feasibility of blending karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine. Fuel 2009:88. https://doi.org/10.1016/j.fuel.2008.09.011.
[29] Canakci M, Ozsezen AN, Arcaklioglu E, Erdil A. Prediction of performance and exhaust emissions of a diesel engine fueled with biodiesel produced from waste frying palm oil. Exp Syst Appl 2009;36:9268–80. https://doi.org/10.1016/j.eswa.2008.12.005.
[30] Rajasekar E, Murugesan A, Subramanian R, Nedunchezhian N. Review of NOx reduction technologies in CI engines fuelled with oxygenated biomass fuels. Renew Sustain Energy Rev 2010;14:2113–21. https://doi.org/10.1016/j.rser.2010.03.005.
[31] Valente OS, Pasa VMD, Belchior CRP, Sodre JR. Exhaust emission from a diesel power generator fuelled by waste cooking oil biodiesel. Sci Total Environ 2012;431:57–61. https://doi.org/10.1016/j.scitotenv.2012.05.025.
[32] Rao GLN, Sampath S, Rajagopal K. Experimental studies on the combustion and emission characteristics of a diesel engine fuelled with used cooking oil methyl ester and its diesel blends. Int J Eng Appl Sci 2008;4:64–70. https://doi.org/10.5281/zenodo.1061368.
[33] Stringer FW, Clarke AE, Clarke JS. The spontaneous ignition of hydrocarbon fuels in a flowing system. Proc Inst Mech Eng 1969;184:212–25. https://doi.org/10.1243/PIME_CONF_1969_184_334_02.
[34] Ozsezen AN, Canakci M, Turkcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009;88:629–36. https://doi.org/10.1016/j.fuel.2008.09.023.
[35] Lin YF, Wu YG, Chang CT. Combustion characteristics of waste - oil produced biodiesel/diesel fuel blends. Fuel 2007;86:1772–80.
[36] Labeckas G, Slavinskas S. The effect of rapeseed oil methyl ester on direct injection Diesel engine performance and exhaust emissions. Energ Conver Manage 2006;47:1954–67.
[37] Sugozu I, Oner C, Altun S. The Performance and Emissions Characteristics of a Diesel Engine Fueled with Biodiesel and Diesel Fuel. Int J Eng Res Dev 2010;2:50–3.