INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 18, ISSUE 4, 9349 – 9361
DOI: https://doi.org/10.15282/ijame.18.4.2021.16.0719

Universiti Malaysia PAHANG

ORIGINAL ARTICLE

Performance of Waste Insulating Mineral Oil-Based Biodiesel in a Direct-Injection CI Engine

A. Sivakumar[1], R. Sathiyamoorthi[2], V. Jayaseelan[3], R. Ashok Gandhi[4], and K. Sudhakar[5,6,7*]

[1]Department of Mechanical Engineering, Christ College of Engineering and Technology, 605110 Puducherry, India.
[2]Department of Mechanical Engineering, Panimalar Engineering College, Chennai, 600123 Tamil Nadu, India
[3]Department of Mechanical Engineering, Prathyusha Engineering College, Chennai, 602025 Tamil Nadu, India
[4]Department of Mechanical Engineering, Sri Sai Ram Engineering College, Chennai, 600069 Tamil Nadu, India
[5]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Pekan, 26600, Pahang, Malaysia.
[6]Autmotive Engineering Centre, Universiti Malaysia Pahang, Pekan, 26600, Pahang, Malaysia
[7]Energy Centre, Maulana Azad National Institute of Technology Bhopal,462003, India
Phone: +6094246249;Fax: +6094246222

ABSTRACT – Mineral oil has been used as an insulating fluid in the power industry. However, surplus waste oil poses serious environmental threats because of disposal concerns. Waste to biofuel is an excellent way to deal with waste material from various sources. In this study, the trans-esterification method was utilised to convert the waste-insulating mineral oil into a quality bio-fuel. Waste-insulating transformer oil was converted to biodiesel, and it was tested according to ASTM standards. Four different blends of waste-insulating biodiesel with diesel in 25 per cent (WIOBD25), 50 per cent (WIOBD50), 75 per cent (WIOBD75), and 100 per cent fractions (WIOBD100), were used for performance testing in a direct injection compression ignition (DICI) engine. The combustion parameters such as BSFC, EGT, and BTE were evaluated with varying crank angles and constant engine speed. The waste-insulating biodiesel performance results are then compared with diesel fuel. BSFC increased as the biofuel mixture in diesel was raised, and the brake thermal efficiency (BTE) was significantly reduced compared to diesel for all WIOBD diesel mixtures. Due to the combustion process, a high pressure and heat release rate (HRR) were noticed inside the cylinder with the waste-insulating oil-derived biodiesel samples. WIOBD biodiesel blends produced lower levels of hydrocarbon, carbon monoxide, and smoke emissions than diesel fuel, but greater levels of nitrogen oxides (NOx) were produced than diesel fuel. In addition to lower emissions combined with improved engine performance, the WIOBD25 fuel blend has been found to be experimentally optimal for practical application. As a result, the test findings indicated that WIOBD biodiesel might be used as a substitute for conventional diesel fuel.

ARTICLE HISTORY
Received: 27th Jan 2021
Revised: 15th Nov 2021
Accepted: 22nd Dec 2021

KEYWORDS
Bio-diesel;
Waste insulating oil;
Combustion;
Emission;
Performance

INTRODUCTION

The utilisation of unused waste oils can replace the current challenges of petroleum product depletion. Waste oils from various resources lead to severe environmental challenges because of their disposal issues. Waste oils, namely waste plastic oil, waste transformer oil, waste gear oil, oil from waste automobile tires, oil from cooking waste, waste furnace oil, waste turbine oil and heat transfer oil, spent oil, etc., can be utilised as fuel. Waste insulating oil is used in electrical transformers as a cooling medium and insulation material. Insulating oil can be synthesised from wax-free naphthenic oils. Three different types of insulating oil are used in electrical transformers. After continuous usage of coolant oil, it gets deteriorated and becomes waste. However, waste insulating physical, chemical properties, and heating values need to be assessed before testing diesel engines. In recent years, recycling waste oils and utilising them in diesel engines have become a focus for researchers.

Dorado et al. [1] have used methyl ester to fuel diesel engines from olive oil wastes. Reductions in CO emission up to 58.9%, NO emission up to 37.5%, and SO2 up to 57.7% were observed, whereas brake specific fuel consumption (BSFC) rises to 8.5%. Pugazhvadivu and Jeyachandran [2] examined pre-heated fried oil properties as a fuel that potentially reduced CO and smoke emissions. Lin et al. [3] examined waste cooking oil; experimental findings showed that CO and HC had decreased. Kumar et al. [4] used waste plastic oil (WPO), leading to reduced BTE and HC emissions, whereas the NOx, CO, and BSFC increased with the WPO mixing ratio. Hariharan et al. [5] have studied the diethyl ether (DEE) using tire pyrolysis oil (TPO) from useless automobile tires in the direct injection of fuel into diesel engines. DEE was supplied in the inlet air with specific flow levels of 65, 130, and 170 g / h. The test results showed that DEE-TPO worked better at 130 g/h and reduced emissions. The peak pressure using TPO was higher at 130 g/h with diesel fuel. Can [6] examine the influence of waste cooking oil (WCO) bio-fuel mixtures (5 per cent, 10 per cent) on the diesel engine. The pressure variation does not occur suddenly due to the addition of biodiesel. BSFC increased 4 %, BTE reduced 2.8 % for the entire engine load, while emissions decreased.

*CORRESPONDING AUTHOR | K. Sudhakar | sudhakar@ump.edu.my

Hurdogan et al. [7] have investigated waste tire pyrolysis oil-diesel blends; the test results revealed a comparable engine performance with diesel fuel operation concerning torque and energy output. Damodharan et al. [8] have investigated WPO; it was extracted from catalytic pyrolysis, the timing of injection (21°, 23°, 25° CA bTDC), and EGR (10%, 20%, and 30%) on combustions and emissions were studied. NOx emission decreased up to 52.4% at 30% EGR and 21°CA bTDC, whereas smoke emission was decreased by 46% and 9.5% for EGR10% and 20% respectively at 25°CA bTDC. Wang and Ni [9] have used biodiesel from waste lubrication oil. BSFC reduced by 3% at lower and medium loads by using biodiesel from lubrication oil. NOx emission increased slightly at lower and higher loads with higher smoke emission at a medium load condition. It was used in high-speed diesel engines with zero issues. Senthilkumar and Sankaranarayanan [10] have utilised biodiesel from WPO through the pyrolysis process, mixing Jatropha methyl ester (10 %, 20%) and WPO. The findings showed a 2.24 % improvement in BTE for WPO-JME blends in full load condition relative to WPO. BSFC increased with a rise in the JME blend ratio at increasing engine load. Smoke emission decreased by 11.4% at PJ20 fuel blend than WPO. UTO and acetylene have been used by Behera et al as fuel in the DI diesel engine Behera et al. [11]. Acetylene was supplied with air as the primary fuel at varying flow rates, UTO was injected at optimised injection timing as pilot fuel. The test showed that the ignition delay decreased 3°CA, and cylinder pressure decreased 25 % relative to UTO. This also received higher BTE and lesser exhaust gas temperatures at full load. Smoke emission becomes reduced by 13.7% than UTO operation. In this investigation, waste transformer oil was converted to biodiesel and mixed in 25%, 50%, 75%, and 100% fractions with diesel and tested in a DICI. BSFC, EGT, and BTE were surveyed, compared to diesel fuel, and analysed combustion parameters with various crank angles and constant engine speed. Emission parameters, such as HC, NOx, CO, and smoke, are analysed and compared to standard fuel emission levels.

PRODUCTION AND CHARACTERISATION OF TEST FUEL

In this work, waste insulating oil was collected from a diesel-electric power station located in Panimalar Engineering College/Medical College Campus, Chennai, India. The used oil type was Paraffin based. Methanol WIOBD methyl esters were obtained with an alkali - catalysed through a single-step trans-esterification process. Triglycerides react with methanol alongside NaOH, which results in the formation of fatty acids ester and glycerol. Initially, 800 ml of transformer oil methyl ester is mixed with methanol 200 ml and 2g of NaOH. The blend was gradually mixed till the ester was formed. Then, the mixtures were applied to the heating process of 80°C and 12 hours. Two layers are eventually formed; glycerol is in the base layer and the ester in the top layer. The reaction mechanism for WIOBD biodiesel production using the trans-esterification process is indicated in Figure 1.

The excess alcohol removal process was carried out for the purification process of esters. The heating of esters removed the alcohol condensate at 70 °C and the pressure reduction in the distillation column cooling unit to speed up the alcohol evaporation. The biodiesel production is completed when water is evaporated away from the biodiesel at the temperature of 120 °C. The biodiesel yield obtained using the trans-esterification process is 96.5% (m/m). The stages of the transesterification of WIOBD are shown in Figure 2.

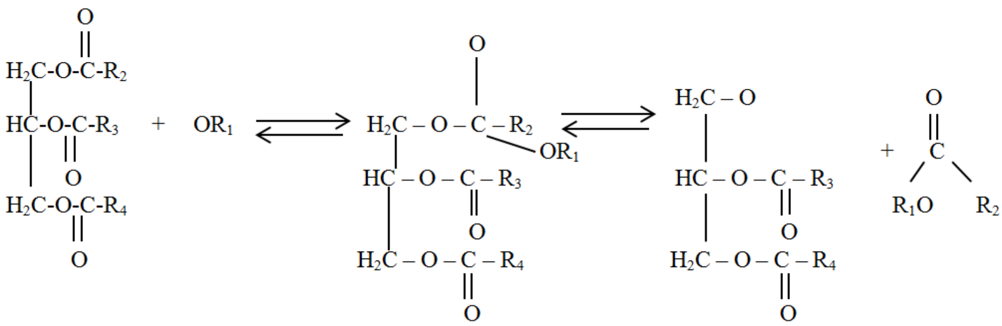
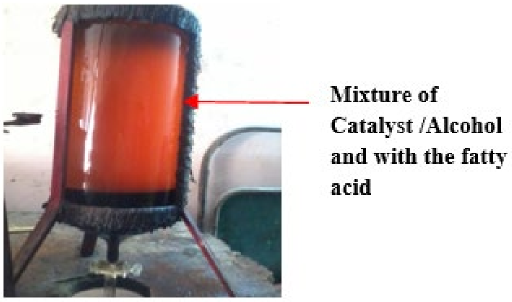
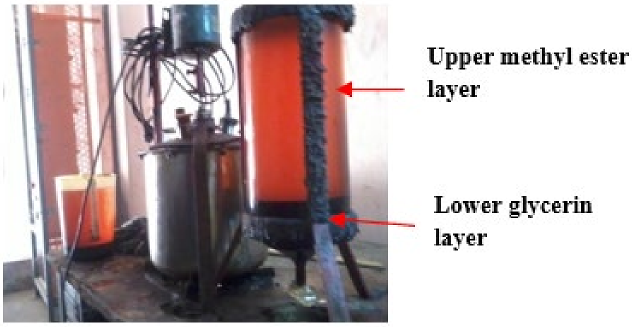


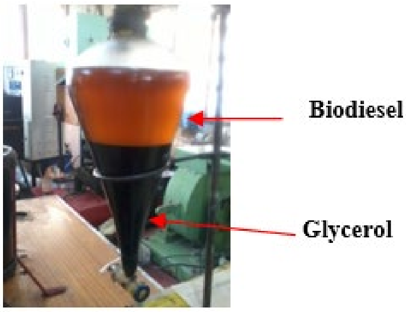
Figure 1. Biodiesel trans-esterification process.



(a) reaction between the mixture of catalyst/alcohol and with the fatty acid (triglycerides)



(b) lower glycerin layer and Upper methyl ester layer



(c) separation of glycerol from biodiesel

Figure 2. Stages of transesterification of WIOBD.

After eliminating excess alcohol, the glycerine was separated from the ester process and filtered to eliminate any strong impurities. Table 1 demonstrates the experimental investigation using four different blends of WIOBD biodiesel (WIOBD25, WIOBD50, WIOBD75, and WIOBD100). In unmodified engines, the higher viscosity of waste insulating oil leads to severe problems. The higher viscosity of fatty oils results in choking injector tips because of improper arrangements in atomisation and incomplete combustion. The viscosity of the fuel can be decreased by non-saturation but can result in degradation by mono, di, or triglycerides; this provides a measure of the quality of the combustion. Fuels with lower cetane numbers result in an increase in emissions due to incomplete burning. Cetane numbers up to 55 are the most appropriate for better combustion efficiency Lawlor and Olabi [12]. WIOBD contains compounds in its chemical structure, such as alkanes, amines, aromatics, nitriles, carboxylic acids, alcohols, and phenols.

WIOBD has 89.94% carbon, 9.22% hydrogen, 0.0299% nitrogen, and 0.345% sulfur based on the ultimate analysis carried out by Sathiyamoorthi et al. [13]. WIOBD has an alkane group of Hexadecane, which is highly flammable and anti-corrosive. It vaporises quickly in the combustion chamber without forming any droplets, resulting in uniform combustion. Another element present in the WIOBD is Eicosane which has higher melting points and becomes too thick to flow. Table 2 displays the chemical compounds of WIOBD and its chemical structure analysed by Gas chromatography-Mass spectrometer analysis. Table 3 delivers the details of the volumetric percentage of fuel used.

Table 1. WIOBD-blends and diesel properties.

Properties	ASTM Standard	Diesel	WIOBD25	WIOBD50	WIOBD75	WIOBD100
Density (kg/m^3)	ASTM D445	857	871	885	899	912
Flash point (°C)	ASTM D93	52	79	108	135	163
Fire point (°C)	ASTM D92	56	86	116	146	176
Cetane number	ASTM D 976	52	49	47.5	45.25	43
Kinematic viscosity (cSt at temperature 40°C)	ASTM D2217	2.54	3.03	3.53	4.02	4.52
Carbon residue (%)	ASTM D4530	27	20.25	13.51	6.76	0.021
Sulphur content (%)	ASTM D2622	0.041	-	-	-	-
Gross calorific value (MJ/kg)	ASTM D240	43.35	42.13	40.91	39.69	38.47

Table 2. Various chemical compounds and the chemical structures of WIOBD analysed by GC-MS.

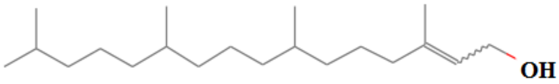
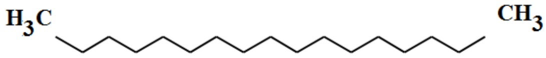
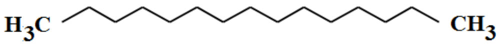
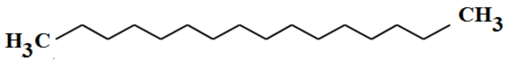
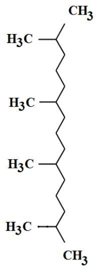
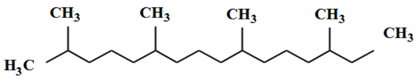
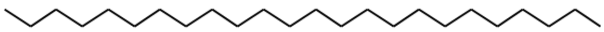
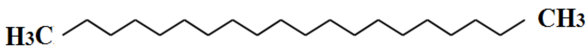
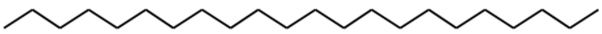
Name of the component	Chemical structure	Chemical formula
Tridecane		$C_{13}H_{28}$
Tetradecane		$C_{14}H_{30}$
3, 7, 11, 15,-Tetramethyl-2-Hexadecen-1-OL		$C_{20}H_{40}O$
Heptadecane		$C_{17}H_{36}$
Pentadecane		$C_{15}H_{32}$
Hexadecane		$C_{16}H_{34}$
2, 6, 10, 14-Tetramethylpentadecane		$C_{19}H_{40}$
2, 6, 10, 14-Tetramethylhexadecane		$C_{20}H_{42}$
Tetracosane		$C_{24}H_{50}$
Tricosane		$C_{23}H_{48}$
Eicosane		$C_{20}H_{42}$
Heneicosane		$C_{21}H_{44}$
Docosane		$C_{22}H_{46}$
Nonacosane		$C_{29}H_{60}$

Table 3. Volumetric percentage of fuel used.

Abbreviation	Volumetric percentage of fuel
WIOBD25	25% Waste insulating Oil biodiesel + 75% Diesel
WIOBD50	50% Waste insulating Oil biodiesel + 50% Diesel
WIOBD75	75% Waste insulating Oil biodiesel + 25% Diesel
WIOBD100	100% Waste insulating Oil biodiesel + 0% Diesel

EXPERIMENTAL WORK

Figure 3 depicts the diesel engine's experimental setup and the instrumentation details. Table 4 describes the engine specifications. Stopwatch and burette are used to calculate fuel consumption for each load. The piezoelectric pressure sensor measures the cylinder pressure, and the magnetic pick-up sensor measures the crank angle. The combustion data includes the ignition delay, combustion time, HRR, and cylinder pressure at its peak values. The AVL Digas 444 is used to quantify gas emissions such as CO, CO_2, HC, and NOx, whereas the EGT AVL437 smoke meter is used to assess smoke emissions using a chromel-alumel thermocouple. The detailed specifications of the smoke meter and gas analyser are shown in Table 5. The research engine was run for 30 minutes after each loading to achieve a steady-state speed of 1500 rpm. Before starting the research engine, the lubricating oil level was checked. The experimental results were averaged by taking the readings thrice to get the accurate readings. The injection pressure is 200 bar, and the injection time is 23°b TDC for all the blends.

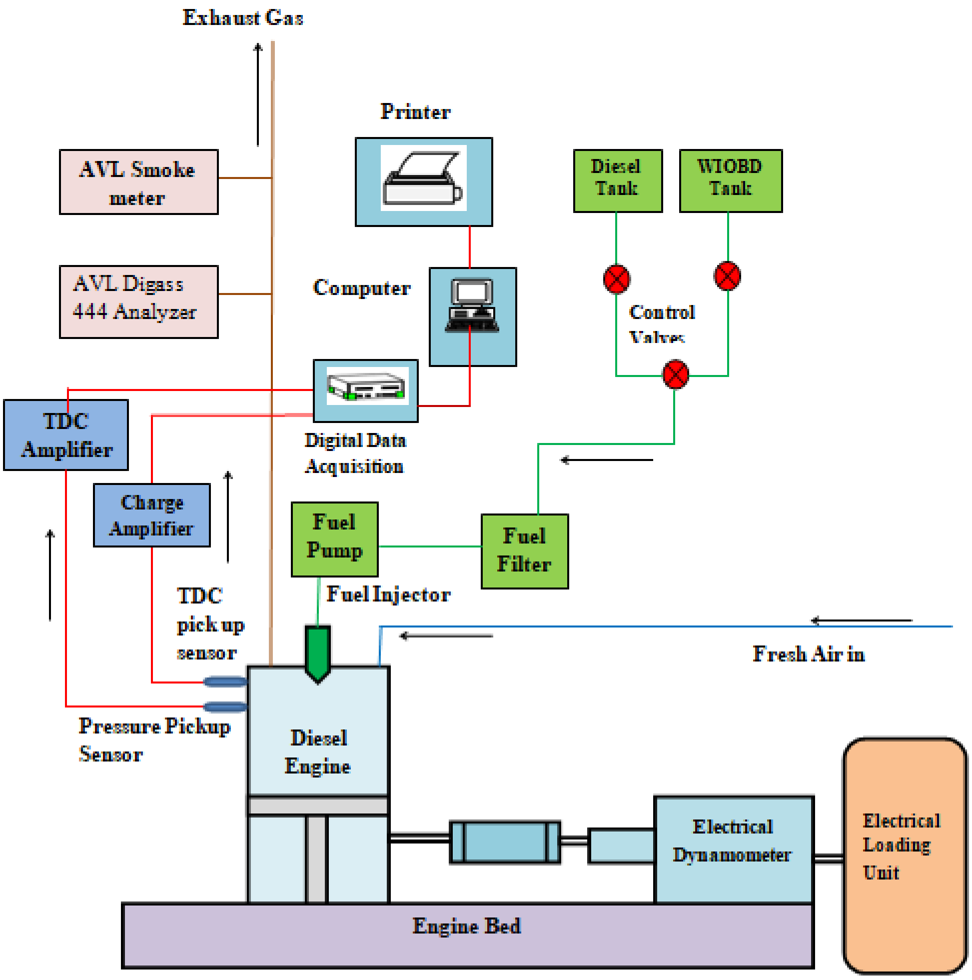


Figure 3. Experimental setup of the diesel engine along with the instrumentation.

Table 4. Engine details.

Model	Kirloskar TV1	Compression ratio	17.5:1
Type	Single-cylinder, 4- stroke, DI	Speed (rpm)	1500
Power (kW)	5.20 kW	Cooling type	Water
Bore (mm)	87.5	Number of holes	3
Stroke (mm)	110	Diameter of the nozzle hole (mm)	0.25
Cubic capacity (litres)	0.661	Fuel injection timing	23˚ bTDC

Table 5. Smoke meter and gas analyser specification.

Instrument/analyser	Gas-emission	Accuracy	Range	% Error
Smoke meter	Smoke Intensity	+1%	0-100	± 2
Gas analyser	HC	+ 10 ppm	0-20000 ppm	± 1 ppm
	CO	0.01	0-10 volume %	± 0.01 %
	NO_x	+ 10 ppm	0-5000 ppm	± 1 ppm
	CO_2	0.01	0-10 volume %	± 0.01 %

Uncertainty Analysis

Instrument inaccuracies are determined by calibration, reading observation, atmospheric conditions, and instrument selection. It's utilised to figure out how accurate the instruments employed in the study performed. It was used to calculate uncertainties of different engine parameters such as BSFC, brake power (BP), BTE, EGT, HC, CO, CO2, NOx, and smoke emissions Gharehghani et al. [14]. Usually, uncertainty arises based on the various conditions like the selection of instrument, its calibration, working environment, observation and record of the experiment. Generally, the reliability of an investigation is supported with the help of uncertainty analysis. Taylor's theorem [15] has been used to establish the exactness of the experiments conducted, and the uncertainty is ± 2.27 %. Overall uncertainty is given by the following Eq. (1).

$$\sqrt{(BP)^2+(BSFC)^2+(EGT)^2+(BTE)^2+(HC)^2+(CO)^2+(Smoke)^2+(NO_x)^2+(CO_2)^2+(Pre.pickup)^2} \quad (1)$$

RESULTS AND DISCUSSION

Analysis of Performance Parameters

Brake specific fuel consumption (BSFC)

Figure 4 indicates variation in BSFC to BP for the different WIOBD-diesel mixtures. BSFC shows the quantity of fuel delivered to the engine for power generation per cycle. It is evident from the obtained results, WIOBD -diesel blends exhibit an increase in BSFC for all the loads. The actual reason behind the BSFC increase is the calorific value of WIOBD-blends requiring large amounts of fuel to produce the same energy as diesel Ospina et al. [16]. BSFC increases by 3.62% for WIOBD25 fuel blend than diesel fuel. Moreover, BSFC increases by 2.52 %, 3.04 %, and 3.52 % for WIOBD50, WIOBD75, and WIOBD100 fuel blends, respectively, compared to WIOBD25. BSFC at lower loads exhibited higher values and decreases at high engine loads for the fuel blends. The explanation should be the reduction in the residence time of all combustion products and the improved volumetric performance at higher engine loads during the exhaust, which would lead to a decrease in the BSFC [17].

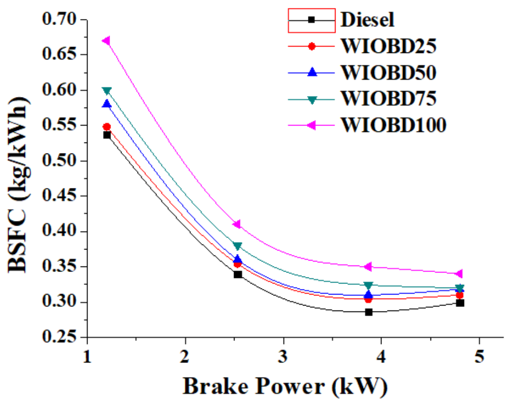


Figure 4. BSFC Vs BP for diesel and WIOBD-blends.

Brake thermal efficiency (BTE)

BTE is the ratio of the availability of heat energy from fuel combustion to a transfer of energy from the engine to the crankshaft [18]. The BTE variation with BP is revealed in Figure 5. BTE of the WIOBD-diesel blends showed lower value at all the engine loads when compared with diesel. BTE of WIOBD25 decreases by 7.21% than diesel fuel. Furthermore, BTE decreases by 4.94%, 9.18% and 4.83% for WIOBD50, WIOBD75, and WIOBD100 fuel blends, respectively, than WIOBD25. The lower BTE can be credited to the lesser calorific value of WIOBD mixtures than standard fuel [19]. Decreases in BTE are attributed to poor combustion features and low stability of WIOBD-blends than diesel [14].

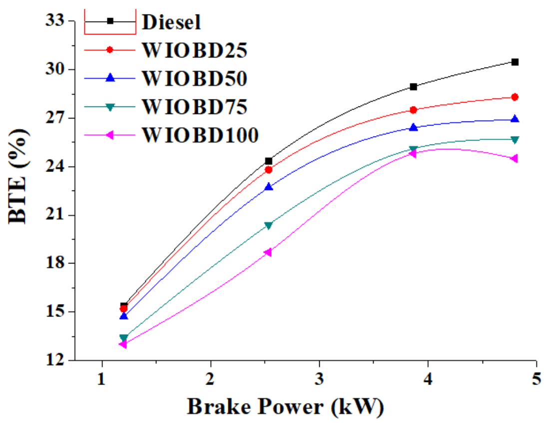


Figure 5. BTE Vs BP for diesel and WIOBD-blends.

Exhaust gas temperature (EGT)

Figure 6 shows EGT variation with BP; when an increase in load, EGT increases for all the blends of diesel and WIOBD. It was due to the higher reaction rate, HRR, and flame velocity of fuel blends during the combustion cycle. EGT for WIOBD25 increases by 2.69% than diesel. On the other hand, EGT increases by 3.05%, 5.52%, and 8.62% for WIOBD50, WIOBD75, and WIOBD100, respectively, then diesel. In addition, an increase in EGT due to unburnt fuel particles take part in the burning progression.

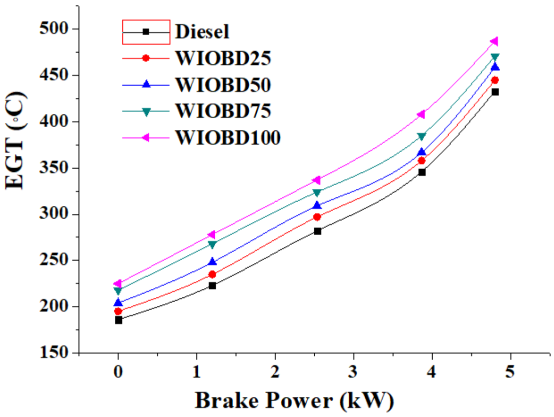


Figure 6. EGT Vs BP for diesel and WIOBD-blends.

Analysis of Combustion Parameters

Ignition delay and cylinder pressure

Ignition delay (CA) was calculated as the difference between the crank angle, at which 5% of the heat emitted and the crank angle at which the fuel was fed into the combustion chamber. Figure 7 illustrates the variation of BP to ignition delay for all WIOBD diesel mixtures. As the engine load increases for WIOBD-diesel mixtures, the ignition delay decreases. Figure 8 indicates the difference in the cylinder pressure at various crank angles for the different WIOBD diesel mixtures at various engine loads. At the WIOBD100 fuel mix, the average cylinder pressure is 71.91 bar, 11.04 per cent higher than diesel. The result indicates the ignition occurs sooner for WIOBD fuel blends than for diesel during peak loads. It is owing to high cetane numbers and oxygen molecules, early ignition in the biodiesel blends.

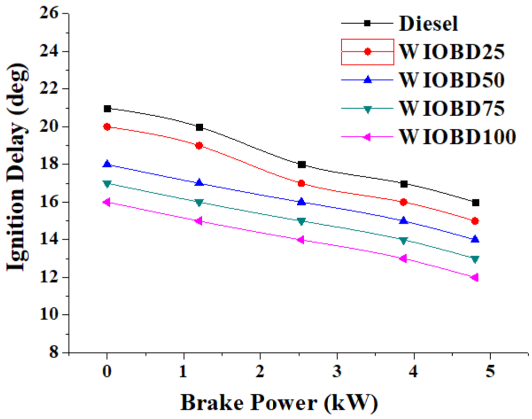
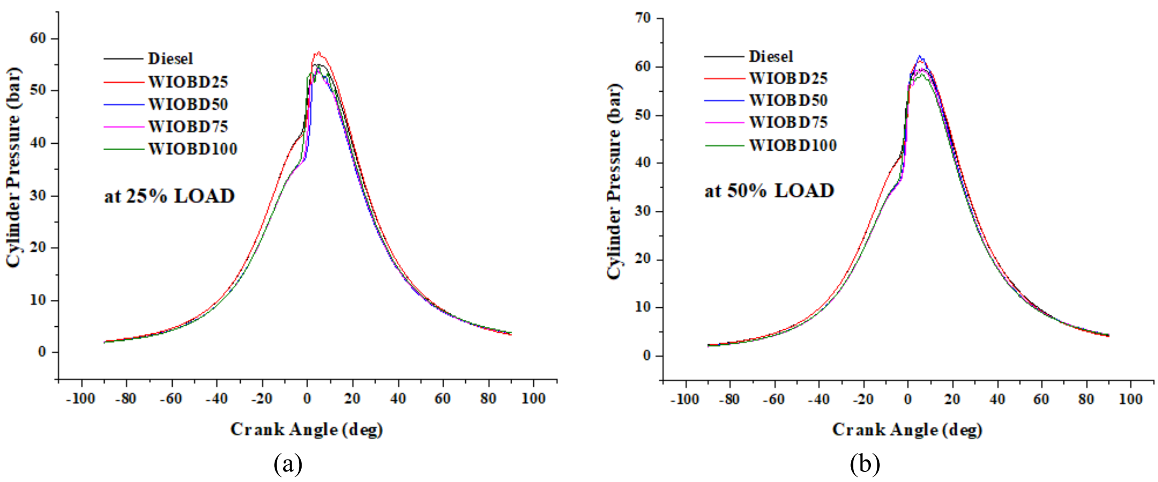


Figure 7. Ignition delay vs BP for diesel and WIOBD-blends



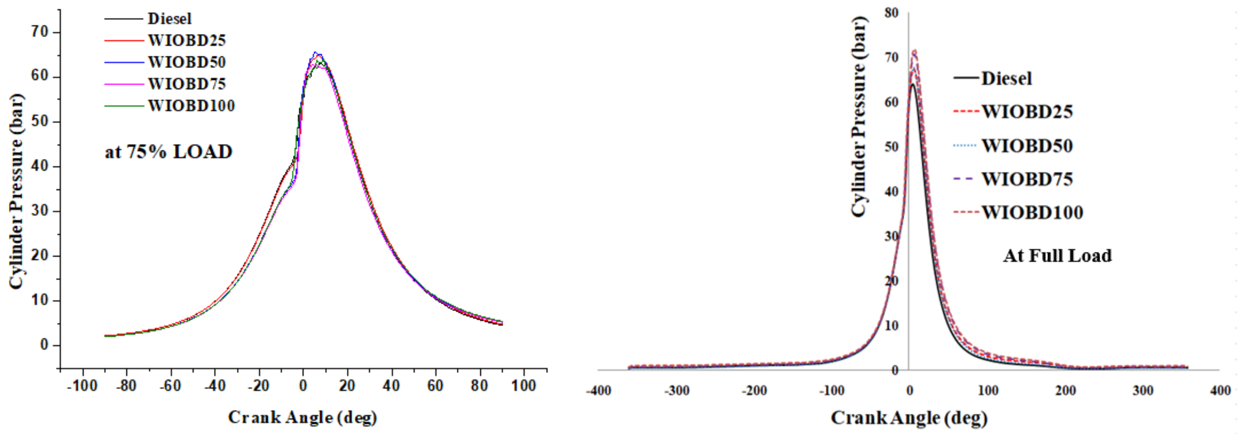


Figure 8. Cylinder pressure vs. crank angle for diesel and WIOBD-blends at different loads.

The ignition occurs early at 1.8°, 2.1°, 2.4° and 3.2° CA for WIOBD25, WIOBD50, WIOBD75, and WIOBD100 fuel blends, respectively. The cylinder pressure increases by 5.15 %, 5.69 %, 9.57 % and 11.04 % respectively for WIOBD25, WIOBD50, WIOBD75 and WIOBD100 in comparison with diesel fuel. For different WIOBD-diesel mixtures, the peak cylinder pressure to BP is shown in Figure 9. The peak cylinder pressure was observed as 63.97 bar, 67.4 bar, 67.83 bar, 70.75 bar, and 71.91 bar for Diesel, WIOBD25, WIOBD50, WIOBD75, and WIOBD100 fuels, respectively.

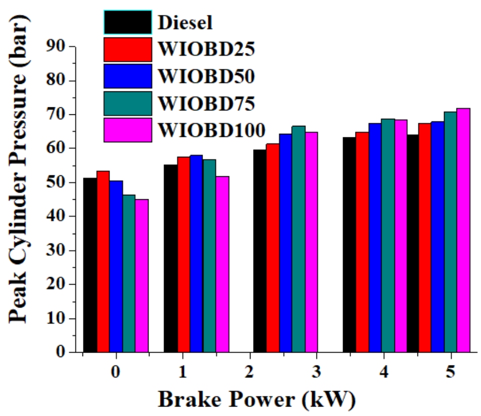


Figure 9. Peak Cylinder pressure vs BP for diesel and WIOBD-blends.

Heat release rate (HRR)

HRR was developed by the energy conservation law and the state equation. Equation (2) provides the measurement for the HRR [14].

$$Q = \frac{\gamma}{(\gamma - 1)} P \left(\frac{dv}{d\theta}\right) + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \tag{2}$$

where, Q - HRR, P - Cylinder pressure, γ -Specific heat ratio (C_p/C_v), V -Cylinder volume and θ -Crank angle. Figure 10 indicates the variation of HRR to the crank angle for specific WIOBD-diesel blends. The HRR curve consists mainly of premixed combustion and diffusion combustion stages, with an improvement in HRR relative to diesel for all mixtures. Figure 11 shows the maximum HRR with BP for the various WIOBD-diesel blends. The maximum HRR are observed as 97.287 kJ/m^{3}deg, 100.48 kJ/m^{3}deg, 109.99 kJ/m^{3}deg, 113.74 kJ/m^{3}deg and 130.03 kJ/m^{3}deg for diesel, WIOBD25, WIOBD50, WIOBD75 and WIOBD100 respectively. The higher WIOBD cetane number initiates the early stages of combustion and results in the highest HRR during the diffusion stage of combustion. Improved diffusion in biodiesel mixtures is due to an increased oxygen content [20], [21].

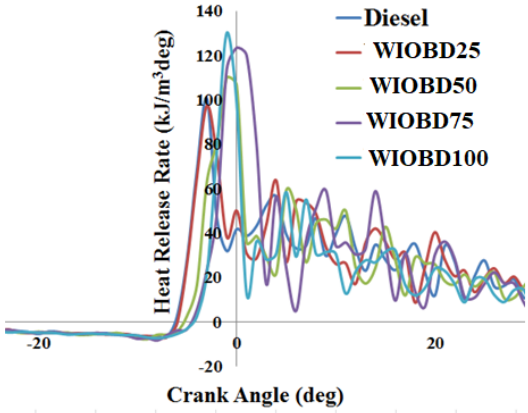


Figure 10. HRR vs crank angle for diesel and WIOBD-blends.

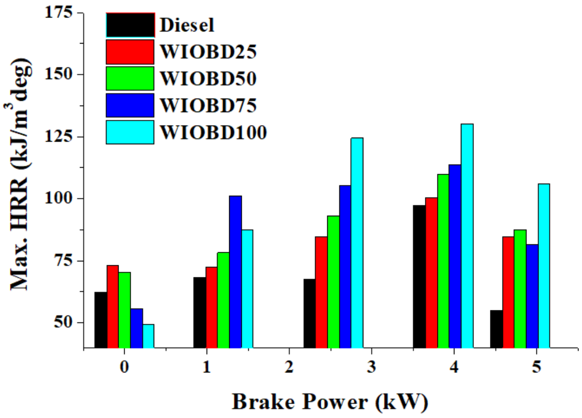


Figure 11. Maximum HRR vs BP for WIOBD-diesel blends.

Combustion duration

The mass burning of fuel can measure the combustion time from 10% to 90% for the respective crank angle position [14]. Figure 12 depicts the variance in the period of combustion with BP for different WIOBD-diesel blends. The result indicates a decrease in combustion duration for these WIOBD-diesel mixtures. Because WIOBD biodiesel has higher oxygen content, this increases the oxidation rate and thus shortens the combustion time [22].

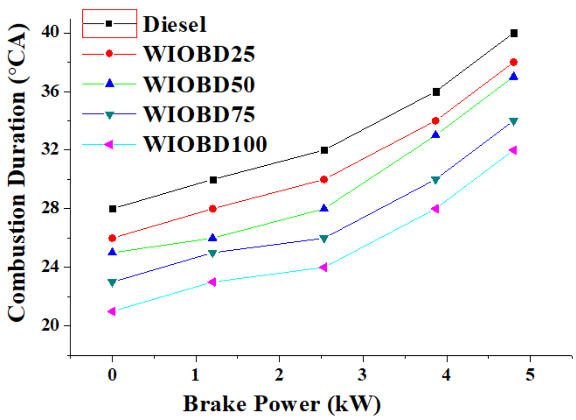


Figure 12. Combustion duration vs BP for WIOBD-diesel blends.

Mass -fraction-burned (MFB)

MFB is estimated from the cylinder pressure, combustion rate and energy conversion. Equation (3) was applied to determine MFB [23].

$$MFB = \frac{m_b(i)}{m_b(total)} = \left(\sum_{0}^{i} \Delta p_c / \sum_{0}^{N} \Delta p_c \right) \quad (3)$$

where 0 - Beginning of combustion process, N -Completion of the combustion process. Figure 13 shows MFB variance to the crank angle for various WIOBD-diesel mixtures. The combustion starts earlier by 5.3° CA bTDC for diesel, but it starts earlier by 3.5°, 3.45°, 3.3°, 3.22°CA bTDC for WIOBD25, WIOBD50, WIOBD75, and WIOBD100 fuel blends, respectively. The mass fraction burnt for WIOBD mixtures increases as oxygen molecules is present in its chemical structure [23]. Early combustion occurs because of increased air-fuel mixing. It is influenced by the factors such as lower viscosity, more significant premixed portion, and higher WIOBD-diesel oxygen content [24].

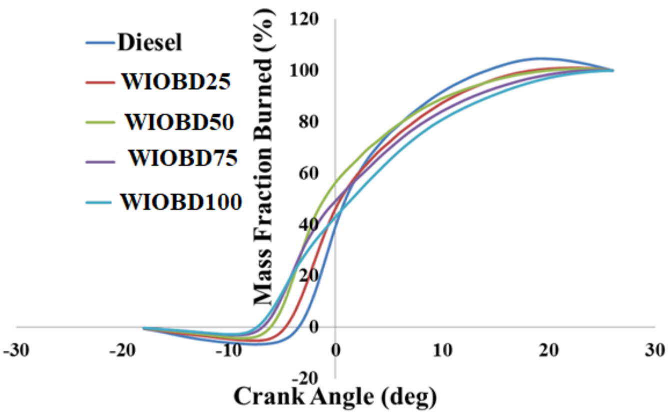


Figure 13. MFB vs crank angle for various blends of WIOBD-diesel at full load.

Analysis of Emission Parameters

CO emission

CO emissions are caused by a lack of oxygen, lower air exercise during combustion [25]. Figure 14 demonstrates the CO emission variability to BP for WIOBD diesel blends; CO emissions decrease for these WIOBD-diesel blends.CO emissions for WIOBD25 decrease by 7.69% than standard diesel. CO emission was reduced by 8.33%, 12.5%, and 16.66% for WIOBD50, WIOBD75, and WIOBD100 fuel blends, respectively, than WIOBD25. Moreover, the sprayed WIOBD fuel elements for injection duration were slightly higher and heavier than standard diesel fuels [26]. Fuel particles weight increases bring them away from the injector. Therefore complete mixing takes place, resulting in lower CO emission [27]. Further, the combustion chamber surface temperature will increase when the engine load increases, which helps CO in the oxidation process [28].

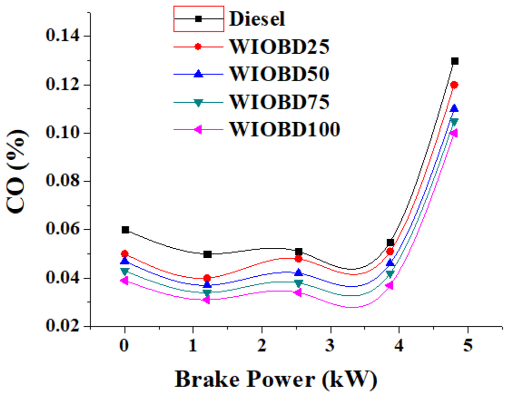


Figure 14. CO emission vs BP for different blends of WIOBD-biodiesel.

HC emission

An HC emission is due to flame quench, exhaust valve leakage, and inadequate oxygen at the end of combustion [29]. Variation in HC emissions with respect to BP for different WIOBD-diesel mixtures is shown in Figure 15. HC emissions are showing a growing trend at lower loads due to the over-leaning equivalence of air-fuel at the fuel spray periphery. The fuel content was mixed below the combustion stage, greater than for higher amounts of fuel [30]. From the results, the engine's increase in HC emission load also increased for all blends due to higher unburned or partially burned hydrocarbons that cannot be converted to CO [31]. HC emission for WIOBD25 decreases by 2.11% than diesel. WIOBD fuel blends contain some amount of oxygen which influences the reduction in HC emission than diesel. HC emission decreases by 2.04%, 3.31% and 6.12% for WIOBD50, WIOBD75 and WIOBD100 respectively than WIOBD25. On the other hand, the lower HC emission using WIOBD-blends could be due to the higher injection volume, reducing the residence time inside the combustion chamber and mitigating the over-leaning effect Mikulski et al. [30].

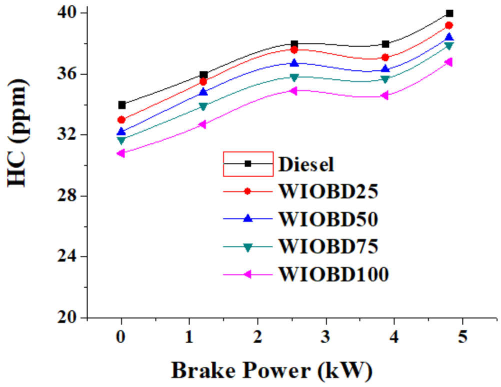


Figure 15. HC emission vs BP for different blends of WIOBD-biodiesel.

NO_x emission

NOx emissions consist of NO and NO2which influence the atmosphere for ozone depletion. NOx emissions produced are due to the combustion temperature, residence time, and oxygen molecules. NOx emission increases by the two factors such as fuel injection strategy and combustion temperature phenomenon. Another factor could be the fuel spray characteristics and the influence of the thermal NOx formation over the prompt NO [32]. Figure 16 indicates the variation of the NOx emissions in comparison to BP for various WIOBD-diesel blends. The production of NOx is higher because of the rise in the combustion temperature of the WIOBD biodiesel in the mixed fuel. NOx emission for WIOBD25 increases by 5.8% than diesel. The biodiesel blends' oxygen can also stimulate effective combustion and increase the combustion temperature [16]. NOx emission increases by 9.8%, 12.9% and 16.4% for WIOBD50, WIOBD75, and WIOBD100 fuel blends respectively than WIOBD25. Furthermore, the combustion process generally develops more biodiesel fuels than petroleum-based fuels. The content of oxygen in the biodiesel mixture is high, and a higher HRR during the combustion. The adiabatic flame temperature is slightly greater for WIOBD biodiesel blends due to the oxygen [33].

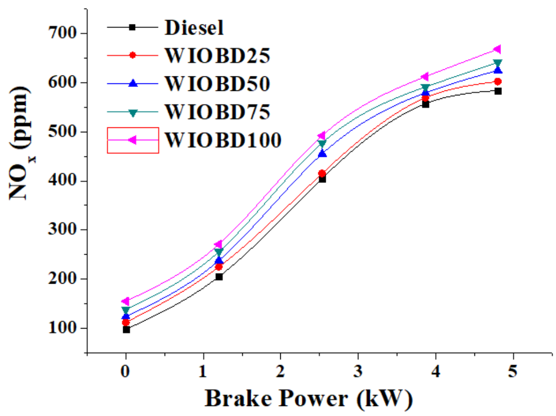


Figure 16. NO_x emission vs BP for different blends of WIOBD-biodiesel.

Smoke emission

The primary source of smoke emission is the formation of agglomeration of soot particles in engine exhaust; another consideration is incomplete hydrocarbon combustion during the combustion cycle. Furthermore, stoichiometry, pressure, and air-fuel mixture temperature [34]. Smoke emission concerning BP is presented in Figure 17. Smoke emission for WIOBD25 decreases by 4.91% than diesel. The availability of oxygen content in WIOBD-blends at high temperatures and pressures allows the soot oxidation cycle in a fuel-rich environment. Smoke emission was reduced by 2.44%, 6.52%, and 10.1% for WIOBD50, WIOBD75, and WIOBD100 blends, respectively, than WIOBD25. By comparison, partially oxygenated fuels can reduce fuel-rich regions locally and minimise soot nucleation, reducing smoke and particulate matter

[32]. The longer delay in ignition of WIOBD fuel blends leads to a more prominent premixed combustion process that allows the oxygen-rich area for soot particles to burn.

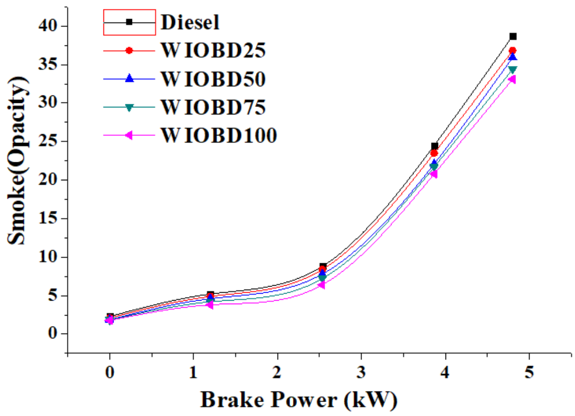


Figure 17. Smoke emission vs BP for various blends of WIOBD-biodiesel.

CONCLUSION

This research study was conducted to determine the potential usage of used transformer oil biodiesel as an alternative fuel for diesel engines. The following results were summarised from the experimental analysis.

i. The diesel engine operates stably on all WIOBD-diesel blends at part loads and full load. The WIOBD biodiesel blends caused lower brake thermal efficiency and higher brake-specific fuel consumption.
ii. The cylinder pressure and heat release rate increased for a higher percentage of WIOBD-blends in diesel fuel. Moreover, the ignition delay and combustion duration for WIOBD biodiesel blends were observed as lower when compared with diesel.
iii. WIOBD biodiesel blends caused lower HC, CO, and smoke emissions than diesel fuel, whereas they exhibited higher NOx emissions than diesel.
iv. Lower emission gases with better engine performance, WIOBD25 fuel blend is experimentally an optimum blend. Therefore, the test results suggested that the WIOBD biodiesel can be an alternative fuel to conventional diesel.

The effect of using thermal barrier coating (semi-adiabatic) can be investigated using WIOBD-diesel blends. The effect of injection of gaseous fuels such as hydrogen or LPG or natural gas or CNG as dual fuel mode in a diesel engine can be investigated. The effect of various combustion geometrics (toroidal, trapezoidal) and the effect of swirl can be applied. A tribological study can be carried out for WIOBD-biodiesel blends, while fuel spray, evaporation, and flame analysis in combustion modelling for WIOBD-blends can be investigated.

ACKNOWLEDGEMENT

The authors sincerely thank Engine Research Center, Sri Venkateswara College of Engineering, Sriperumbudur, Tamilnadu, for providing the facility for the research work.

REFERENCES

[1] M.P. Dorado *et al.*, "Exhaust Emissions from a diesel engine fueled with transesterified waste olive oil," *fuel*, vol. 82, pp. 1311-1315, 2003, doi: 10.1016/S0016-2361(03)00034-6.
[2] M. Pugazhvadivu, and Jeyachandran K., "Investigations on the performance and exhaust emissions of a diesel engine using pre-heated waste frying oil as fuel," *Renew. Energy,* vol. 30, pp. 2189-2202, 2005, doi: 10.1016/j.renene.2005.02.001.
[3] Y.C. Lin, K.H. Hsu, and C.B. Chen, "Experimental investigation of the performance and emissions of a heavy-duty diesel engine fueled with waste cooking oil biodiesel/ultra-low sulfur diesel blends," *Energy*, vol. 36, pp. 241-248, 2011, doi: 10.1016/j.energy.2010.10.045.
[4] S. Kumar *et al.*, "Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine," *Energy Convers. Manag.,* vol. 74, pp. 323-331, 2013.
[5] S. Hariharan, S. Murugan, and G. Nagarajan, "Effect of diethyl ether on Tyre pyrolysis oil fueled diesel engine," *Fuel*, vol. 104, pp. 109-115, 2013, doi: 10.1016/j.fuel.2012.08.041.
[6] O. Can, "Combustion characteristics, performance and exhaust emissions of a diesel engine fueled with a waste cooking oil biodiesel mixture," *Energy Convers. Manag*., vol. 87, pp. 676-686, 2014, doi: 10.1016/j.enconman.2014.07.066.
[7] E. Hurdogan *et al.*, "Experimental investigation on performance and emission characteristics of waste tire pyrolysis oil-diesel blends in a diesel engine," *Int. J. Hydrog.,* vol. 42, pp. 23373-23378, 2017, doi: 10.1016/j.ijhydene.2016.12.126.
[8] D. Damodharan *et al.*, "Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fueled with neat waste plastic oil," *Energy Convers. Manag*., vol. 161, pp. 294-305, 2018, doi: 10.1016/j.enconman.2018.01.045.

[9] X. Wang, and P. Ni, "Combustion and emission characteristics of diesel engine fueled with diesel-like fuel from waste lubrication oil," *Energy Convers. Manag*., vol. 133, pp. 275-283, 2017, doi: 10.1016/j.enconman.2016.12.018.

[10] P. Senthilkumar, and G. Sankaranarayanan, "Effect of Jatropha methyl ester on waste plastic oil fueled DI diesel engine," *J. Energy Inst.,* vol. 89, pp. 504-512, 2016, doi: 10.1016/j.joei.2015.07.006.

[11] P. Behera, S. Murugan, and G. Nagarajan, "Dual fuel operation of used transformer oil with acetylene in a DI diesel engine," *Energy Convers. Manag*., vol. 87, pp. 840-847, 2014, doi: 10.1016/j.enconman.2014.07.034.

[12] V. Lawlor, and A.G. Olabi, "Review of scientific research regarding PPO, tallow and RVO as diesel engine fuel," *Fuel*, vol. 145, pp. 25-38, 2015, doi: 10.1016/j.fuel.2014.12.034.

[13] R. Sathiyamoorthi *et al.*, "Environment-friendly fuel Cymbopogon flexuosus: Analysis of fuel properties, performance and emission parameters of a Direct Injection Compression Ignition research engine," *Heat Transfer*, vol. 50, pp. 1-39, 2021, doi: 10.1002/htj.22194.

[14] A. Gharehghani *et al.*, "Simultaneous reduction of CO and NOx emissions as well as fuel consumption by using water and nano particles in Diesel Biodiesel blend," *J. Clean. Prod.,* vol. 210, pp. 1164-1170, 2019, doi: 10.1016/j.jclepro.2018.10.338.

[15] J.P Holmon, *Experimental methods for engineers*, Tata McGraw Hill Publications New York, 2011.

[16] G. Ospina *et al.*, "Engine roughness and exhaust emissions of a diesel engine fueled with three biofuels," *Renew. Energy,* vol. 134, pp. 1465-1472, 2019, doi: 10.1016/j.renene.2018.09.046.

[17] S. Aydin, C. Sayin, and H. Aydin, "Investigation on the usability of biodiesel obtained from residual frying oil in a diesel engine with thermal barrier coating," *Appl. Therm. Eng.,* vol. 80, pp. 212-219, 2015, doi: 10.1016/j.applthermaleng.2015.01.061.

[18] O.M. Ali *et al.*, "Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel," *Renew. Energy,* vol. 86, pp. 59-67, 2016, doi: 10.1016/j.renene.2015.07.103.

[19] A.N. Ozsezn, and M. Canakci, "Determination of performance and combustion characteristics of a diesel engine fueled with canola and waste palm oil methyl esters," *Energy Convers. Manag*., vol. 52, pp. 108-116, 2011, doi: 10.1016/j.enconman.2010.06.049.

[20] P. Behera, and S. Murugan, "Combustion, performance and emission parameters of used transformer oil and its diesel blends in a DI diesel engine," *Fuel*, vol. 104, pp. 147-154, 2013, doi: 10.1016/j.fuel.2012.09.077.

[21] H. Xiao *et al.*, "Combustion performance and emissions of 2-methylfuran diesel blends in a diesel engine," *Fuel*, vol. 175, pp. 157-163, 2016, doi: 10.1016/j.fuel.2016.02.006.

[22] W. Tutak *et al.*, "Alchol-diesel fuel combustion in the compression ignition engine," *Fuel*, vol. 154, pp. 196-206, 2015,doi: 10.1016/j.fuel.2015.03.071.

[23] E.R. Mamat, *et al.*, "An overview of Higher alcohol and biodiesel as alternative fuels in engines," *Energy Reports*, vol. 5, pp. 467-479., 2019, doi: 10.1016/j.egyr.2019.04.009.

[24] P. Behera, and S. Murugan, "Combustion, performance and emission parameters of used transformer oil and its diesel blends in a DI diesel engine," *Fuel*, vol. 104, pp. 147-154, 2013, doi: 10.1016/j.fuel.2012.09.077.

[25] R. Sathiyamoorthi, and G. Sankaranarayanan, "Effect of antioxidant additives on the performance and emission characteristics of a DICI engine using neat lemongrass oil-diesel blend," *Fuel,* vol. 174, pp. 89-96, 2016, doi: 10.1016/j.fuel.2016.01.076.

[26] R. Sathiyamoorthi, and G. Sankaranarayanan, "Fuel injection timings of a direct injection diesel engine running on neat lemongrass oil-diesel blends," *Int. J. Automot. Mech.,* vol. 11, pp. 2348-2363, 2015, doi: 10.15282/ijame.11.2015.16.0197.

[27] M. Kousoulidou *et al.*, "Biodiesel blend effects on common-rail diesel combustion and emissions," *Fuel*, vol. 89, no. 11, pp. 3442-3449, 2010, doi: 10.1016/j.fuel.2010.06.034.

[28] R. Vallinanayagam *et al.*, "Pine oil-biodiesel blends: A double biofuel strategy to completely eliminate the use of diesel in a diesel engine," *Appl. Energy,* vol. 130, pp. 466-473, 2014, doi: 10.1016/j.apenergy.2013.11.025.

[29] Y. Liang, G. Shu, and WW. Zhang, "Effect of oxygen enriched combustion and water-diesel emulsion on the performance and emissions of turbocharged diesel engine," *Energy Convers. Manag.,* vol. 73, pp. 69-77, 2013, doi: 10.1016/j.enconman.2013.04.023.

[30] M. Mikulski, K. Duda, and S. Wierzbicki, "Performance and emission of a CRDI diesel engine fuelled with swine lard methyl esters-diesel mixture," *Fuel*, vol. 164, pp. 206-219, 2016, doi: 10.1016/j.fuel.2015.09.083.

[31] D. Singh, K.A. Subramanian, and S.K. Singal, "Emissions and fuel consumption characteristics of a heavyduty diesel engine fueled with Hdroprocessed Renewable Diesel and Biodiesel," *Appl. Energy,* vol. 155, pp. 440-446, 2015, doi: 10.1016/j.apenergy.2015.06.020.

[32] E.G. Giakomis *et al.*, "Exhaust emissions of diesel engines operating under transient conditions with biodiesel fuel blends," *Prog. Energy Combust. Sci.,* vol. 38, pp. 691-715, 2012, doi: 10.1016/j.pecs.2012.05.002.

[33] C.D. Rakopoulos *et al.*, "Comparative performance and emissions study of a direct injection diesel engine using blends of diesel with vegetable oils or biodiesels of various origins," *Energy Convers. Manag.,* vol. 47, pp. 3272-3287, 2006, doi: 10.1016/j.enconman.2006.01.006.

[34] D.R. Tree, and K.I. Svensoon, "Soot processes in compression ignition engines," *Prog. Energy Combust. Sci.,* vol. 33, pp. 272-309, 2007, doi: 10.1016/j.pecs.2006.03.002.