Experimental Investigation on Brake Thermal Efficiency and Emission Characteristics of Plastic Oil-Mahua Biodiesel Blends in CRDI Diesel Engine

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Abstract. The adoption of sustainable fuels has gained momentum due to increased environmental awareness issues and increased energy needs in the world. This study is concerning the use of biodiesel produced out of plastic oil and Mahua oil methyl ester (PMME) in relation to its performance and emission characteristics. To find out the performance of PMME synthesized by a two-step transesterification method, an investigation was done. It was a single cylinder, four stroke Common Rail Direct Injection diesel engine that was tested at 1400 rpm of constant speed load beneath a load of 25 percent up to 100 percent. Brake thermal efficiency (BTE) was measured in 100 per cent load, which was 8.31 per cent and 12.81 per cent lower than the diesel, likely due to the low calorific value and high viscosity of the latter. Relative to diesel, PMME25 showed a 16.49 percentage change in brake-specific fuel consumption (BSFC) that indicated the use of more fuel. Emission analysis showed that oxygenated nature of PMME25 reduced CO emission by 0.8 percent and HCs emission by 50.15 percent at full load. Nevertheless, due to reduced combustion temperatures, NO emissions fall 55.5% in comparison to diesel. These results demonstrate the potential of PMME as a green biofuel, lending credence to the idea of carbon neutrality and long-term energy sustainability.
Keywords:Plastic oil, Mahua oil, Engine performance, Carbon monoxide, Renewable biofuel, Brake-specific fuel consumption

1.Introduction

Energy is the basic need to improve the development of industries, society and ecnomics. This study evaluates areca-nut husk (ANH) additive with hydrogen enrichment (10 LPM) in a CRDI diesel engine running on D80P10E10. Up to 20 ppm ANH lowered NOx, cylinder pressure, and heat release rates, while improving BTE and BSFC. The optimum D80P10E10 + H_2 + 30 ppm ANH blend enhanced efficiency (34.5%) and reduced CO, HC, and smoke emissions [1]. The work investigates diesel–plastic oil–ethanol blends in a CRDI engine to address fuel scarcity and plastic waste. Among five tested combinations, D80P10E10 produced the lowest NOx with BTE similar to diesel. This ternary blend offered minimal penalties in CO, HC, and smoke emissions, emerging as the most balanced fuel [2]. Diesel–WPO blends enhanced with CeO_2 nanoparticles were tested in a CRDI diesel engine. The D70WPO30 + CeO_2 (100 mg/L) blend improved BTE (28.2%), lowered BSFC, and reduced CO, HC, NOx, and smoke emissions. CeO_2 addition significantly optimized combustion and performance, especially at higher dosing [3]. Prosopis Juliflora biodiesel blended with WPO was tested with EGR in a CRDI engine. B10 and B15 blends improved BTE, while B10 + 20% EGR cut NOx by up to 43%. B20 blends further reduced smoke and HC emissions, outperforming diesel in efficiency and sustainability [4]. Hydrogen enrichment was combined with WPO20 in a CRDI diesel engine. Adding H_2 improved BTE and reduced BSFC but increased NOx by 24%. Water emulsification (WPO20 + W10 + H_2) mitigated this, lowering NOx emissions by 19% while maintaining efficiency gains [5]. Hybrid epoxy composites reinforced with coconut fibre and marble dust were fabricated and tested for dry sliding wear. The 12% marble dust + 16% fibre composite showed best mechanical properties (tensile 34.27 MPa, flexural 37.23 MPa, impact 16.32 kJ/m²). Wear was lowest up to 12 wt% filler, beyond which it increased slightly [6].

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Hydrogen–WPO–diesel blends (10–30% WPO + 8 LPM H_2) were tested in a CRDI engine. Hydrogen enrichment reduced CO, HC, and CO_2 emissions while improving BTE under full load. NOx increased with higher exhaust temperatures, and greater WPO ratios extended ignition delay and lowered efficiency [7]. WPO–1-pentanol blends were studied in a CRDI engine with EGR. The 30% pentanol blend achieved comparable performance to diesel, with slightly higher BSFC but reduced NOx emissions. EGR further lowered NOx but increased CO, making 30% pentanol–70% WPO a viable alternative fuel [8]. Sequential deposition of Sb, Se, Sn, and Zn on Ag substrates was studied using potentiodynamic electrochemical impedance spectroscopy (PDEIS). Results showed distinct interface behavior, with Sn deposition on Sb–Se bilayers shifting oxidation potentials irreversibly. PDEIS proved effective for monitoring multilayer assembly in electrochemical nanotechnologies [9]. A VCR engine study examined DEE–WPO blends under naturally aspirated (NA) and boost pressure (BP) at CR 17–18. P90DEE10 with BP at CR 18 achieved higher BTE and lower CO and NOx than diesel, though HC rose slightly. BP improved overall efficiency and emissions, making P90DEE10 competitive with diesel [10]. Medical plastic waste was pyrolyzed and distilled to produce oil (DPO), blended with diesel and nanographene. A 20DPO + 100 ppm graphene blend enhanced energy and exergy efficiencies by 5.8% and 10.9%, respectively, while cutting BSFC by 14.7% versus diesel. Optimization confirmed 20DPO100G as the most efficient and cost-effective blend [11].

Fe_2O_3 nanorods (≈30 nm) synthesized hydrothermally showed cubic crystallinity and excellent electrochemical properties. As supercapacitor electrodes, they achieved 489 F/g capacitance at 10 mV/s, low ESR (3.26 Ω), and retained stability over 500 cycles at 6 A/g. The material shows strong promise for high-performance energy storage [12]. Physicochemical properties of distilled and crude WPO were analyzed and tested in a VCR engine. Increasing CR (16–18) and load improved BTE but also raised NOx, CO, and HC due to long-chain hydrocarbons in WPO. High CR and load alleviated emission drawbacks, making WPO closer in behavior to diesel [13]. A Taguchi optimization was applied to a DI VCR engine fueled with WPO–ethanol–diesel blends. CR was better (18.1) and full load enhanced BTE and emissions low. The 20 percent WPO and 20 percent ethanol blend produced the hundred percent efficiency and lowest emission, and it proved that WPO is a viable fuel as a sustainable energy source[14]. P95DEE5, P90DEE10, P100 The blends at CR 18 were investigated in a VCR engine: (P95DEE5, P90DEE10, P100). P90DEE10 was the best performing as it exhibited higher BTE, low BSFC, low CO, and much lower NOx in comparison to diesel. HC emissions were marginally increased, although the general combustion and efficiency increased with the additions of DEE. [15]. CRDI engines were used with 2-ethylhexyl nitrate content mixed with metallic (SiO 2) and non-metallic (rice husk) nano additives in a diesel-mahua oil corresponding mixture. SiO 2 served as an oxygen buffer, and enhanced BTE by 7.82% as compared to RH40 and RH80 blends that enhanced BTE by a maximum of 13.2% because of enhanced fuel atomization and combustion. The two additives also improved efficiency and quality of combustion highly[16]. In CRDI engine, a ternary fuel (diesel -mahua methyl ester-pentanol) was tested at injection pressure of 20-50 MPa. Better atomization at 50 MPa yielded BTE improvement (4.39) and CO (22.24) and HC (9.49) and smoke (7.5) reduction. However, NOx raised by 12.46% and SFC increased, reflecting fuel property trade-offs [17]. Mahua oil biodiesel was tested in a low heat rejection (LHR) engine with PSZ coating and retarded injection timing. BTE improved by 9.15% and SFC dropped by 6.23% compared to the uncoated engine. CO and UBHC fell by 20.35% and 12.28%, while NOx and EGT increased by 5.36% and 18.64% due to higher combustion temperatures [18]. Mahua oil methyl ester blends (M10, M20, M30) were tested in a VCR engine at CR 17–18. At CR 18:1 with B20 blend, superior performance was observed with higher BTE, lower SFC, and reduced HC, CO, and smoke emissions. However, engine vibration and noise limited practical CR to 18:1 [19].

Plastic oil and Mahua oil are two of the most understudied non-edible oil feedstocks for biodiesel production, even though there have been extensive studies on this topic. A survey of the current literature reveals that a restricted number of research have investigated biodiesel generation from these oilseeds, with an even smaller subset examining its use in diesel engines. Significantly, no previous studies have examined their joint application as a composite feedstock for biodiesel synthesis.

This research presents an innovative method employing a composite mixture of plastic oil and Mahua oil for biodiesel generation and its utilization in direct injection compression ignition engines. Even though the two oils have been individually explored, they have not been explored as a combined feedstock. It is a gap that is filled by this study, which makes use of locally accessible yet underutilized non-edible oilseeds to improve the manufacturing of renewable bio-diesel.

Plastic oil, which is the result of the pyrolysis of discarded plastics is an alternative source of fuel that has significant potential in terms of energy recovery. It is typically produced by the thermal or catalytic division of combined plastic waste in controlled circumstances, resulting in a liquid hydrocarbon fraction that is similar in structure to traditional diesel. The plastic oil production depends on the feedstock composition and the process conditions, and the average recovery of plastic mass received is 60-80 percent of the feedstock. Plastic oil has an excellent calorific value (4044MJ/kg) and contains a high proportion of unsaturated hydrocarbons and aromatics, which makes it a viable option as of biodiesel additive or direct use as a fuel.

Plastic oil produces fuel which exhibits desirable physicochemical properties, including reduced viscosity when compared to crude vegetable oils, high ignition quality, and high combustion performance. Moreover, its implementation does not only address the issue of managing plastic waste, but also reduces the reliance on fossil fuels, which align with the sustainable energy programs.

Mahua (Madhuca longifolia), which is alternatively referred to as the Mahua Tree, is the property to the relatives of Sapotaceae. It is a low to large tree that is usually 15-20 m tall with thick gray bark, long and giant leaf shapes, and lacks fragrant cream-colored flowers. Native to India and widely distributed in central, northern, and southern regions, Mahua grows in the tropical and subtropical regions with dry and wet deciduous forests. Its fruits are juicy, greenish-yellow and it bears brown seeds, the average annual seed production of the tree being 20-200 kg/tree depending on age and the environment.

Mahua seeds contain between 35-50 percent of oil with a major fraction of long-chain fatty acids like oleic and stearic acids, which makes it a potentially feasible non-edible feedstock to produce biodiesel. Biodiesel produced using the Mahua seed oil has shown to possess desirable qualities such as high oxidative stability, good cetane number and performance as a lubricant, which is vital in combustion and reliable engine performance.

Plastic oil and Mahua (Madhuca longifolia) seed oil have a high potential of being a sustainable biodiesel feedstock due to their high abundance, desirable fuel properties and synergies. Plastic oil, which is produced by pyrolysing of waste plastics has a high calorific value and efficient combustion characteristics and at the same time addresses the pressing concern regarding the management of plastic waste. Mahua seed oil, a non-edible, resource containing high percentage of oil, has high oxidative stability and satisfactory cetane number and is, therefore, a reliable renewable feedstock. Notably, Mahua biodiesel also avoids competition with edible oils, which means an enhanced food-fuel security.

Even the innovation of thestudy lies in the utilize of a composite feedstock technology, where plastic oil is combined with Mahua seed oil to overcome the limitations of the single feedstock. Plastic oil normally has high aromatic content and is less stable and Mahua oil exhibit high viscosity and free fatty acid levels. Combination of the two produces a balanced fatty acid profile and hydrocarbon composition, which increases the cold flow properties, optimum viscosity, better ignition quality, and higher combustion efficiency. This joint approach ensures performance of the engine and longer lifespan compared to the use of single feedstocks.

The transesterification process is done in two steps in order to optimize the biodiesel production and meet the international standards like ASTM D6751 and EN 14214, namely, reduce the free fatty acid of Mahua oil. Systematic analyses are done on the physicochemical characteristics of the bio-diesel produced such as density, viscosity, calorific value, cetane number and the oxidative stability to ascertain whether the bio-diesel can be used as a substitute to diesel. The engine performance shall be evaluated in a number of load conditions with focus on brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust emissions such as CO, HC, NOx, and smoke opacity.

This study provides workable solution in terms of waste-to-energy conversion and rural economic growth through the exploitation of Mahua resources sourced. The dual feedstock concept enhances efficiency of resources, reduces reliance on fossil diesel and helps in reducing green house gas emissions, according to the United Nations Sustainable Development Goals. This study offers an environmentally sustainable and economically viable alternative to traditional fuels by combining waste plastic valorization with the use of non-edible oils.

2.Materials and methodology

2.1 Extraction of oil

Pyrolysis of post-consumer mixed plastic feedstock was conducted under controlled conditions to produce waste plastic oil (PO) [20]. The study's chemicals and reagents, including phenolphthalein, sodium hydroxide, methanol, and sulfuric acid were purchased at laboratory-grade purity.Prior to oil extraction, the gathered Mahua seeds were sun-dried for three days to lower their moisture[21]. Mechanical expeller pressing was used to the dried seeds and out of 10 kg of seeds was extracted. Mechanical expeller extraction of non-edible oils guarantees excellent output with minimum destruction of beneficial components. On the other hand, 4.3 kg of pyrolytic oil were created from 10 kg of mixed plastic trash following condensation of the vapor fraction; this was known as waste plastic oil.Figure 1 depicts the general procedure for making PM (Plastic oil-Mahua oil) methyl ester. Eq. (1) was used to evaluate the oil content of Mahua seeds, and the recovered liquid fraction relative to the input plastic mass were used to compute the yield of plastic pyrolysis oil[22].

$$\text{Oil extracted } (\%) = \frac{\text{Pure oil obtained}}{\text{Seeds used to crush}} \times 100 \qquad (1)$$

A mixture known as PMO is made by combining 50% plastic oil with 50% Mahua oil. The biodiesel production process makes use of the mixed PMO oil.

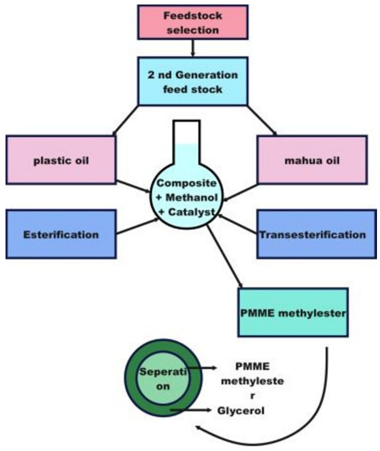

Fig. 1. Process Flow Diagram for PM Methyl Ester Synthesis.

2.2 Production of PM biodiesel

To determine the concentration of FFA in PM oil, the titration method is used. Before moving on to the next step, the titration procedure involved heating the mixture to 35°C, adding 50 ml of isopropyl alcohol to 10 g of PMO, and shaking thoroughly. The mixture was stirred at 500 rpm in order to achieve effective mass transfer. Then 0.1 N NaOH was carefully added in small drops to be a color indicator and the mixture was titrated until it turned into a bright pink. The mixture was then transferred into another funnel, left to settle at least 12 hours after completion. There were two distinct layers created during the process of separation. The biodiesel content in one of the layers is PM methyl ester and the other layer contains glycerol that is a by-product.

Care was taken in collecting the layer of biodiesel after which it was heated to remove any remaining alcohol followed by recovery of the methanol. Multiple washes with hot water were used to eliminate any remaining FFA in the PMO, further purifying the biodiesel. Eq. (2), were used to determine the FFA percentage in PMO. In order to extract biodiesel from PMO, a procedure known as acid esterification followed by trans-esterification is necessary due to the 3.5% FFA level of PMO[23].

$$FFA = \frac{28.2X\ \text{Normality of NaoH X Titration value}}{\text{Weight of the oil}} \quad (2)$$

Tabel:1 Physical Properties of Diesel Fuel

SI. NO.	Property	Standard (ASTM/ISO)	Typical Value Range	Unit
1	Density at 15 °C	ASTM D4052	820 – 860	kg/m³
2	Kinematic Viscosity at 40 °C	ASTM D445	2.0 – 4.5	mm²/s
3	Flash Point	ASTM D93	≥ 52	°C
4	Pour Point	ASTM D97	-15 to -35	°C
5	Cloud Point	ASTM D2500	-15 to 5	°C
6	Cetane Number	ASTM D613	40 – 55	–
7	Calorific Value (Net)	ASTM D240	42 – 45	MJ/kg
8	Sulfur Content	ASTM D4294	< 10 (Ultra Low Sulfur Diesel)	ppm (mg/kg)
9	Distillation (90 % Recovery Temp)	ASTM D86	≤ 360	°C
10	Water Content	ASTM D6304	≤ 200	ppm (mg/kg)

2.2.1. Esterification method

500 ml flat-bottomed 3-necked flask was used to mix the PM oil. The flask had a condenser attached to the center neck and was put on a magnetic stirrer to ensure even distribution of the oil. The amount of PM oil used to determine the

proportions of H_2SO_4 and CH_3OH (Methanol) added to reaction mixture were 15%. For 60 minutes at 65 ◦C, the esterification reaction was carried out with a continuous stirring speed of 600 rpm to guarantee that the reactants interacted correctly. Once the reaction was finished, the methanol and sulfuric acid that had not yet reacted were strained out using a separating funnel. There was an excess of sulfuric acid and methanol in the top layer, and esterified oil in the bottom. In preparation for the second phase of transesterification, the esterified oil was then gathered and put aside.

The esterified oil's free FFA level was determined to be 0.9%, which is a marked decrease from original value. According to Eq. (3), the esterified oil production was 91.50%[24].

$$\text{Yield (\%)} = \frac{\text{Initial } FFA - \text{Final } FFA}{\text{Initial } FFA} X100 \quad (3)$$

2.2.2. Trans-esterification method

Phase I's esterified PM oil was transesterified with an alkali catalyst to yield biodiesel. In order to maintain continuous agitation, a precisely measured quantity of sodium hydroxide and methanol were included to aflat-bottomed flask, three-neckedand locatedatthe magnetic stirrer.Methanol to oil ratio was 6:1. Using methanol and catalyst leftovers, the transesterification reaction were conducted at 55 ◦C for 50 minutes. Equation (4) was used to determine that the ultimate yield of PM methyl ester (PMME) biodiesel was 85%[25].

$$\text{PMME yield (\%)} = \frac{\text{Achieved quantity of PMME}}{\text{Used Quantity of esterified PMO}} \quad (4)$$

For non-edible feedstocks, the best biodiesel yields are achieved with a methanol to oil molar ratio of 6:1 and a sodium hydroxide concentration of 1wt%. Results from this investigation corroborate the feasibility of using PM oil as a feedstock for biodiesel, thanks to its high conversion efficiency. Table 1 shows the physio-chemical properties of the biodiesel and the raw oil.

2.3. Test fuel preparation

Diesel and PMME were fuels that were experimented on. The diesel fuel was supplied by a fuel station owned by Indian oil. Five samples of fuels were produced in each case, having a different percentages of pure diesel and PMME mixtures (10% 15% 20 and 25) in combination with different proportions of diesel (85, 80, 75 and 90 respectively). Blends PMME10, PMME15, PMME20 and PMME25 were named correspondingly. Table 2 details the physicochemical parameters of diesel, PMME, and the constructed fuel mixes. A high-speed mixing procedure was used to prepare the PMME-diesel blends, guaranteeing a homogeneous composition. The mixtures were homogenized by subjecting them to 25 minutes of magnetic stirring. After 24 hours of monitoring, no signs of phase separation were found, confirming that the mixes were stable. We can certify that the formulas are stable, because no layering or segregation were noticed.

Tabel:2 Properties of Plastic Oil–Mahua Oil Methyl Ester (PMME) Blends.

Properties	**Standard**	**Diesel**	**PMME10**	**PMME15**	**PMM20**	**PMME25**
Density at 150 Kg/m^3	ASTM D4052	835.9	848.5	854.7	861.3	868.9
Viscosity at 40C	ASTM D445	2.475	3.12	3.45	3.82	4.15
Flash point (°C)	ASTM D92	47.5	78.0	96.5	115.0	132.0
Cetane number	ASTM D4737	48	50	52	54	55
Calorific value	ASTM D4240	45.6	42.3	41.2	40.1	39.0

(MJ/Kg)						

2.4. Experimental engine test rig and test procedure

A Kirloskar-made 4-stroke CRDI diesel engine test setup with one cylinder and water cooling is utilized in this inquiry[26]. Fig. 2 shows the experimental test setup is shown. Engine's output shaft is connected to the eddy current dynamometer so we could put it through its paces. Accurate control of the fuel injection system is made possible by the integration of the Nira i7r open Electronic Control Unit into the engine. To further monitor the crankshaft's angular displacement, a German-made Kubler Crank Angle Sensor was employed, which generated the pulse signal of each degree of rotation. In order to efficiently record several engine parameters, a National Instruments USB-6210 DAQ system was used to ease sensor data collecting.

For precise measurement and control, the experimental setup was outfitted with state-of-the-art gear. The motor's properties were recorded in real time using a data acquisition (DAQ) system from NI that was driven by the USB-6210 bus. The load sensor was supplied by SensotronicsSanmar Ltd. ensuring that the loads are measured accurately. In order to record the crank position with high resolution, a Kuebler, Germany manufactured crank angle sensor (Model: 8.3700.1321.0360) was added. The point of pressure measurement in the cylinder is a piezoelectric pressure sensor (SM111A22) by PCB Piezotronics. A load was applied to the engine using an eddy current dynamometer in order to measure performance and accuracy when applying the load.

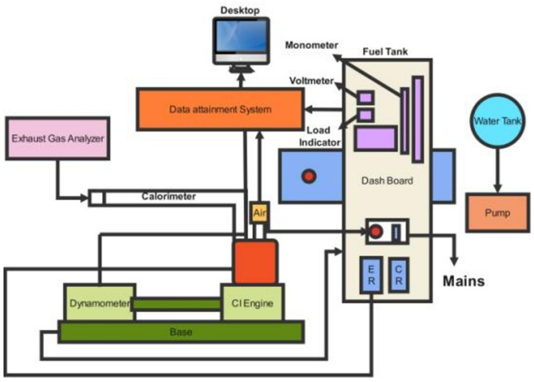

Fig. 2. Configuration of the Engine Test Bench.

Exhaust emissions could be evaluated through the use of an exact AVL DI Gas analyzer. While the load were systematically varied between 25%, 50%, 75%, and 100% of maximum capacity, the engine at a constant speed of 1400 rpm throughout experiment. Along with a rail pressure of 800 bar, the fuel injection time was set at 23◦ BTDC[27]. The data collection was initiated after a 30-minute of warm-up. Trials with various fuel blends followed initial testing using diesel fuel as a reference.

The Kirloskar single-cylinder CRDI diesel engine, which has a displacement of 661 mL and a rated power output of 3.5 kW is utilized as the experimental engine in this study. A compression ratio between 12:1 and 18:1 is used when the engine is running. Its dimensions are 87.5 mm in diameter and 110 mm in stroke length. The common rail direct injection (CRDI) system allows for fuel injection to be carried out at a pressure of 800 bar, 23° before top dead center (BTDC).

3. Results and discussion

This section focuses on engine performance and emission characteristics as well as implications of various fuel mixtures. The outcomes in terms of KPIs like BTE and BSFC was discussed and we look at the effects on emissions like NO_x, CO and CO_2 were also focused.

3.1. Brake thermal efficiency

The brake thermal effiiceiency is an important metric that shows how well fuel energy is transformed into mechanical work. It is given by Eq. (5) and is defined as the ratio of the fuel energy input to the braking power output.

$$\text{BTE } (\%) = \frac{\text{Brake Power } (BP)}{\text{Fuel Energy Input}} \times 100 \quad (5)$$

Figure 3 shows the effect of blended fuels on BTE under all loading conditions. Diesel fuel outperformed biodiesel blended fuels in terms of thermal efficiency across the board. The block temperature efficiency (BTE) for B0, PMME10, PMME15, PMME20, and PMME25 at full load is 30.07%, 28.87%, 28.07%, 27.0%, and 27.27%, respectively. Blends of petroleum, methane, and ethanol (PMME10), 15% (PMME15), 20% (28.51%), and 25% (32.57%) lower BTE than diesel, respectively. In previous study, nanographene additives (50–100 ppm) were dispersed in 20% waste plastic oil–diesel blends for DI engines at CR 16–18. The 100 ppm graphene blend improved BTE by 1.16% at CR 17 and reduced CO, HC, and NOx compared to diesel [28]. A lower BTE trend was observed when the biodiesel-to-diesel ratio increased. Because biodiesel blends have a greater volumetric efficiency than diesel, they provide stronger braking power. Furthermore, it has a detrimental impact on atomization because it reduces the spray cone angle, decreases penetration velocity, and increases the Sauter mean droplet diameter, all of which impede efficient mixing and evaporation. Spray penetration increases with increasing density, however droplet breakage may get worse due to the increased mass of fuel injected per cycle. When related to diesel fuel, the BTE is much lower due to all of these factors' detrimental effects on combustion. Results did reveal that PMME15 was more valuable than diesel fuel at lower blend ratios.

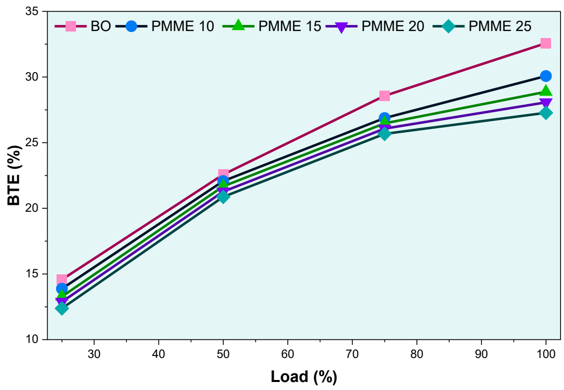

Fig. 3. Effect of Load Conditions on BTE.

3.2. Brake specific fuel consumption

Another metric that reveals how well an engine turns energy into usable work is BSFC. Engine fuel consumption for base gasoline and its blends under all loading conditions is shown in Fig. 4. The engine demonstrated increased fuel consumption compared to diesel fuel when operated with biodiesel blends. For B0, PMME10, PMME15, PMME20, and PMME25, the fuel consumption at 100% load is 0.72, 0.74, 0.76, 0.78, and 0.8 kg/kW-h, correspondingly. When compared to diesel fuel, PMME10, PMME15, PMME20, and PMME25 have fuel consumption that is 13.14%, 22%, 30.57 %, and 33.03% greater, respectively. In earlier study, diesel–waste plastic oil blends with hydrogen enrichment (8 LPM) were studied in a CRDI engine under varying loads and timings. WPO10 + H_2 improved BTE by 15.1%, cut BSFC by 11.2%, and lowered CO, HC, CO_2, and smoke emissions. However, NOx rose across all hydrogen-enriched blends [29].

Because of its poor fuel characteristics, biodiesel blends cause a significant increase in fuel consumption. Because of its greater cetane number, biodiesel typically reduces ignition delay during this period. On the other hand, fuel atomization is negatively affected by its reduced volatility and increased viscosity, incomplete mixing with air before igniteand leading to bigger fuel droplets. As a result, ineffective zones of rich fuel are created. During the first heat release phase, the effectiveness of the air-fuel mixing is diminished due to biodiesel's increased viscosity and density, which result in more spray penetration and weaker spray breakup. This might cause the engine to burn slowly, especially when the load is low. All of these things could be contributing to the increased gas mileage.

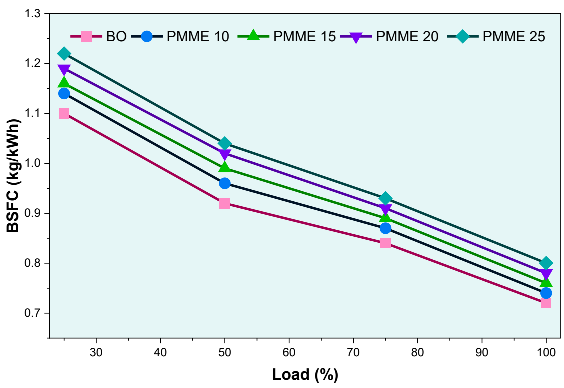

Fig. 4. Effect of Load Conditions on BSFC

3.3. Carbon monoxide emissions

Fig. 5 shows the CO emission for all test fuels under different loading situations. Biodiesel blends reduce CO emissions as seen in the graph. Incomplete combustion is the main culprit responsible for the creation of CO emissions in the exhaust. Inadequate fuel-air mixing and an absence of oxygen during the delay period phase both contribute to incomplete combustion. Because oxygen is an integral part of biodiesel's molecular structure, mixes using this fuel produce less carbon monoxide than diesel fuel. The 10–12% oxygen content of biodiesel improves fuel oxidation and leads to a more thorough combustion process. Compared to base gasoline, shown CO emission reductions of 0.98%, 0.93%, 0.90%, and 0.80% at 100% load. If the fuel has weak characteristics, it might not burn properly during the delay and major heat release phases. Nevertheless, the mixture that was not burned moved on to the latter stages of combustion, when the increased cylinder temperature and biodiesel's inherent O_2 molecules aid in complete combustion and result in reduced CO emissions[30]. It is useless to let the heat energy that is released into the atmosphere through exhaust gas during the later stages of combustion.

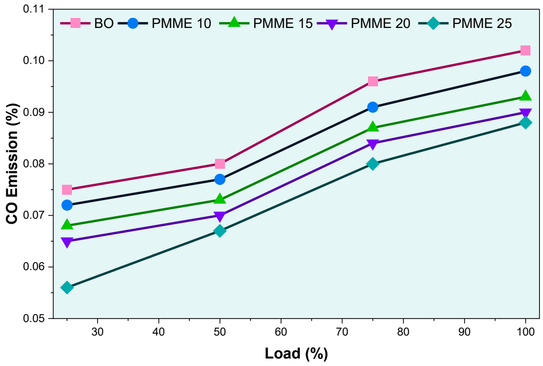

Fig. 5. CO Emission Trends at Different Loading Levels

3.4. Hydrocarbon emission

A good indicator of engine cylinder combustion quality is the concentration of unburned HC in exhaust emissions. Cylinder temperature, oxygen concentration, fuel characteristics, and a host of other variables all contribute to combustion quality. For each test blend, Figure. 6 displays the concentration of Hydrocarbon emissions in the exhaust. Low HC emissions at 100% load for PMME10, PMME15, PMME20, and PMME25 are 55.5%, 53.5%, 57.5%, and 50.15% lower than base fuel, respectively. One probable explanation for the observed decrease in HC emissions when biodiesel is added to diesel is the higher cylinder temperature and the availability of oxygen in biodiesel's molecular structure.

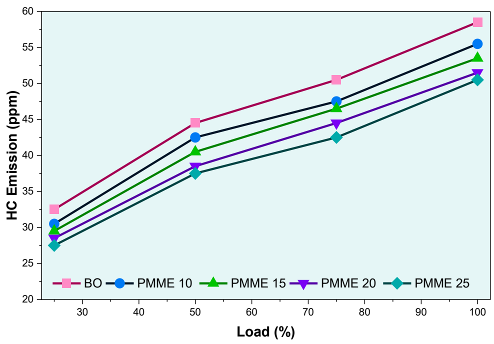

Fig. 6. HC Emission Trends at Different Loading Levels

3.5. NO emission

Nitrogen oxides (NOx) are produced when nitrogen is oxidized at high temperatures in an air-containing environment, as happens in a diesel engine. There are two components to nitrogen oxides (NOx): nitrogen and nitrogen oxides (NO_2). However, diesel engines release about 90% to 95% NO as NO when it leaves the engine, and the atmospheric conversion to NO_2 happens later. There are three main ways that NO can be formed: thermally, by prompting, and by fuel-bound processes. Out of all these processes, the one that matters most is thermal NO generation. Here is a description of the thermal NO production process that follows the Zeldovich Mechanism[15]:

$$N_2 + O \rightarrow NO + N \qquad (6)$$

(6)

$$N + O_2 \rightarrow NO + O \qquad (7)$$

(7)

$$N + OH \rightarrow NO + H \qquad (8)$$

(8)

A byproduct of NO's atmospheric emission is NO_k, which is formed when NO reacts with oxygen and ozone.

$$NO + \frac{1}{2} O_2 \rightarrow NO_2 \qquad (9)$$

(9)

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (10)$$

(10)

For each fuel type tested, Fig. 7 shows the NO emission under load conditions. Residence time and cylinder temperature are the main factors that cause NO emissions to occur. Compared to the other fuels tested, diesel fuel exhibited much higher NO production. The complete oxidation of diesel fuel causes the cylinder temperature to rise, which is the primary cause of the greater NO emissions. Biodiesel blends, on the other hand, had better fuel qualities and reduced NO emissions. No emissions are 795, 805, 815, and 825 ppm higher for PMME10, PMME15, and PMME20 at 100% load compared to diesel fuel. Because of its greater density and viscosity, biodiesel has a negative impact on fuel atomization, which in turn heat release phaseand impacts the delay. When the last of the fuel is burned out, the combustion process enters its late phase, where the generation of NO is slowed down by a lack of residence time for the reaction.

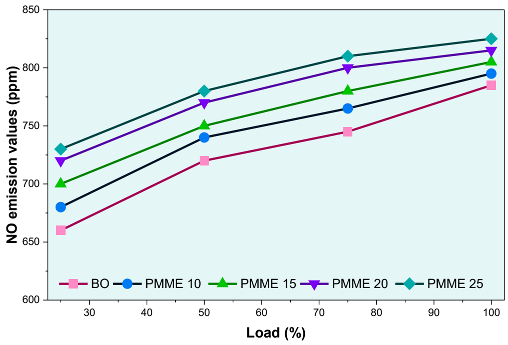

Fig. 7. Effect of Load Conditions onnitrogen oxideEmission

3.6. Performance Comparison with Literature Reports

Outcomes of the research has been related to the results of previous core studies to understand congruence and attract new knowledge.
In this experiment, the researchers concluded that the higher the contents of PMME biodiesel homogenates, the lesser the BTE. The findings showed that BSFC improved with PMME mixes and PMME20 in particular. This upsurge is believed to be as a result of the lowered energy content of biodiesel.

This makes our methodology sound and PMME can be a viable biodiesel feedstock, as our findings are in line with other studies. Also, different feedstock types, engine configurations, and operating conditions can cause slightly different outcomes.

4. Conclusion

The feasibility, efficiency, and environmental impact of biodiesel made from plastic and mahua (PMME) oils were examined in this study. To meet international fuel regulations and lower the free fatty acid level, a two-stage transesterification process was used. While experimenting with different amounts of biodiesel and diesel, we maintained a constant speed for a one-cylinder CRDI diesel engine was maintained under varying load conditions.
At lower blend percentages, the results show that PMME is an attractive alternative fuel that has little effect on engine performance and improves the environment. At maximum load, PMME10 achieved a BTE of 8.31%, which was the closest to diesel performance, according to the engine performance analysis. The BTE declined as the biodiesel content increased. Because of its lower heating value and higher viscosity, PMME25 showed a 12.81% decrease in BTE. Optimisation is required because fuel consumption raised with each biodiesel mix; yet, PMME25 had a 16.49% higher BSFC than diesel.
Because of its oxygenated nature, PMME25 significantly reduced emissions of carbon monoxide (0.8% decrease) and hydrocarbon (50.15% reduction) in the examination of emissions. Because of its higher combustion temperatures and higher oxygen content, PMME25 exhibited 55.5% greater NO emissions than diesel, although this trend was observed across all biodiesel mixes.
Biodiesel is a sanitizer and more renewablesubstitute to fossil fuels and this study's results back up the idea that it should be incorporated into the current energy system. Air quality can be improved and the ecological effect of the industrial sectors and transportationreduced by using blends like PMME10 and PMME15, which greatly reduce hazardous emissions.
This research broke new ground in methodology by introducing a composite feedstock to overcome important drawbacks of using only one type of oil, including poor cold flow characteristics, high viscosity, and restricted supply. The fuel properties were improved, the fatty acid structure was enhanced, and the stability of the blend was upheld with the 50:50 oil mixture without the use of additives and pre-heating.
To bring PMME to reality, more research into the optimization methods in engines like optimized injection timing, catalytic after-therapeutic intervention system to minimize **nitrogen oxide** emissions is requiredand exhaust gas recirculation (EGR). Collectively, the results of the current research highlight the urgent necessity of moving beyond fossil-based energy and toward renewable biofuels to combat the climate change problem, to have a more stable and

sustainable future in energy security, and, as a means of transportation and power generation, to achieve a more sustainable and greener future.

References

1. D. Saha, P. Majumder, B. Roy, and P. P. Kundu, "Effect of areca nut husk bio-additive on combustion, performance, and emission characteristics of a hydrogen enriched CRDI CI engine fueled with a plastic oil-ethanol-diesel blend," vol. 153, 2025, doi: 10.1016/j.ijhydene.2025.150134.
2. D. Saha, B. Roy, and P. P. Kundu, "A comprehensive investigation on the prospects of ternary blends of ethanol-plastic grocery bag derived oil-diesel for CRDI CI engine: combustion, performance, and emission analysis," 2025, doi: 10.1007/s10098-025-03162-4.
3. D. M. Madhuvanesan and J. M. Babu, "Impact of nano cerium oxide addition with pyrolysis waste plastic oil on combustion, performance and emission characteristics of CRDI diesel engine," vol. 6, no. 4, 2024, doi: 10.1088/2631-8695/ad923e.
4. J. Jaiganesh, R. Ramasamy, and M. G. Gowthama Krishnan, "Exploring the synergistic potential of prosopis juliflora and waste plastic oil biodiesel through investigation of performance, combustion, and emission in a CRDI engine: A shift towards sustainable fuel," vol. 184, pp. 720–735, 2024, doi: 10.1016/j.psep.2024.02.036.
5. E. R. K. Rama Krishna Reddy and M. K. Pal, "Influence of hydrogen induction in a CRDI engine fuelled with water emulsified waste plastic oil blend," vol. 49, pp. 1282–1293, 2024, doi: 10.1016/j.ijhydene.2023.09.025.
6. T. Bothiraj, K. Boopathi, K. Kalaiselvan, A. Benham, and S. Mayakannan, "Experimental investigations on mechanical and wear behavior of waste marble dust and coconut fiber reinforced hybrid bio composites," in *Materials Today: Proceedings*, 2022, pp. 2239–2242.
7. T. Anand and S. Debbarma, "Influence of Fuel Injection Timing and Hydrogen Enrichment on Waste Plastic Oil: Performance, Combustion, and Emissions Analysis," vol. 433, pp. 85–90, 2024, doi: 10.4028/p-pX49ib.
8. A. V. K. Krishna Chaitanya and D. K. Mohanty, "Experimental investigation on the combustion, performance and emission characteristics of 1-pentanol blended waste plastic oil in a CRDI engine with EGR," vol. 256, 2022, doi: 10.1016/j.energy.2022.124574.
9. H. V Ganvir*et al.*, "Monitoring Atomic Layer Deposition by Potentiodynamic Electrochemical Impedance Spectroscopy of Multielement Adlayers," vol. 27, no. 3, pp. 172–181, 2024, doi: 10.14447/jnmes.v27i3.a02.
10. R. Prasad *et al.*, "Effect of Boost Pressure and Compression Ratio on the Performance and Emission Characteristics of Diethyl Ether Fuelled Engine," vol. 17, no. 2, pp. 182–188, 2025, doi: 10.4273/ijvss.17.2.01.
11. A. K. Das and T. Mohapatra, "Exergetic performance optimization and thermoeconomic analysis of a variable compression ratio diesel engine fueled with distilled plastic oil and diesel doped with nanographene," 2024, doi: 10.1177/09544089241229563.
12. V. R. Khawale*et al.*, "Study on Electrochemical Stability and Charge Transfer Efficiency for the Development of High-Performance Supercapacitors Using Iron Oxide (Fe2O3) Nanorods," vol. 27, no. 3, pp. 163–171, 2024, doi: 10.14447/jnmes.v27i3.a01.
13. K. Wathakit*et al.*, "Characterization and impact of waste plastic oil in a variable compression ratio diesel engine," vol. 14, no. 8, 2021, doi: 10.3390/en14082230.
14. A. K. Das, M. R. Padhi, D. Hansdah, and A. K. Panda, "Optimization of Engine Parameters and Ethanol Fuel Additive of a Diesel Engine Fuelled with Waste Plastic Oil Blended Diesel," vol. 4, no. 4, pp. 465–479, 2020, doi: 10.1007/s41660-020-00134-7.
15. B. G. Rao, Y. D. Bharadwaz, and P. S. R. Krishna, "Characterisation of diethyl ether blended waste plastic oil used as a fuel in variable compression ratio engine - an experimental study," vol. 24, pp. 44–51, 2020.
16. P. P. Prasad Kumar, S. Pendyala, and S. K. Gugulothu, "Influence of the Metallic (SiO) and Non-metallic (Rice Husk) nano additives blended with 2-ethylhexyl nitrate on the Engine Characteristics of CRDI Diesel Engine," vol. 15, no. 12, pp. 5149–5161, 2023, doi: 10.1007/s12633-023-02425-3.
17. J. Ramachander, S. K. Gugulothu, G. R. Sastry, and B. Bhsker, "An experimental assessment on the influence of high fuel injection pressure with ternary fuel (diesel–mahua methyl ester–pentanol) on performance, combustion, and emission characteristics of common rail direct injection diesel engine," vol. 29, no. 1, pp. 119–132, 2022, doi: 10.1007/s11356-021-13909-3.
18. R. Dhairiyasamy and D. Gabiriel, "Performance and emission characteristics of Mahua oil biodiesel in low heat rejection diesel engines with retarded injection timing," vol. 17, 2025, doi: 10.1016/j.ctta.2024.100158.
19. S. J. D. Vijayakumar, S. Paulsingarayar, A. Augustine, K. Vetrivelkumar, and R. Rajendran, "Impact of compression ratio and effect of biodiesel blends in performance, combustion and emission characteristics of VCR DI diesel engine," 2020, pp. 967–974. doi: 10.1016/j.matpr.2020.06.182.
20. A. K. Das, S. S. Sahoo, and A. K. Panda, "Production of Waste Plastics Oil and Its Prospective Use in a Variable Compression CI Engine," vol. 25, no. 3, 2021, doi: 10.1061/(ASCE)HZ.2153-5515.0000606.
21. S. R. Srinivasa Reddy, H. R. Y. Venkata, D. Vallapudi, N. Narmatha, and A. R. Kumaravel, "Prediction of recital characteristics of a CI diesel engine operated by bio-fuel extracts from cotton seed oil, linseed oil and mahua seed oil using ANN method," vol. 9, no. 2, pp. 366–376, 2023, doi: 10.18186/thermal.1284626.

22. Prabhahar, M., Manohar, M., & Sendilvelan, S. (2012). Performance and emission characteristics of diesel engine with various injection pressures using biodiesel. Indian Journal of Science and Technology, 5(6), 2880-2884.
23. Kotaiah, K., Periyasamy, P., & Prabhahar, M. (2020). Performance and emission characteristics of small agricultural diesel engine using Lemongrass oil and its diesel blends. Materials Today: Proceedings, 33, 658-662. https://doi.org/10.1016/j.matpr.2020.05.773
24. Krishnamoorthi, S., Prabhahar, M., Kumar, M. S., & Sendilvelan, S. (2018). Yield characteristic of biodiesel derived from used vegetable oil methyl ester (UVOME) blended with diesel, in the presence of sodium hydroxide (NAOH) and potassium hydroxide (KOH) catalyst, as alternative fuel for diesel engines. International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), 8(1), 9-16. DOI: 10.24247/ijmperdfeb20182
25. Prabhahar, M., & Sangeetha, K. (2008). Experimental investigations on dual bio-fuel (pine biodiesel and palm biodiesel) blended with diesel on a single cylinder diesel engine. International Journal of Mechanical and Production Engineering Research and Development, 8(2), 87-92. V. Gnanamoorthi and M. Manickam, “Effect of DEE and MEA as additives on a CRDI diesel engine fueled with waste plastic oil blend,” vol. 44, no. 2, pp. 5016–5031, 2022, doi: 10.1080/15567036.2019.1657206.
26. T. Anand and S. Debbarma, “Experimental Analysis of Hydrogen Enrichment in Waste Plastic Oil Blends for Dual-Fuel Common Rail Direct Injection Diesel Engines,” vol. 146, no. 1, 2024, doi: 10.1115/1.4063665.
27. A. K. Das and A. K. Panda, “Improvement of performance and emission characteristic of waste plastic pyrolytic oil blended diesel fuel in variable compression diesel engine using graphene nano additive,” vol. 34, no. 1, pp. 212–229, 2023, doi: 10.1177/0958305X211060405.
28. T. Anand and S. Debbarma, “Experimental investigation of fuel injection timing effects on a CRDI diesel engine running on hydrogen-enriched waste plastic oil,” vol. 57, pp. 1051–1069, 2024, doi: 10.1016/j.ijhydene.2024.01.052.
29. M. Mariappan, M. S. Panithasan, and G. Gnanamoorthi, “Pyrolysis plastic oil production and optimisation followed by maximum possible replacement of diesel with bio-oil/methanol blends in a CRDI engine,” vol. 312, 2021, doi: 10.1016/j.jclepro.2021.127687.