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Original Article

Experimental Analysis on Performance and Emissions of Mahua Pyro Oil Biodiesel Blends as a Fuel for DI-CI Diesel Engine: A Sustainable Alternative for Reducing Engine Emissions

C. Thiagarajan[1*], M. Prabhahar[1], J. Senthil[1], M. Saravanakumar[1], S. Prakash[1]

[1]*Department of Mechanical Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation, Deemed to be University, Tamil Nadu, India.*

[*]*Corresponding Author : ctr.rajan@gmail.com*

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Abstract - *This research describes the working behaviours of the Compression Ignition (CI) engine using Mahua Pyrolysis Oil (MPO) obtained from Mahua seed using the fast pyrolysis technique. The diesel engine test was performed with four different MPO-diesel mixtures such as MPO15, MPO25, MPO35 and MPO50 and the test results were compared to diesel engine According to the results of the tests, the Brake Thermal Efficiency (BTE) in MPO-diesel mixture was decreased by 2-5% with an increase in the Brake Specific Fuel Consumption (BSFC) compared to diesel. Higher Carbon Monoxide (CO) and Hydrocarbon (HC) emissions were observed when the mixture's ratios increased. At maximum power, Nitrogen Oxide (NO) and smoke were diminished by 9% and 17% for the MPO25-diesel mix. Results also revealed that the combustion parameters like cylinder peak pressure and the Heat Release Rate (HRR) were increased in an increased blend. The results suggest that up to 25% of the MPO mixture is the optimum fuel for running the engine without much affecting the performance and emissions.*

Keywords - *Diesel engine, Mahua Pyro Oil, Emission, Combustion, Performance.*

1. Introduction

As the population grows and the number of automobiles on the road grows, energy demand and fuel costs have risen inexorably over the last 3-4 decades. Air and water pollution have increased, most likely causing continuous environmental degradation. The burning towards fossil fuels is the primary source of hazardous emissions [1]. Research on promising diesel substitute fuels has been accelerated to satisfy the ever-demand for energy. Biofuels have demonstrated the potential for alternative energy sources, and their use can significantly lessen reliance on fossil fuels [2]. Recently, biomass-to-energy conversion has concentrated mainly on upgrading fossil fuels [3]. After related to diesel, biodiesel could be utilized in engines at lower blends without causing any differences in performance and emissions. Biodiesel is a natural resource that is non-toxic and renewable [4]. Higher cetane ratings, the absence of sulphur, and the excess oxygen in the fuel are additional benefits over petro-diesel. However, the obstacles to the utilization of biodiesel have been identified, including low production compared to crude oil availability, higher NO emissions, poor oxidation, and poor cold flow properties [5].

There is a lot of interest in developing new technologies for harvesting energy from biomass. Waste biomass materials are widely converted into valuable liquid fuels using pyrolysis and catalytic cracking. Nowadays, pyrolysis, a type of thermochemical conversion, will be very significant in producing possible liquid fuels from highly volatile material from biomass. This pyrolysis oil is called 'bio-oil' [6].

Many researchers have tested the performance of diesel engines using bio-oil, and the results showed that, when compared to diesel, there is a substantial decrease in BTE and a marginal increase in BSFC. Unburned hydrocarbon and Carbon Dioxide (CO_2) emissions were slightly reduced, while exhaust emissions like CO and NO were reduced [7-10]. Examined towards the flash Wood Pyrolysis Oil (WPO) in CI engines.

Investigated the behaviour of a CI engine using WPO with various proportions of oxygenated additives. Their results showed that stable operations with WPO-oxygenated blends containing up to 44.1% WPO by weight were feasible. [11] Studied the engine characteristics of using Mahua Pyro Oil blends. Tested and analysis of a diesel engine using pyro oil made from tomato peels. According to the findings, the BTE of a blend containing 5% tomato peel oil is higher, and the level of CO emissions was discovered to be a minor change from those of diesel oil.

Vikranth et al. [12] examined mustard cake pyro oil blends in an engine and obtained that a 30% mix yielded 4.7% greater BTE and fewer exhaust emissions than diesel. Bio-oil produced from scrap wood as fuel for petrol engines was examined. In a diesel engine test, the emulsions of coffee bean pyrolysis oil [13] reduced smoke emissions while improving combustion efficiency and NOx emissions.

Rajamohan et al. [14] created Cottonseed Pyrolysis Oil (CPO), an intermediate pyrolysis process in a fixed-bed reactor. The CPO-diesel mixture fueled a diesel engine. At peak load, the most remarkable BTE was obtained for the lower CPO blend at C.R. 18:1. The minimum NOx emission was observed as 106 ppm for C.R. 16:1 at half load, while HC and CO emissions were lowered.

By pyrolyzing leftover tomato peel, Mithun et al. [15] obtained a bio-oil in a fast pyrolysis. A diesel engine was tested using diesel (5%, 15%, and 25%) and Tomato peel Pyrolysis Oil (TPO). TPO 5% peak-load mix has a 7–10% higher BTE than diesel. TPO 25% blend has a greater HRR, which rises towards the cylinder temperature and results in NOx emissions of around 5-8% and a CO2 increase of 8–13% as the blend% increases due to the rise in oxygen% in the blend.

The enhancement of engine performance and emission was investigated by utilising bio-oil, ceramic-coated pistons, and adding nanoparticles to the bio-oil. Conferring to test results, engine performance increased by 3-4% compared to mineral diesel fuel, while gaseous emissions decreased by 15% to 25%, including NOx and nanoparticle emissions [16, 17].

Pyrolysis oil treated by emulsification can burn readily and releases less CO, claim Van et al. [18]. Additionally, the bio-oil emulsion may enhance engine efficiency and exhaust emissions. Due to oxygenated compounds and polar groups produced in bio-oil through a frictional chemical reaction, emulsified bio-oil may have more excellent friction performance than diesel [19]. Mahua seed oil can be obtained by the pyrolysis method.

Mahua seed oil has become a significant biofuel due to a few identified properties that improve performance. Mahua seed pyrolysis can be combined with other conventional fuels or utilized immediately as a substitute [20, 21].

There is evidence that Mahua oil reduces CO and smoke emissions in the exhaust. Different blends also have improved emission and performance statistics compared to conventional diesel [22]. Mahua biodiesel addition % boosts the thermal efficiency of the brakes, allowing for energy consumption comparable to that of diesel [23–25].

Even though it is often believed that fuel consumption is higher, research indicates that using aluminium oxide nanoparticles significantly lowers fuel consumption [26].

1.1. Research Gap and Objective of the Research Work

After an in-depth examination of the literature, it has been determined that only a tiny amount of investigation has been revealed on the manufacture of bio-oil from vegetable seeds and its use in diesel engines using lower mixes (up to B20).

The prior research identified the gap as higher bio-oil blends had not been investigated in diesel engines and have not been published. As a result, this investigation aims to examine the performance of CI engines using various MPO combinations, such as MPO15, MPO25, MPO35, and MPO50, to diesel and bio-oil and the outcome compared to diesel.

2. Materials and Methods

2.1. Production of Mahua Pyro Oil

The Mahua oil had been created using a rapid, semi-batch pyrolysis process. The pyrolysis system is depicted in Figure 1, and it consists of a stainless-steel semi-batch reactor with an interior and outside diameter of 4.7 and 5 cm, respectively.

First, a semi-batch pyrolysis reactor with a very sensitive PID controller was used to heat the seed. Temperatures in the reactor were maintained between 450 and 600ºC at a rate of 20ºC/min. The reactor received nitrogen gas to maintain its inert interior throughout each average run.

After that, the volatiles were passed through a condenser cooled by water, and the gases were released towards the atmosphere. The aqueous phase and oil phase were separated from the produced liquid product. Both products' further physical and chemical characterization showed they could serve as petro-diesel fuel substitutes. The colour variations of neat MPO are given in Figure 2.

The chemical characterizations revealed that the bio-oil contained more aliphatic compounds than aromatics. The bio-oil properties are tested in ETA Lab, Chennai. The comparable belongings of test fuels with ASTM are listed in Table 1.

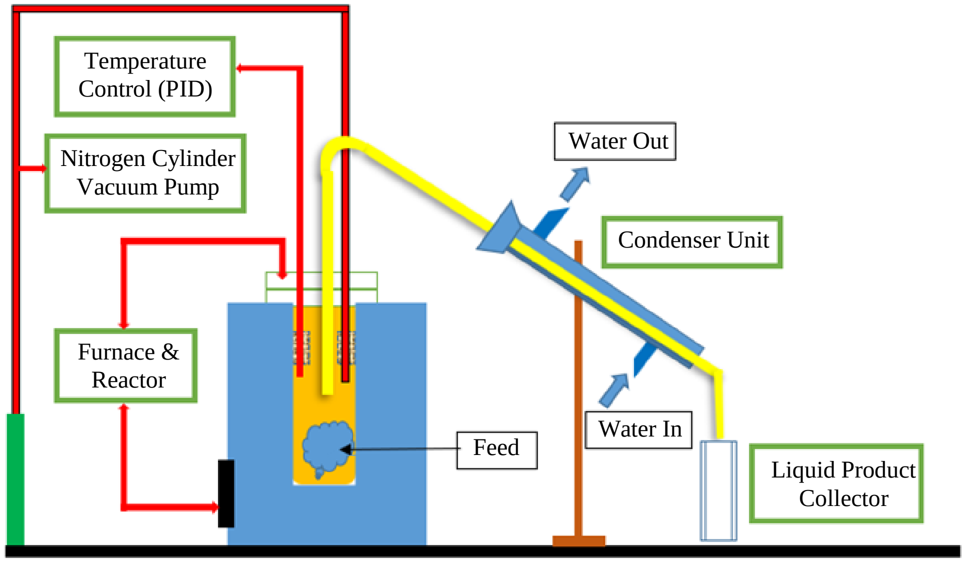

Fig. 1 Pyrolysis setup

Table 1. Physio-chemical properties of test fuels with ASTM

Properties	Diesel	MPO
Density at 40°C (kg/m^3)	833	921
Kinematic Viscosity at 40°C (cSt)	2.7	23.19
Energy Content (J/kg)	42.5	39
Flash Point (°C)	54	184
Cetane Number	47	38

Fig. 2 Photographic view of MPO

3. Methodology

3.1. Experimental Engine Setup

The Kirloskar was used to examine the engine connected to the eddy current dynamometer. Figure 3 displays a line diagram of the machine utilized for the test by applying a load and changing the electrical current, which places an electric impedance on the movement of the area. A centrifugal governor is what keeps the engine running at the correct speed. The essential technical characteristics of the machine are broken down into more detail in Table 2. Both diesel and biodiesel fuel were stored in their overhead fuel tanks, which were kept separate from one another.

Using a regular burette and a stopwatch, the duration of time that it takes the combustion chamber to consume ten cc of fuel is measured. This time is referred to as the burn rate. The temperatures of the test engine were measured using a thermocouple of the Chromel Alumel (K-Type) variety, which had a temperature range of 0 to 500 degrees Celsius. A gas system was used to detect the levels of CO, HC, and no emissions in the exhaust, and AVL brand smoke equipment was utilized to determine the level of smoke opacity.

To protect against the impacts of passaging, a piezoelectric pressure sensor manufactured by KISTLER was flush placed inside the cylinder head. The history of the connection between combustion and crank angle was recorded towards the crank angle of the encoder, which monitored the crank angle. To pinpoint the precise location of the TDC, an electrical optical sensor was utilized. A fast, automatic data acquisition system was used to capture the value for measuring cylinder pressure and TDC position.

The signals collected for over 100 cycles were analysed for the combustion value. Every five minutes, measurements of engine output and emissions for each fuel were conducted for each load to ensure the results did not change. Each experiment set's three runs' means were recorded. The parameters for the performance evaluation and the emissions were recorded for each load condition.

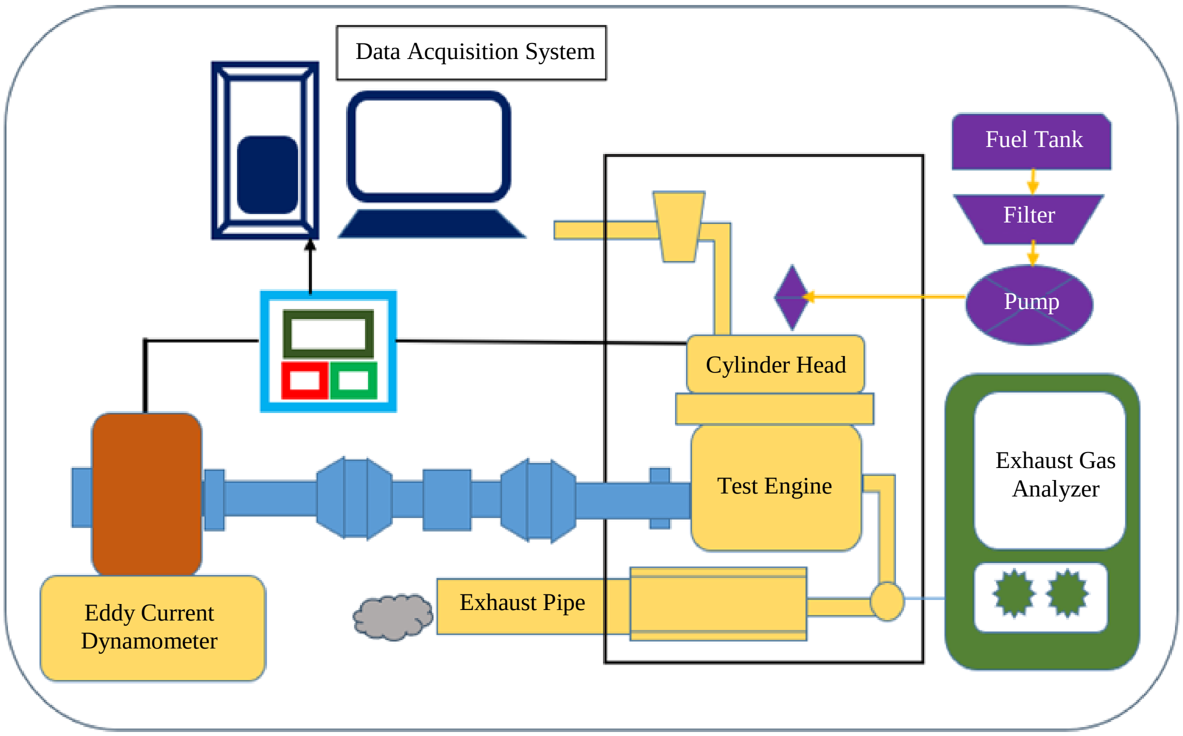

Fig. 3 Line diagram of the test engine

Table 2. Test engine technical details

Make	Kirloskar, Vertical, 4S
Bore (mm)	87.45
Stroke (mm)	110
Power (kW)	4.4
Composition Ratio	17.5:1
Speed (rpm)	1500
Injection Timing (°C)	23°b TDC
Injection Pressure (bar)	200

3.2. Uncertainty Analysis

Estimates of uncertainty and error analysis were made using various factors, including visualization, selection, equipment, the atmosphere, calibration, and time, with the latter subdivided into two types of errors: randomized and controlled. An examination of uncertainty must first be carried out to acquire precise results. To compute the Uncertainties, the transmission of uncertainty technique, additionally referred to as the mean square root approach, was utilized regarding the system. In direction to calculate the degrees of uncertainty associated with the engine performance characteristics, the formula was used.

$$\varphi_R = \left[\left(\frac{\partial R}{\partial x_1}\varphi_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\varphi_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\varphi_n\right)^2\right]^{\frac{1}{2}} \quad (1)$$

R is a function that relies on several independent variables, including x1, x2, x3, and xn. In addition, the value of R is defined as the overall proportion of uncertainty in the experiment's results, whereas φ1, φ2, φn are the uncertainties of the independent variable quantity (Holman 2012). Table 2 summarizes the percentages of luck for several quantities. An error analysis was performed using Taylor's theorem to validate the reliability of the examination outcomes. The overall sense of unpredictability is conveyed by

The overall uncertainty can be expressed as the = Square root of $[(BTE-1.0)^2 + (BSFC - 1.0)^2 + \text{Emission } (0.2)^2 + (1)^2 + (1)^2 + (1.0)^2 + (0.5)^2 + (0.5)^2] = \pm 2.35\%$.

4. Results and Discussion

Engine trials were achieved on a diesel engine with diesel and MPO-diesel mixtures to assess the engine working characteristics, and the results contrast diesel.

4.1. Cylinder Pressure

The difference in-cylinder pressure to the Crank Angle (CA) is depicted in Figure 4, and it applies to all of the fuels and mixtures. It is possible to calculate the peak cylinder pressure of a CI engine by using the quantity of fuel consumed during the premixed phase, which is computed using the delay period and fuel spray.

The MPO mixture has lower cylinder pressure than diesel due to its higher viscosity and low cetane number. The combustion of MPO mixtures begins significantly slower than diesel. This is because the MPO has a lower cetane and is less volatile. Because of its greater density, the biofuel accumulated in the premixed combustion phase has a slower combustion of MPO blends.

The peak cylinder pressure obtained for MPO15, MPO25, MPO35 and MPO50 are 67.7 bar, 69.2 bar, 66.7 bar and 63.5 bar, respectively, whereas diesel is 70.4 bar. Diesel exhibits the highest cylinder pressure of 70.4 bar, followed by MPO25, MPO15, MPO35 and MPO50. A similar result is per the researchers [27] with Mahua oil blends.

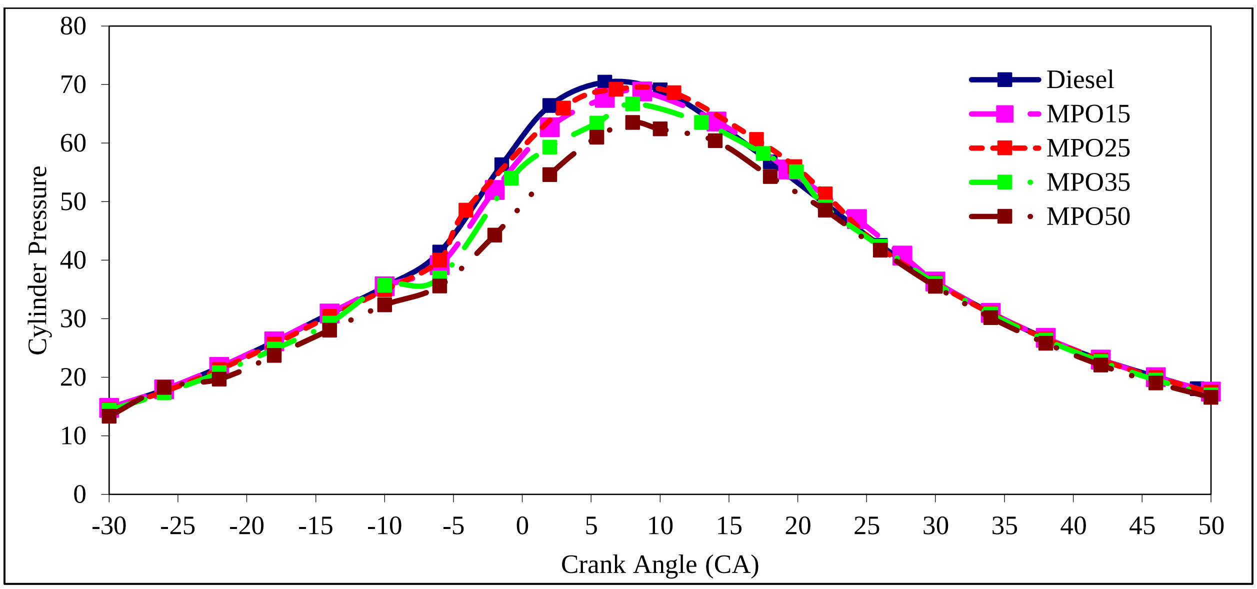

Fig. 4 Change of cylinder peak pressure with CA

4.2. HRR

Figure 5 depicts how well the HRR varies with C.A. for diesel, and MPO blends at maximum power. During the first stage, which lasts until the heat release rate slows down, the fuel-air combination that was ready during the delay period ignites. The second stage is the period of combustion that begins at the end of the first stage and lasts until it is completed. Because of less cylinder heat transfer losses and fuel evaporative cooling. Diesel has the lowest HRR, followed by MPO15, MPO25, MPO35, and MPO50 mixtures at peak load. HRR patterns for MPO-diesel mixtures are rising steadily because of an increase in the delay period resulting from fuel deposition in the cylinder. According to predictions, the HRR for diesel, MPO15, MPO25, MPO35, and MPO50 is 59.6, 61.6, 63.5, 64.4, and 65.8 J/°CA, respectively, were obtained. A similar trend of curve patterns follows the researchers [27] with Mahua oil blends and Sterculia oil blends.

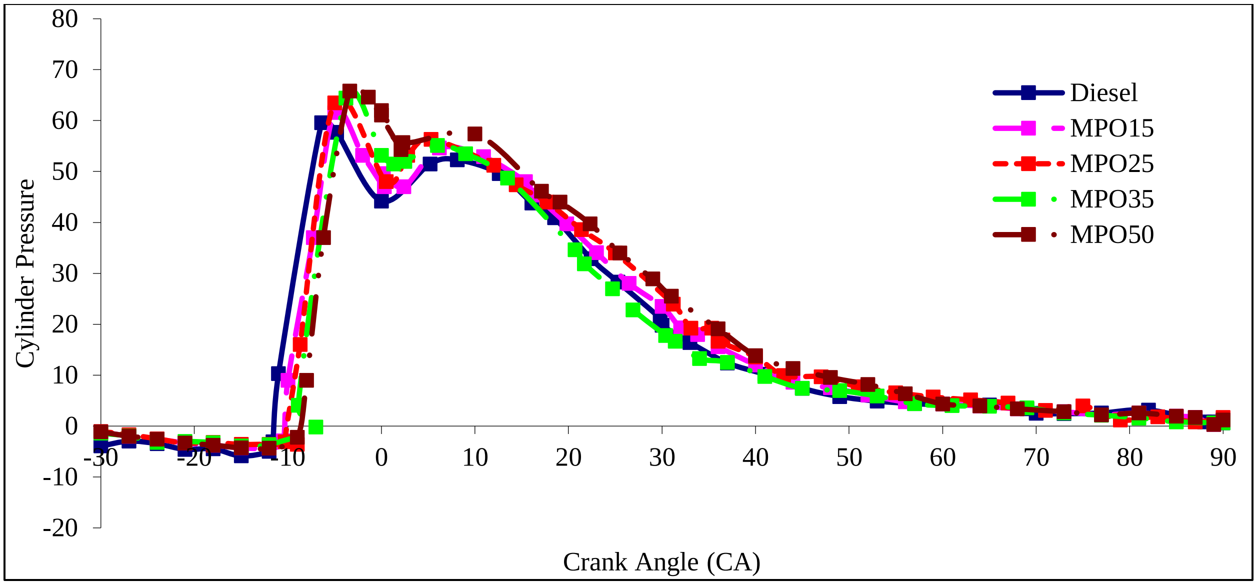

Fig. 5 Change of HRR with CA at full load

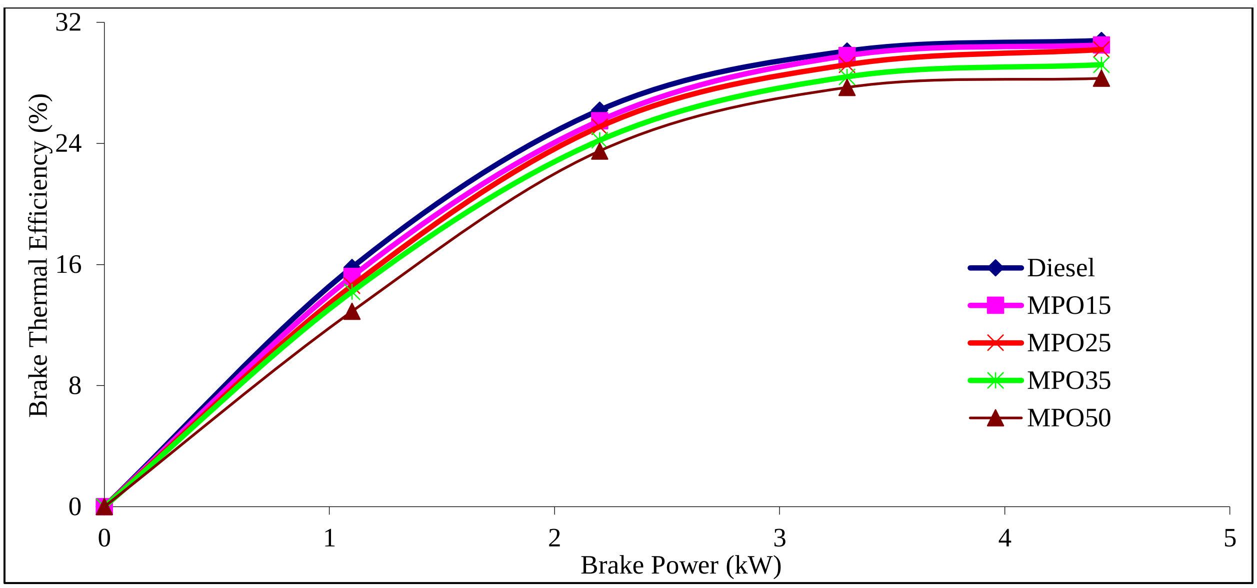

Fig. 6 Change of BTE Vs BP

4.3. BTE

Figure 6 signifies the change in BTE with Break Power (BP) for the test fuels. With all biofuel mixtures, the BTE gradually rises as the load. BTE of all mixes is lower than diesel, but the BTE of MPO15 and MPO25 are closer to diesel.

Diesel has the greatest BTE of 30.8% at maximum load, whereas the BTE of MPO15 and MPO25 is 30.5% and 30.2%, 0.3 and 0.6% lower than diesel. BTE of MPO35 and MPO50 blends seems to be 29.2% and 28.3%, respectively. Owing to its high viscosity and lower calorific value, which both drop, the BTE for the more excellent MPO blends has decreased. At maximum power, the BTE of the higher bio-oil combinations MPO35 and MPO50 is 1.6% and 2.5% lower than diesel.

4.4. BSFC

Figure 7 represents the difference between BSFC and BP for the test fuels. At all fuel mixtures, the BSFC profile patterns are opposite the BTE profile patterns. At maximum load, the BSFC of diesel and MPO25 were observed to correspondingly 0.26kg/kWh and 0.28kg/kWh.

Because of the decreased density and higher calorific value, diesel fuel has the smallest BSFC. MPO35 and MPO50 blends have BSFCs of 0.29 and 0.3 kg/kWh, respectively. MPO blends require more fuel injection than diesel to produce the same power output. This higher viscosity and lower energy content of biofuel blend is the motive for increased BSFC at all blends compared to diesel. BSFC was increased for MPO15, MPO25, MPO35 and MPO50 by 3.8%, 7.7%, 11.5% and 15.5% respectively compared to diesel.

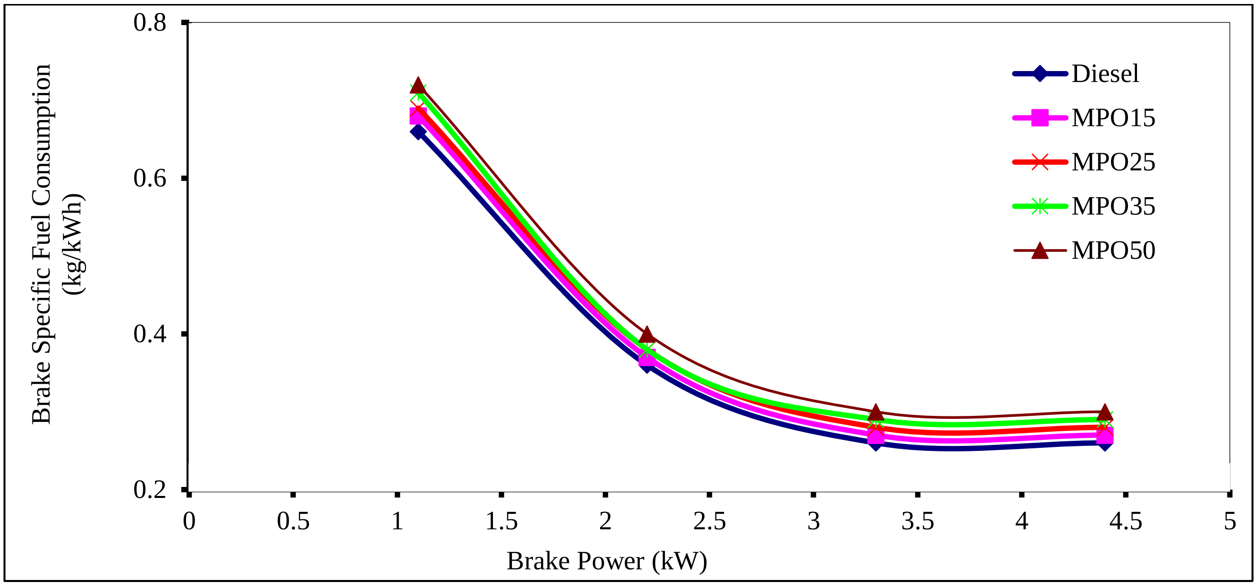

Fig. 7 Change of BSFC Vs BP

4.5. CO Emission

The correlation between CO emission and BP for the test fuel mixtures is shown in Figure 8. CO is a by-product of combustion developed primarily due to the fuel-rich zone and a shortage of oxygen, resulting in incomplete combustion of the fuels throughout the burning process. Due to the lack of oxygen and the high viscosity of MPO-diesel mixtures, CO emissions are higher than diesel for all MPO-diesel mixtures.

At full load, CO emissions for MPO15, MPO25, MPO35 and MPO50 are 0.13, 0.16, 0.19 and 0.21%, respectively, and for diesel, it is 0.15%. The CO emission for higher blends of MPO35 and MPO50 are decreased by 27% and 40% higher than diesel.

This could be because the larger fuel particles in more fantastic MPO mixtures do not receive enough oxygen for combustion, resulting in more significant CO emissions. These findings are consistent with the researchers [28] who used pyrolytic oil mixtures.

4.6. HC Emission

The primary causes of HC emissions in CI engines are poor fuel volatility, high viscosity resulting in improper fuel atomization, and rapid flame cooling at the cylinder walls. The difference in HC emission for test fuel mixes to BP is shown in Figure 9. Poor fuel volatility, high viscosity, which leads to improper fuel atomization, and rapid flame cooling at the cylinder walls are the leading causes of HC emissions in CI engines. Increased bio-oil proportion causes an increase in HC emissions. Increased bio-oil ratio causes an increase in HC emissions, which are caused by partial oxidation caused by poor fuel atomization. At maximum power, HC emissions for MPO15, MPO25, MPO35 and MPO50 are 65, 68, 72 and 76ppm, respectively and for diesel it is 60ppm.

HC emission obtained for MPO15, MPO25 and MPO35 was increased by 7-27% compared to diesel. A rise in HC emission for MPO-diesel combinations might be due to incorrect spray resulting from elevated viscosity and aromatic compounds in bio-oil. The results are by researchers tomato peel oil blends.

4.7. NO Emission

The cylinder's temperature, pressure, and overall oxygen content all impact NO emission. Greater NO emissions are produced by all test fuels when BP is used to raise the combustion chamber temperature. Figure 10 demonstrates the NO emission differences with BP for all the test fuel mixtures. At maximum power, NO emissions for MPO15, MPO25, MPO35, and MPO50 are 842, 817, 794, and 762ppm, respectively, while diesel emissions are 874ppm. In contrast to diesel, NO emissions for MPO15, MPO25, and MPO35 were significantly lowered by 4-9%. This could be due to a greater viscosity resulting from a lower HRR and, hence, lesser NO emissions. Unlike diesel, NO emissions for MPO15, MPO25, and MPO35 were significantly lowered by 4-9%. The results match the researchers' tomato peel oil blends.

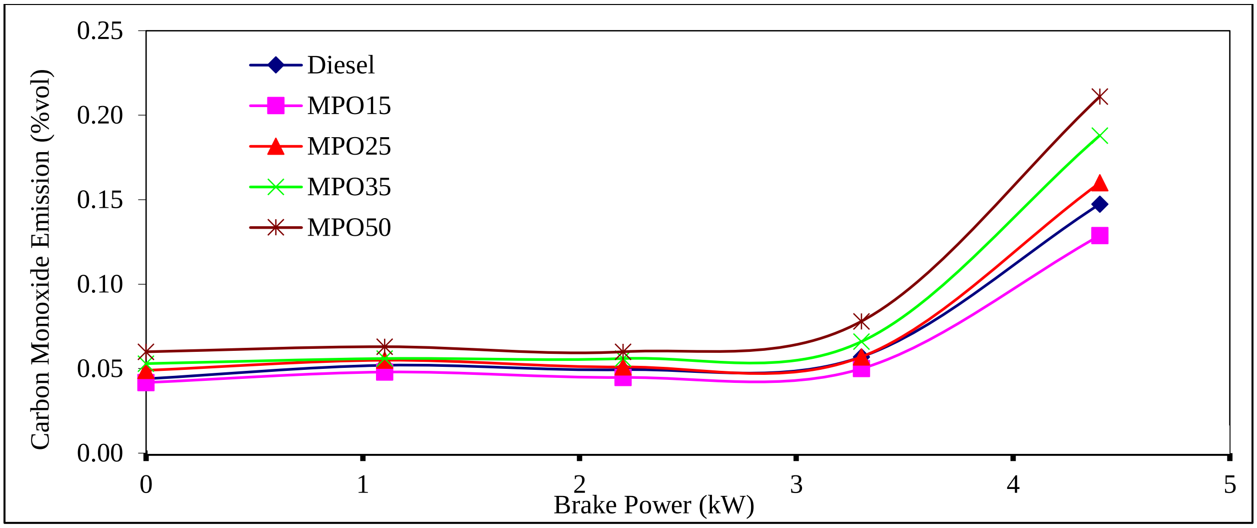

Fig. 8 Change of CO vs BP

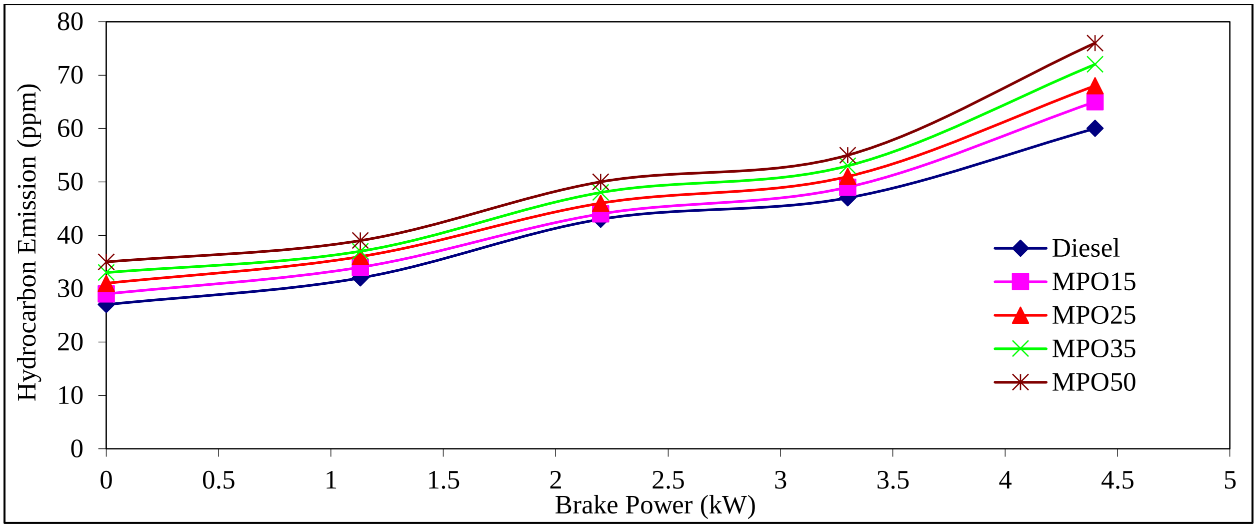

Fig. 9 Change of HC vs BP

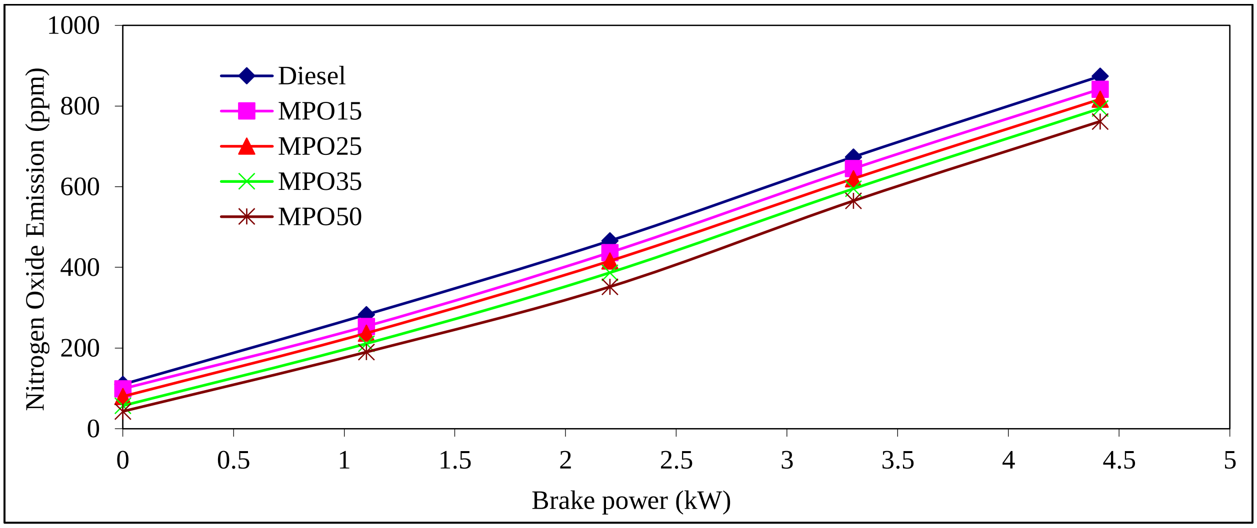

Fig. 10 Change of NO vs BP

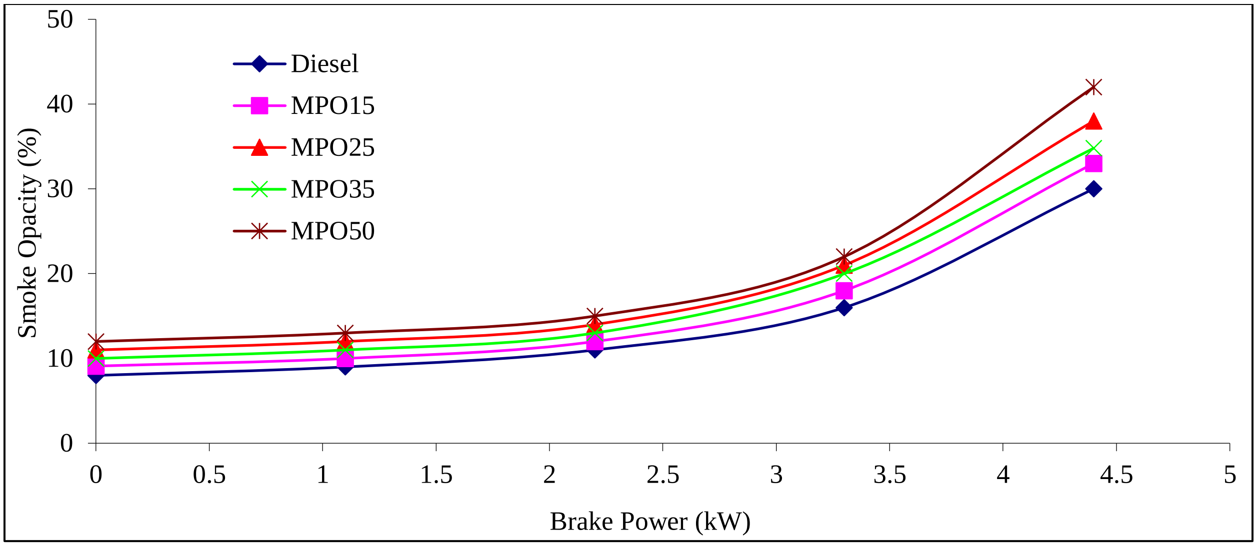

Fig. 11 Change of smoke vs BP

4.8. Smoke

Smoke emission occurs primarily during the diffusion phase; at higher loads, it happens during combustion. Figure 11 depicts the relationship between smoke emission and BP for all fuel mixtures.

Smoke is produced in the combustion chamber's fuel-rich zones. Higher smoke emission impacts from a reduced air-fuel ratio because of more fuel consumption. At maximum power, smoke opacity obtained for MPO15, MPO25, MPO35, and MPO50 is 33%, 38%, 35%, and 42%, respectively, and for diesel, it is 30%. Excess oxygen in the bio-oil may be why smoke opacity for MPO mixtures is lower than for diesel.

The smoke opacity of MPO15 to MPO35 is increased by 10-27% compared to diesel. Increasing the BSFC for MPO blends gradually causes a slight increment in smoke opacity throughout operational conditions. These findings are consistent with the researchers [29] who used Mahua Pyrolysis Oil mixtures.

5. Conclusion

The efficiency of a diesel engine when MPO-diesel mixtures are operating was extensively studied. The results of the experiment have led to the following conclusions:

- At maximum power, the cylinder pressure of MPO25 is 69.2 bar, whereas diesel's is 70.4 bar. The heat release rate of MPO mixtures is more significant than diesel.
- BTE obtained for MPO15 and MPO25 blends is closer to diesel fuel. BTE of MPO15 and MPO25 was 30.2% and 30.5%, respectively, whereas diesel is 30.8% at maximum power.
- At maximum power, HC and CO emissions were enhanced for MPO25 mixtures than diesel. For MPO25 mixtures, CO and HC emissions were improved by 27% and 9% compared to diesel.
- As a result of the longer delay, the MPO25 mixture produced 9% less NO emissions than diesel at peak power. MPO25 had a marginal (17%) decrease in smoke opacity compared to diesel.

The research findings strongly suggest that up to 25% MPO-oil mixtures could be used in diesel engines for enhanced performance and decreased emissions without modifying the engine hardware.

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