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RESEARCH ARTICLE

Enhancing the engine parameters of compression ignition engine using mahua biodiesel blend with alumina nanoparticles and exhaust gas recirculation

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Abstract

The performance, combustion, and exhaust emissions analysis was carried out on a one-cylinder Direct Injection Diesel engine that was done using Mahua biodiesel blend contains (25% Mahua BD and 75% diesel along with 100 ppm of (Al_2O_3) nano additive and 20% exhaust gas recirculation with varying load from 0 to full load with a step of 25%. This study shows that the BTE was improved by almost 5.53% with the addition of Alumina nano additive to Mahua bio diesel blend. The combination of nano additives and 20% EGR to MB25 fuel, 3.4% raise in BTE was observed. The BSFC for nano additive mahua biodiesel blend with 20% EGR decreased by 2.34% than the Mahua biodiesel blend. This shows that using alumina additive and exhaust gas recirculation with the biodiesel blend increases the brake power and fuel efficiency than the biodiesel blend. However, concerning exhaust emissions, mahua biodiesel blend with alumina nano additive containing 20% EGR, generated 14.8% less nitrogen oxides (NOx), on the other hand, hydrocarbons (HC), carbon monoxide (CO), and smoke were increased 10.2%, 12.7%, and 9.1%, respectively than MB25. Overall, findings suggest that the use of alumina nano additive in Mahua biodiesel with 20% exhaust gas recirculation improves the engine performance and an increase in HC, CO and smoke emissions by reducing the NOx emissions than the nano additive biodiesel fuel and MB25 and biodiesel blend with 20% EGR.

Keywords: Alumina, biodiesel, EGR, emissions, Mahua oil, nano additive, performance

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1. Introduction

In daily life, the fuel demand rises rapidly prompting environmental concerns. Developing sustainable fuel alternatives are vital for mitigating pollution within our ecosystems and reducing dependence on fossil fuels drastically. Pollution caused by burning of fossil fuels, especially air pollution from diesel engines has increased with the use of traditional fuels. Therefore, to reduce emissions and mitigate global warming, biodiesel has emerged as an alternative fuel strategy. This study has a lot of importance; by using nanoparticles the combustion of biodiesel can be increased and emissions can be reduced [1,2]. Different types of biodiesel, such as Mahua, Kharanja, tobacco, and rubber seed oils, have been successfully evaluated in compression ignition (CI) engines, resulting in excellent performance and regulated emissions [3]. Vivekugar et al. investigated the usage of a Mahua biodiesel mixture in CI engine and found that biodiesel usage reduced PM, hydrocarbons (HC), CO_2 and CO emissions while increasing fuel consumption and nitrogen oxides (NOx) emissions [4,5]. Mahalingam et al. [6] found that the addition of 10% and 20% Octanol resulted in a considerably lowered emissions in contrast to the use of neat Mahua oil biodiesel, particularly at full load. Results shows that 6.8%, 5.1%, 4.8% and 2.1% reduction in CO, HC, NOx

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and smoke emissions respectively. Prabhu et al [8] evaluated the influence of cerium oxide (CeO_2) and alumina nanoparticles on Jatropa biodiesel. Different proportions of nanoparticles were added, and the researchers observed reductions in smoke emissions (32%), nitric oxide (13%), unburned hydrocarbons (33%), and carbon monoxide (60%). Prasad G.V.L et al [9] focused on the inclusion of alumina nanoparticles to Kharanja emulsified biofuel (diesel) in dissimilar proportions and concluded that the add on of alumina nanoparticles improved brake power (BP) and reduced emissions compared to KBD(Karajnja Biodiesel) emulsion fuel. Anchupogu et. al [10] investigated Calopyllum Inopyllum biodiesel with 40ppm TiO_2 nanoparticles and examined in a diesel engine and observed a significant reduction in CO emissions for B2040TiO_2 fuel, but the remaining emissions were increased. Addition of CuO and Al_2O_3 nanoparticles (at a concentration of 50 ppm) to neat diesel [11], results in an increase in power (1.0% and 3.28% with CuO and Al_2O_3, respectively), a reduction in specific fuel consumption (SFC) (0.5% and 1.12% with CuO and Al_2O_3, respectively), and a reduction in emissions. Prolonged exposure to metal-oxide nanoparticles in the combustion environment can lead to issues such as injector fouling, and abrasive wear, potentially affecting the durability and operational stability of diesel engines. Sajith et al. [12] focused on alumina nanoparticles, despite their role in enhancing atomization and surface catalytic activity, may form deposits on injector nozzles and combustion chamber surfaces during extended usage, especially when agglomeration occurs.

From the previous findings it was observed that biodiesels are suited for the diesel engines up to some percentage and the experiments using mahua biodiesel in combination of additive and EGR is less. The main aim of this study is on the influence of adding (Al_2O_3) nano particles of alumina to the Mahua biodiesel (MB25) mixture with 20% EGR on engine characteristics of the Kirloskar TV1 model diesel engine.

2. Methods and materials

Mahua oil is suitable for the production of biodiesel, owing to its extreme fatty acid content. [13]

Table 1. Biodiesel production process from raw oil

Acidic-Catalyzed Esterification	Base-Catalyzed trans-esterification
Mahua raw oil of 1000 ml	0.25 v/v Methanol
Preheated temperature100 °C	0.7% KOH palletes
0.35 v/v Methanol	at 5000 rpm stirring
1% v/v Sulphuric acid	60°C Temp to react
At 5000 rpm Magnetic stirring	1 hr Time to react
60° C Temp for reaction	12 hr Time to separate
Time to react 1 h	
10 hr Time required to separate	

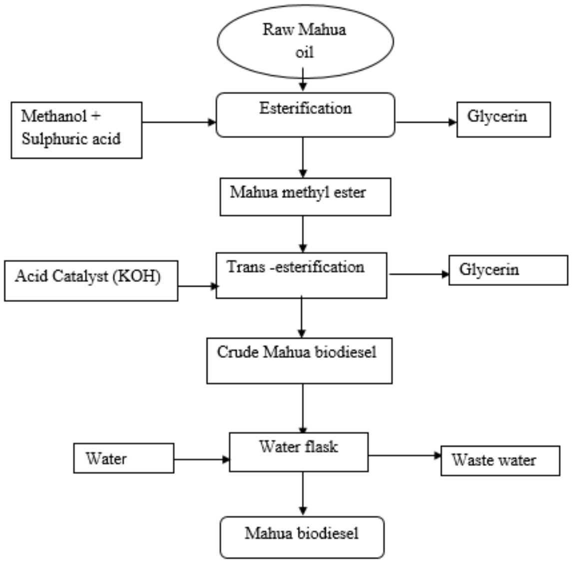

Figure 1. Biodiesel production process from raw oil

The process of producing biodiesel from Mahua oil typically involves a sequential process of esterification followed by trans-esterification and the procedure is shown in Table 1.And the flowchart is depicted in Fig 1. In acid-catalyzed esterification method, the Crude Mahua oil was treated with methanol at a molar ratio of 6:1 using sulfuric acid (H_2SO_4) as a catalyst at 1% v/v of the oil. The chemical reaction was occurred at 60 °C for 60 min under continuous stirring at 600 rpm speed. Next, the mixture was permissible to settle for 4 hours, and the upper esterified layer was separated, washed with warm distilled water to remove residual acid and impurities, and dried under vacuum. In the second stage, base-catalyzed transesterification was carried out using the pretreated Mahua oil with methanol at a molar ratio of 8:1, employing potassium hydroxide (KOH) as a catalyst at 1.0% w/w based on the oil mass. The reaction proceeded at 60 degree C for 90 minutes with continuous stirring at 700 rpm. Following to this process, mixture was admitted to settle for 8 hours to expedite phase separation. The biodiesel (upper phase) was then collected, thoroughly washed with deionized water until removing the all impurities. MB25 biodiesel blend called MB25 by mixing 250 ml of Mahua bio-fuel with 750 ml of diesel. To incorporate alumina nanoparticles into the biodiesel blend, 100 ppm (parts per million) of alumina particles were weighed and assorted with the Mahua biodiesel blend (MB25) using an ultrasonicator at 30 kHz frequency for 30 minutes. To ensure uniform dispersion and prevent agglomeration and deposition of nanoparticles, 2% by volume of Tween 80 surfactant was included to the biodiesel blend. The alumina nanoparticles (Al_2O_3) supplied by Souvenir Chemicals, India were characterized using SEM images and XRD patterns were shown in Figure. 2(a) & 2(b). The nanoparticles were found to have a size of lower than 50 nm, with a white color and 99.9% purity. The crystalline structure of the (Al_2O_3) NP's was determined by observing the

XRD image. The fuel properties of the base mixtures, including the biodiesel blend MB25, were assessed using standard ASTM method [14] and are specified in Table 2.

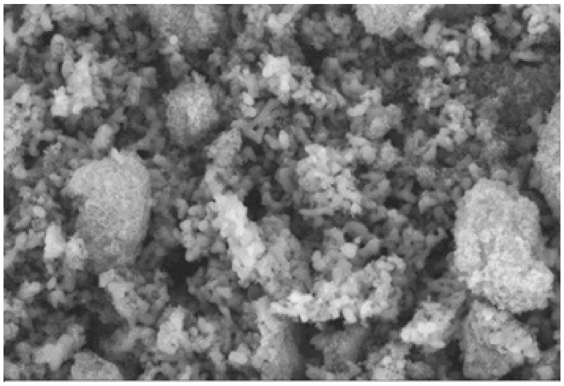

Figure 2(a). SEM image of Alumina Nanoparticles [15]

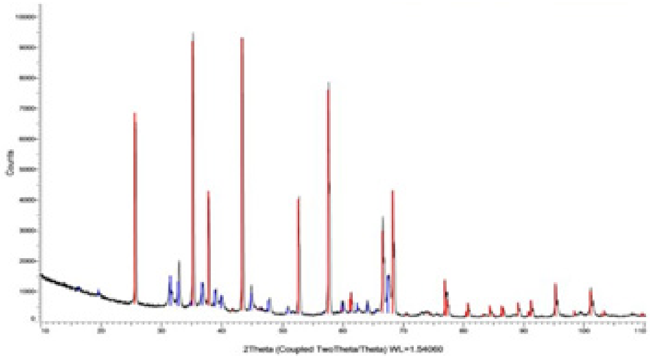

Figure 2(b). XRD pattern of alumina nanoparticles

Table 2. Fundamental fuel properties of tested fuel samples

Fuel sample	Flash Point (°C)	Fire Point (°C)	Density @15°C (kg/ m^3)	Heating Value in (KJ/kg)	Kinematic Viscosity at 40^0C in cST
Diesel fuel	58	62	840	42400	2.7
MB 25	64	71	853	38548	3.2
MB25AONP	65	70	854	39268	3.74

3. Equipment used

The photographic view of engine used is represented in Figure. 3 and the technical specifications in detail are tabulated in Table 3. All the tests on the engine with different fuel blends were executed at a constant engine speed of 1500 revolutions per minute (rpm) and standard conditions of IT (23 degree CA bTDC) and injection pressure of 200 bar at different loads varying from 0 to full load with a step of 25% increase on Kirloskar TV1 model CI engine. In previous research, engine was tested with different Mahua biodiesel blends varying biodiesel percentage from 0 to 30 with a step of 5 and in that 25% bio diesel blend resulted in the optimum performance and emission values. Alumina nano additives were included in to the optimum biodiesel blend to conduct engine tests. From the results blend MB25AONP shown good results and the further tests were conducted using exhaust gas recirculation. In this work, the results obtained from the optimum blends MB25, MB25AONP, MB25AONP+ 20% EGR are compared and presented. Using an AVL Digas 444N Model gas analyzer & AVL 437C smoke meter, all the emissions were measured. Several influencing factors like environment, type of device, calibration, observation influences the errors occurrence and their uncertainties. To specify the accuracy of the readings, Uncertainty analysis is required [17]. By the account of the affecting parameters shown in Table 4 like measurement of pressure, EGT, emissions, load, smoke, speed and fuel measurement, the overall uncertainty is assessed as ± 2.16% using SRSM method.

$$= \text{Square root of } \{(Pr)^2+(EGTI)^2+(N)^2+(CO)^2+(HC)^2+(NOx)^2+(S)^2+(L)^2+(F)^2\}$$

$$= \text{Square root of } \{(1.4)^2+(0.2)^2+(0.1)^2+(0.2)^2+(0.3)^2+(0.1)^2+(1.1)^2+(0.2)^2+(1)^2\}$$

$$= \pm 2.16\ \%$$

Figure 3. Tested engine, smoke meter and exhaust gas analyzer

Table 3. Technical specifications of engine set up

Product	Engine test setup- 4 stroke, 1 cylinder, Diesel (Computerized)
Engine	Make Kirloskar, Model TV1, Type 1- cylinder, 4- stroke Diesel, water -cooled, 110 and 87.5 mm of stroke and bore. Maximum Power 5.2 kW at 1500 rpm, CR 17.5, 661 cc,
Dynamometer	with loading unit Type eddy current, water cooled,
Data acquisition system	NI USB-6210, 250kS/s, 16-bit

Table 4. Uncertainty of instruments in percentage

Instrument	Accuracy	Percentage of uncertainties
Pressure transducer(Pr)	±0.1MPa	± 1.4
Exhaust gas temperature indicator (EGTI)	± 4^0C	±0.2
Speed indicator(N)	± 10rpm	±0.1

Exhaust Gas Analyzer		
• CO	± 0.2%	±0.2
• HC	± 8ppm	±0.3
• NOx	± 5ppm	± 0.1
Smoke meter(S)	± 1%	± 1.1
Load indicator(L)	± 0.1 Kg	±0.2
Fuel Measurement(F)	± 0.2 cc	±1

4. Results and discussions

The combustion, performance & characteristics of emission of 1-cylinder engine was tested by using diesel, MB25, MB25AONP, MB25+20%EGR, MB25AONP+20% EGR fuels at different loads from (0-100 %) with a step of 25% (0 , 25%, 50%, 75%, 100%) and the results were discussed.

4.1. Engine performance characteristics

4.1.1. Brake thermal efficiency (BTE)

Figure. 4 describes the variation in BTE for mixed fuel samples under varying load. The BTE increases as the load increases. Diesel fuel has a higher heating value than MB25, resulting enhancement in BTE for diesel. The BTE of MB25 fuel is lower compared to diesel because of its lower heating value. However, BTE is found to be more for MB25 + Alumina nanoparticles in comparison to diesel fuel and MB25 fuel [7]. This increase can be explained by the higher availability of oxygen due to the inclusion of NP's into the MB25 blend. Specifically, related to the BTE of MB25 fuel, the BTE of MB25 fuel with 20% EGR was decreased by 7.9%. This decrease leads to less brake thermal efficiency due to less oxygen content in the air resulting from the EGR. The BTE of MB25AONP + 20% EGR fuel decreased by 7.23% and 2.7% than MB25AONP blend and Diesel fuels, respectively.

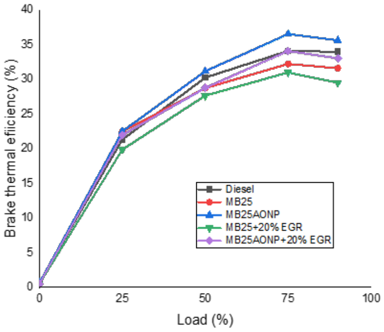

Figure 4. Change in BTE with load %

4.1.2. Brake specific fuel consumption (BSFC)

Figure 5 shows BSFC values for all fuel blend samples at various loads. When compared with diesel, the BSFC of MB25 fuel (a biodiesel blend) is approximately 4.3% higher owing to the lower heating value and more viscosity of MB25 fuel as opposed to normal diesel. The apendage of nano particles into the biodiesel blend improves combustion quality by its catalytic effect [16] thus it reduces 6.25% BSFC in comparison to MB25 fuel. The existance of less oxygen in the air with EGR leads to poor combustion, resulting in increased BSFC for MB25 with 25% EGR. The BSFC of MB25AONP fuel blend with 20% EGR is increased by 8.6% and 4.1% compared to diesel and MB25AONP.

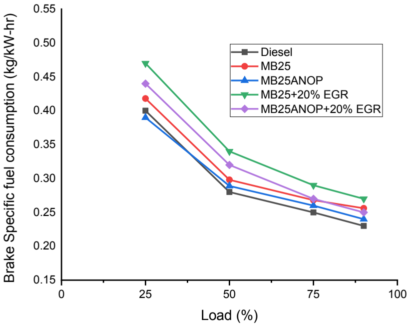

Figure 5. Change in Brake Specific fuel consumption (BSFC) with changing load %

4.2. Combustion characteristics analysis

4.2.1. Engine cylinder pressure

Figure 6 exhibits the change in cylinder pressure across various crank angles from 320 degrees to 390 degrees for each of fuel samples that were tested. The highest cylinder pressures observed for each fuel type as diesel - 65.73 bar, MB25 - 68.97 bar, MB25AONP - 69.53 bar, MB25+20%EGR - 60.19 bar, and MB25AONP+20%EGR - 63.76 bar. These peak pressures were observed at 9 degrees CA BTDC for all fuel samples. In the case of MB25, the internal cylinder pressure is superior than that of diesel because of the higher HRR caused by the insertion of nano aluminum particles to the MB25 biodiesel mixture [17]. This increase in cylinder pressure is a result of the reduced delay in ignition [18]. However, for MB25+20% EGR and MB25AONP+20% EGR, the maximum cylinder pressures are lower than the other fuel samples due to low available oxygen for combustion [17].

4.2.2. Heat release rate (HRR)

Figure 7, which demonstrates the difference in the rate of heat release (HRR) at different crank angles from 320 degrees to 390 degrees for various fuel samples. When alumina nano additives are added to the MB25 biodiesel mixture, the combustion process is enhanced owing to their higher surface-to-volume ratio [20] and results in increased rate of heat release than MB25. However, when the EGR technique is applied, incomplete combustion occurs [18]. Consequently, the rate of heat release for the fuel samples MB25+20% EGR and MB25AONP+20% EGR decreases in contrast to MB25 and MB25AONP samples. The maximum rates of heat release for the respective fuel samples are Diesel: 65.06 kJ/m^{3}deg, MB25: 70.95 kJ/m3deg, MB25AONP: 75.46 kJ/m3deg, MB25+20%EGR: 67.42 kJ/m3deg, MB25AONP+20% EGR: 65.69 kJ/m3deg.

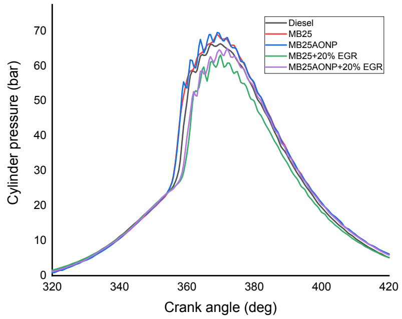

Figure 6. Change in cylinder pressure with changing crank angle (deg)

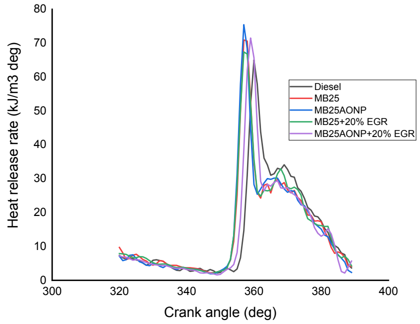

Figure 7. Change in heat release rate with changing crank angle (deg)

4.3. Engine emission characteristics analysis

4.3.1. Co emissions

Figure 8 illustrates and compares the exhaust emissions of carbon monoxide (CO) using various fuel blends and engine conditons. The results show that MB25 biodiesel with enriched oxygen content releases lower CO compared to diesel fuel. The ID was decreased, and the combustion efficiency was increased with fuel course as MB25–AONP (biodiesel blend containing aluminum oxide nanoparticles) [21]. Consequently, CO emissions are reduced by 11% with respect to MB25 biodiesel without AONP. However, with MB25 fuel and exhaust gas recirculation (EGR) applied, CO emissions jump by 15%. The EGR lowers the rates of reactions in the combustion chamber, which thereby causes an increase in CO emissions. Such effect can be seen for both MB25 and MB25AONP fuel. Similarly, when using EGR with different fuel blends, the CO emissions are also observed to differ from one fuel blend to another. The CO emissions were increased by 4% and 11.2% for MB25 and MB25AONP fuel respectively, and a percentage reduction of 5.3% for MB25 + 20% EGR fuel, with respect to MB25AONP + 20% EGR fuel.

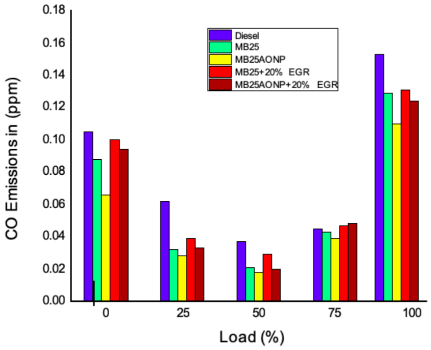

Figure 8. Change in CO emissions with changing load %

4.3.2. Hydrocarbon emissions

Figure 9 illustrates the changes in hydrocarbon (HC) pollutants under varying load conditions. HC emissions from diesel fuel are higher compared to the other fuels considered. The HC emissions from MB25 blend are lesser than diesel fuel, attributed to its higher CN of the biodiesel blend and its better combustion properties. The appending of alumina NP's to the MB25 biodiesel blend causes in a further decrease in HC emissions. The presence of nanoparticles lowers the carbon activation temperatures and improves the combustion process, leading to reduced HC emissions. Compared to MB25 biodiesel blend, HC emissions are reduced by 9.5%. For the MB25 bio-diesel blend, the adoption of 20% EGR raised the HC emissions. The EGR mode lowers the oxygen availability, resulting in incomplete combustion and high HC emissions. HC emissions are raised by 2.3% as compared to MB25 biodiesel blend. MB25AONP + 20% EGR fuel sample has the combined effects of both alumina nanoparticles and EGR. Presence of alumina nanoparticles in bio-diesel blend (MB25AONP) causes 2.3% increase in HC emissions relative to MB25 biodiesel blend which includes 20% EGR and causes 10.2% increase in HC emissions.

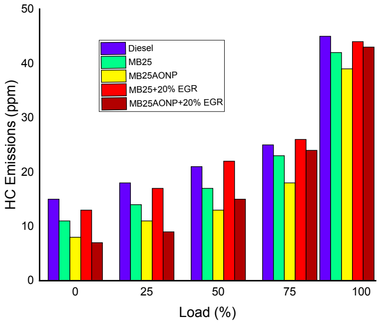

Figure 9. Change in HC emissions with changing load %

4.3.3. Nox emissions

Figure 10 shows the changes of NOx emissions under change of loads for test fuel samples. The results confirm that the NOx pollutants for the MB25 sample were greater than that of diesel owing to the higher oxygen content and this increase in the amount of oxygen [22] increased the flame temperature. NOx emission was increased by 4.6% when alumina nanoparticles (Al_2O_3) were added to the MB25 biodiesel blend because of higher catalytic chemical reaction of the nanoparticles [20]. The NOx emissions reduction was achieved with the EGR addition by 13.6% in comparison to MB25 fuel, which is due to the lesser improvement in the combustion chamber temperature, which results from the raised temperature of EGR compared to fresh air. Notably, NOx emissions further decreased considerably for the MB25AONP + 20% EGR combination. The NOx emissions were decreased by 10.9% and 14.8% compared to MB25 and MB25AONP, respectively. However they are increased by 3.1% compared to MB25 + 20% EGR

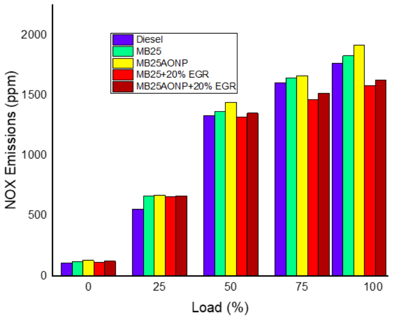

Figure 10. Change in NOx emissions with changing load %

4.3.4. Smoke opacity

Figure 11 describes the changes in smoke opacity for different fuels. Increasing the load causes more quantity of fuel burned leads to increase in smoke for all blends than low load conditions. The occurrence of oxygen (O_2) biodiesel and its more cetane index, promotes better combustion and reduces the smoke opacity [23]. The appendage of AONP results a 6.5% decrease in smoke opacity than MB25 fuel. The existence of NP's in the fuel improved combustion by reducing the delay in the first phase of combustion and enhancing the formation of a better air-fuel mixture. Smoke emissions increased by 4.2% when exhaust gas recirculation (EGR) modification was applied to MB25 fuel. Smoke emissions with MB25AONP +20% EGR are increased by 2.7% compared to MB25 fuel, by 7.5% compared to MB25 with 20% EGR, and by 9.1% compared to MB25AONP fuel without EGR.

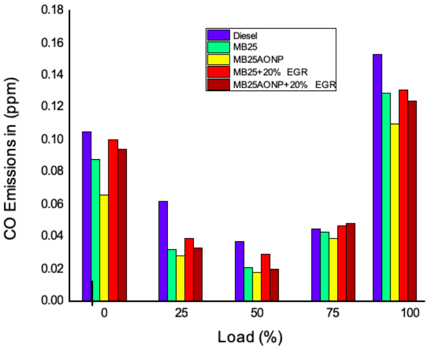

Figure 11. Change in smoke emissions with change in load %

5. Conclusion

To upgrade the performance of the compressed ignition diesel engine with nonedible, abundantly available mahua biodiesel with alumina nano additive by recirculating 20% exhaust gas various tests were conducted. The end results achieved from the experiments conducted on the Kirloskar TV1 engine and were concluded that

- MB25AONP fuel exhibited a 5.4% and 7.6% increase in BTE compared to MB25 fuel and MB25AONP with 20% EGR, respectively.
- BSFC for MB25AONP fuel showed a 6.25% decrease compared to MB25 fuel, but a 4.1% increase compared to MB25AONP with 20% EGR.
- The pressure in the cylinder increased by 1.23% and 5.1% for MB25AONP fuel compared to MB25 fuel blend and MB25AONP with 20% EGR fuel, respectively
- With EGR modification, the HRR for the fuels decreased compared to fuels without EGR modification. MB25AONP fuel blend showed lower CO, HC, and NOx pollutants in comparison to the MB25 fuel.
- The modification of EGR to MB25AONP fuel further reduced NOx emissions but increased smoke opacity compared to MB25 fuel.

In future work, multi-cylinder engine studies will be conducted under transient operating modes to assess real-time performance and emissions behavior. A broader range of alumina concentrations and EGR percentages will be explored to identify optimal combinations through RSM or ML based optimization. Integrating after-treatment systems like SCR and particulate filters with biodiesel-EGR-nano additive strategies could also be investigated to mitigate the secondary increase in HC, CO, and smoke emissions.

Authorship contributions

G. Jamuna Rani: conceptualization, validation, writing original draft, visualization; M. Sumalatha: supervision, review & editing; Sajja Nikhil Teja: Co-supervision, investigation, Data analysis; Anchupogu. Praveen: manuscript preparation, investigation, project administration; R .L.Krupakaran: Review and Editing, Discussion, Validation.

Data availability statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Conflict of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

Statement on the use of artificial intelligence

Artificial intelligence was not used in the preparation of the article.

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Nomenclature

MB25	25% of Mahua Bio-diesel + 75% of Diesel
MB25AONP	MB25+ 100ppmAluminum Oxide Nano Particles
MFB	Mass Fraction of Burned fuel
EGR	Exhaust Gas Recirculation
XRD	X- ray Diffractometer
BTE	Brake Thermal Efficiency
SEM	Scanning Electron Microscopy
HRR	Heat Release Rate
CP	Cylinder Pressure
HC	Hydro Carbons
BSFC	Brake Specific Fuel Consumption
CO	Carbon Monoxide
ppm	Parts per million
NOx	Nitrogen Oxides

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