



# Synergistic Effect of Al<sub>2</sub>O<sub>3</sub> Nanoparticles on the Performance and Emission Characteristics of an Optimum B25 Biodiesel Blend in a Diesel Engine

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Received: 06.11.2025 Accepted: 25.11.2025 Published: 30.12.2025

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## ABSTRACT

This study investigates the performance and emission characteristics of a diesel engine fuelled with jatropha methyl ester (JME) blends and their enhancement using Al<sub>2</sub>O<sub>3</sub> nanoparticles. Among the tested blends, B25 (25% biodiesel) was identified as the optimum blend, exhibiting performance nearly identical to conventional diesel. At maximum load, the brake specific fuel consumption (BSFC) of B25 was 0.280 kg/kWh (8.9% higher than conventional fuel), while its Brake Thermal Efficiency (BTHE) was 32.04%. This blend outperformed higher concentration blends in performance metrics. Regarding emissions, the blend B25 revealed better emission characteristics than conventional fuel, with a 2% reduction in the emission of CO and a 1.7% reduction in HC emission. The incorporation of Al<sub>2</sub>O<sub>3</sub> nanoparticles significantly enhanced the fuel properties. For B25, nanoparticles improved BTHE by 2.2% and it is 32.74% and reduced BSFC (0.272 kg/kWh) by 2.9%. Emissions of Smoke Density, CO, and HC for B25 were dramatically reduced by 13.7%, 14.1%, and 15.5%, respectively. However, the nanoparticle addition further increased NO<sub>x</sub> emissions by 2.7% compared to neat B25. The study concludes that B25 with Al<sub>2</sub>O<sub>3</sub> nanoparticles offers a balanced solution, delivering better performance with substantially lower emissions, except for NO<sub>x</sub>.

**Keywords:** Biodiesel; Jatropha methyl ester; Nanoparticles; Engine performance; Emissions; Aluminium oxide.

## 1. INTRODUCTION

The increasing demands of environmental sustainability and energy security have led to a significant change in the global energy landscape. Due to its high durability and thermal efficiency, the diesel engine is a vital component of the current transportation and industrial sectors. However, its reliance on fossil fuels presents serious issues. The need for alternate, sustainably derived fuels has been emphasised by the limited supply of petroleum. Consequently, the environmental impact of diesel engine emissions, especially particulate matter (PM), unburnt hydrocarbon, and CO, has mandated stringent emission norms worldwide. In this context, biodiesel has emerged as a promising and viable alternative to conventional diesel. Biodiesel, derived from renewable biological sources, is biodegradable, and non-toxic (Al-Kheraif *et al.* 2021). *Jatropha curcas* is one of the non-edible feedstocks that

has received considerable amounts of attention. Its ability to thrive on arid and marginal lands, without competing with food crops, makes it a sustainable and economically feasible source for biodiesel production (Chen *et al.* 2024). Jatropha oil methyl ester (JME) exhibits fuel properties comparable to diesel, allowing it to be used in existing diesel engines with little or no modification. However, the widespread commercialization of JME is often hindered by certain inherent drawbacks, including its higher viscosity, density, and lower volatility, which can lead to inferior atomization, incomplete combustion, and consequently, elevated NO<sub>x</sub> emissions and reduced engine performance (Dhanarasu *et al.* 2022).

To bridge this performance-emission trade-off, recent research has pivoted towards the application of nanotechnology. An innovative approach for improving fuel characteristics and combustion efficiency has been made possible by the inclusion of nanoscale compounds

to biodiesel (Gaur *et al.* 2022). Nanoparticles, characterized by their exceptionally high surface area to volume ratio and catalytic activity, act as energy carriers (Hosseini *et al.* 2017). When dispersed in fuel, they improve atomization, reduce the ignition delay, and facilitate more complete combustion due to their catalytic oxidation effects (Kalaimurugan *et al.* 2023). Metal oxide nanoparticles, such as  $\text{Al}_2\text{O}_3$ , are particularly effective. During combustion,  $\text{Al}_2\text{O}_3$  nanoparticles serves as an oxygen buffer, facilitating the oxidation of soot constituents and unburnt hydrocarbons (Kumar *et al.* 2021). Although it has minimal impact on  $\text{NO}_x$  generation, this catalytic activity has the potential to increase brake thermal efficiency and lowering harmful emissions including CO, HC, and smoke opacity (Kumar *et al.* 2017).

Therefore, this study is dedicated to a comprehensive investigation of the performance and emission characteristics of a single cylinder diesel engine fuelled with jatropha oil methyl ester. Furthermore, the research critically examines the influence of  $\text{Al}_2\text{O}_3$  nanoparticles as an additive on mitigating the limitations of neat JME.

## 2. JATROPHA FEEDSTOCK

The global transition towards renewable energy has highlighted the importance of non-edible oilseed crops, with *Jatropha curcas* emerging as a leading candidate. Because of its remarkable resilience, it may thrive in difficult conditions with low-quality soil and rainfall, avoiding competing on food crops for fertile agricultural land. The economic value of the plant lies in its seeds, which contain a substantial proportion of oil, typically between 30% and 40%, encapsulated within a tough, protective shell. Fig. 1 shows the seeds of jatropha.

To access this oil, the seeds after collection, are cleaned and dried to achieve a low moisture content, a key factor for maximizing oil yield. The subsequent step often involves de-shelling the seeds to isolate the kernels, which are then fed into a mechanical screw press. This locally available screw press works by exerting pressure to squeeze the oil from the solid kernel material, resulting in crude jatropha oil and a residual seed cake.

The crude oil produced, however, possesses several undesirable characteristics that preclude its direct use in standard diesel engines. It is notably more viscous and denser than conventional diesel, leading to inadequate fuel atomization, and incomplete combustion

(Kumar and Simhadri, 2022). As a result, a chemical enhancement approach is necessitated. The appropriate and conventional method for this modification is the transesterification reaction. This process effectively breaks down the large molecules into smaller, reducing its viscosity and improving its combustion properties. Compared to other chemical treatments, transesterification is recognized as the most efficient, uncomplicated, and economically viable approach to produce engine compatible fuel from crude jatropha oil.



Fig. 1: Photograph of jatropha seeds

## 3. TRANSESTERIFICATION

Transesterification provides a chemical pathway to address the challenge of direct vegetable oil utilization in diesel engines by synthesizing a compatible fuel, biodiesel. This mechanism sequentially converts triglycerides into diglycerides, monoglycerides, and finally, the desired fatty acid alkyl esters. The choice of catalyst is a critical determinant of the reaction pathway, with alkaline catalysts being preferred for feedstocks with low free fatty acid content to prevent saponification. Furthermore, the reaction temperature must be precisely regulated to accelerate the reaction and to avoid alcohol loss. Fig. 2 shows the photograph of the batch reactor employed in the present work.

The present work employed methanol and NaOH to form sodium methoxide, the active catalytic solution for the esterification of jatropha oil. The reaction proceeded with a molar ratio of 1:6 (oil to methanol) to ensure a high rate of conversion. In order to produce a homogenous reaction substrate, a temperature of  $60^\circ\text{C}$  and an agitation rate of 200 rpm were maintained for 120 minutes. Following the process, the homogenous mixture

was left undisturbed for a whole day, producing an uppermost layer of raw methyl esters and a bottom layer of glycerol. The procedure provided an overall conversion yield of about 80%. The resulted methyl ester might contain traces of unreacted alcohol and catalysts and therefore it is washed well with water, until the colour of water remains neutral. Finally, the pure form methyl ester was heated above the boiling temperature of water, to mitigate the presence of water particles. Table 1 compares the physicochemical properties of the resultant biodiesel with those of conventional fuel.



Fig. 2: Photograph of reactor

Table 1. Physicochemical properties of diesel and jatropha biodiesel

| Property            | Diesel                 | Jatropha Biodiesel     |
|---------------------|------------------------|------------------------|
| Density (at 15°C)   | 840 kg/m <sup>3</sup>  | 876 kg/m <sup>3</sup>  |
| Viscosity (at 40°C) | 3.0 mm <sup>2</sup> /s | 4.5 mm <sup>2</sup> /s |
| Calorific Value     | 43,600 kJ/kg           | 38,000 kJ/kg           |
| Flash Point         | 65°C                   | 152°C                  |
| Cetane Number       | 48                     | 50                     |

#### 4. PREPARATION OF TEST FUELS

The methodology for fuel preparation was designed to ensure uniformity and accuracy across all test samples. The fuels evaluated ranged from 100% baseline diesel to 100% jatropha biodiesel, with blends prepared at 25%, 50%, and 75% biodiesel by volume, designated as B25, B50, and B75, respectively. Jatropha methyl ester was volumetrically proportioned to the baseline diesel fuel during the blending process. Each blended constituent was combined using a high-speed mechanical blender to achieve optimal dispersion, ensuring a uniform, single-phase liquid. After preparation, the fuels were immediately dispensed into labeled plastic containers to maintain their integrity for the subsequent engine trials.

#### 5. DISPERSION OF NANOPARTICLES

The development of a 50 ppm Al<sub>2</sub>O<sub>3</sub> biodiesel nanofuel is a precise, multi-stage procedure designed to assure exact concentration and prolonged stability of the particles. The first step is to use a high-precision analytical scale to accurately weigh 50 mg of Al<sub>2</sub>O<sub>3</sub> nanopowder per liter of test fuel. For ease of handling and preliminary dispersion, the entire mass of nanoparticles was initially mixed into a very small, defined fraction of the total biodiesel volume. The initial mixture was magnetically stirred for 30 minutes to moisten the nanoparticles and break up big agglomerates. After 30 minutes of gentle mechanical stirring, the stable and concentrated nanofluid was blended with the residual base fuel to create a homogeneous 50 ppm Al<sub>2</sub>O<sub>3</sub>-biodiesel blend.

#### 6. TEST ENGINE SETUP

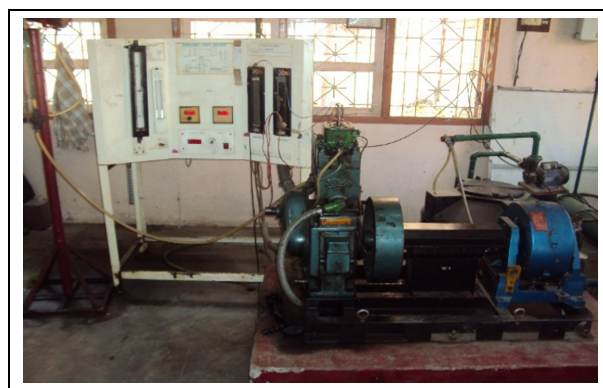


Fig. 3: Photograph of test engine

The experimental investigation was conducted on a single cylinder, four stroke, water cooled diesel test engine with a rated power output of 5.2 kW. The engine featured a bore diameter of 87.5 mm and a stroke length of 110 mm, and it was maintained at a constant rotational speed of 1500 rpm throughout all testing phases. The setup was executed with an electrical dynamometer, which facilitates the application of load to the engine. This loading was systematically increased from zero to the maximum capacity in discrete increments of 20% for each fuel test. To comprehensively monitor the environmental impact of engine, the test engine was integrated with an exhaust gas analyzer for quantifying gaseous tailpipe emissions and a smoke meter for measuring particulate opacity. The experimental procedure was performed in a sequential manner; initial baseline readings were established using conventional diesel fuel, followed by utilizing various blends of jatropha biodiesel. The performance and emission characteristics of these biodiesel blends were meticulously compared against the baseline data to

identify the optimum blend. Subsequently, in the final phase of the study, this identified optimum fuel was doped with 50 ppm of aluminium oxide nanoparticles to create a nanofuel. The operational parameters and exhaust emissions of test engine were then recorded again with this advanced fuel, allowing for a comparative analysis on the effects induced by the nanoparticle addition against the performance of the optimum blend without nanoparticles. Fig. 3 depicts the photograph of the test engine.

## 7. RESULTS AND DISCUSSION

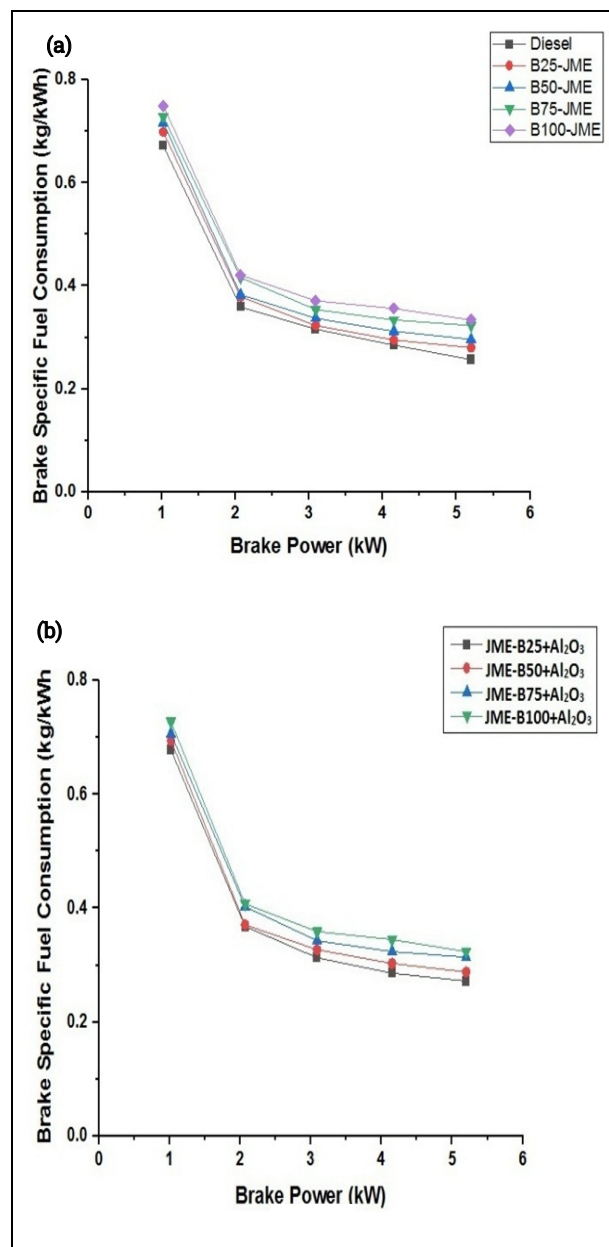


Fig. 4: Variation of BSFC with BP for (a) Standard test fuels and (b) Advanced test fuels

### 7.1 Brake Specific Fuel Consumption (BSFC)

The Brake Specific Fuel Consumption is a critical indicator of an engine's fuel efficiency, representing the mass of fuel consumed per unit of power produced. Lower BSFC values denote superior efficiency. Biodiesel blends, due to their lower calorific value compared to diesel, inherently require a higher fuel mass to produce the same power output (Moorthi *et al.* 2022). Fig. 4 (a) and 4 (b) show the correlation among brake power (BP) and BSFC for standard and advanced test fuels. A detailed analysis reveals that at maximum load, conventional fuel recorded the lowest BSFC of 0.257 kg/kWh. In comparison, the B25 blend showed an 8.9% increase (0.280 kg/kWh), while B100 showed a significant 30.0% increase (0.334 kg/kWh), this is due to the reduced energy content of JME. The addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles notably improved the combustion characteristics, leading to a reduction in BSFC across all biodiesel blends. For instance, at maximum load, In comparison to clean B25, the BSFC for B25 with nanoparticles was 0.272 kg/kWh, an improvement of 2.9% (Mujtaba *et al.* 2020). This is consistent with findings from other studies where nanoparticles enhanced fuel properties and combustion, leading to lower fuel consumption (Nanthagopal *et al.* 2020).

### 7.2 Brake Thermal Efficiency (BTHE)

Brake Thermal Efficiency defines the ability of engine to convert the chemical energy of the fuel into useful mechanical work. It is a direct measure of combustion quality and engine performance. Higher BTHE is always desirable as it indicates less energy is wasted. Fig. 5 (a) and 5 (b) represent the correlation between brake power and BTHE for standard and advanced test fuels.

The results indicate that diesel consistently achieved the highest BTHE of at 32.06% at maximum load. The BTHE for biodiesel blends decreased with increasing JME concentration. The blend B25 showed a minimal reduction of 0.06% (32.04%), while B100 showed 11.1% reduction (28.51%) at the same load. This is due to its higher viscosity and lower heating value. The incorporation of Al<sub>2</sub>O<sub>3</sub> nanoparticles served as a combustion catalyst, enhancing BTHE. At maximum load, the BTHE for B25 with nanoparticles increased to 32.74%, a 2.2% improvement over neat B25 and even marginally surpassing diesel. The inclusion of nanoparticle helps in promoting complete fuel combustion and better heat release (Praveen *et al.* 2018). The high surface area to volume ratio of nanoparticles like Al<sub>2</sub>O<sub>3</sub> improves atomization and accelerates the combustion rate, which directly contributes to enhanced thermal efficiency.

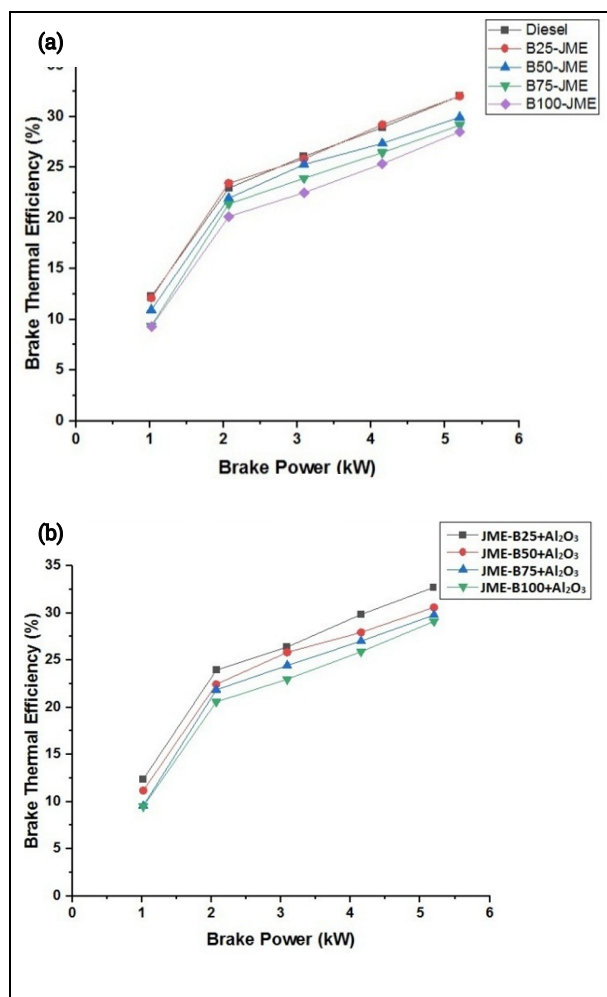


Fig. 5: Variation of BTHE with BP for (a) Standard test fuels and (b) Advanced test fuels

### 7.3 Exhaust Gas Temperature (EGT)

Exhaust gas temperature reflects the heat energy carried away by the exhaust gases and is indicative of the combustion temperature inside the cylinder. Lower EGT can suggest better heat utilization within the cylinder. Fig. 6 (a) and (b) illustrate the variation among brake power and EGT for standard and advanced test fuels.

The graph shows a consistent trend of decreasing EGT with an increase in biodiesel proportion. At maximum load, the EGT for diesel was 320°C. The blend B25 exhibited a slightly lower EGT of 314°C (1.9% decrease), while B100 showed a more pronounced reduction to 298°C (6.9% decrease). This can be attributed to the lower calorific value and earlier combustion phasing of biodiesel (Puchakayala *et al.* 2023). The addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles further reduced the EGT. Nanoparticle incorporated B25

recorded an EGT of 308°C, a 1.9% decrease from neat B25, while B100 with nanoparticles showed an EGT of 292°C, a 2% reduction. This confirms that the nanoparticles enhance the pre-flame reactions and combustion kinetics, leading to more energy being converted to work rather than being lost as exhaust heat (Rao *et al.* 2022).

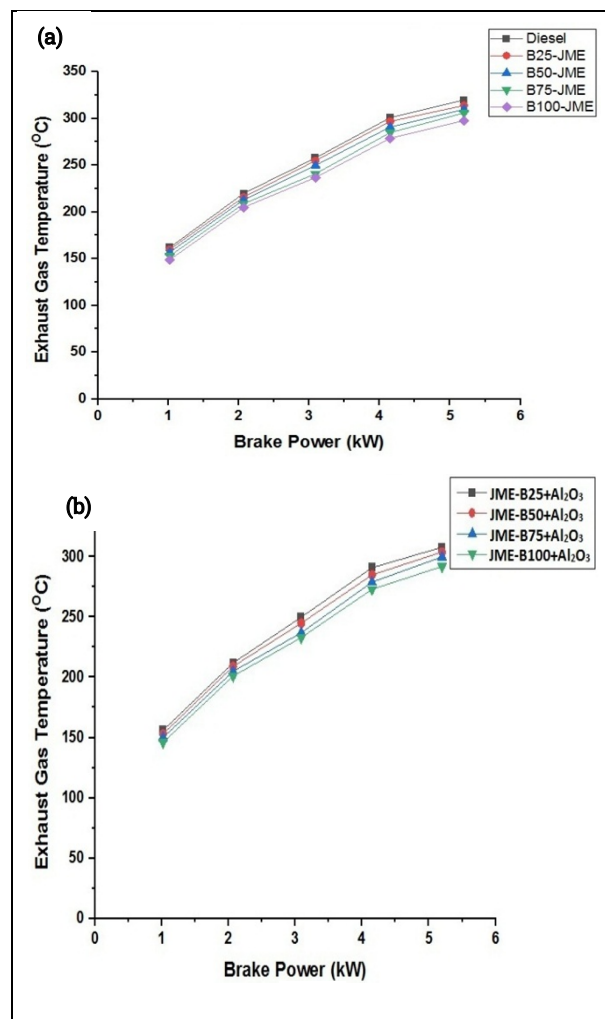


Fig. 6: Variation of EGT with BP for (a) Standard test fuels and (b) Advanced test fuels

### 7.4 Smoke Density (SD)

Smoke density is a measure of particulate matter or soot emissions, resulting from the incomplete combustion of fuel. The significant oxygen content of biodiesel promotes complete combustion, which typically reduces smoke opacity (Reddy and Wani, 2021). Fig. 7 (a) and 7 (b) depict the correlation among brake power and smoke density for standard test fuels and advanced test fuels. From the graph, it is evident that

the conventional fuel produced the highest smoke density, reaching 51 HSU at maximum load.

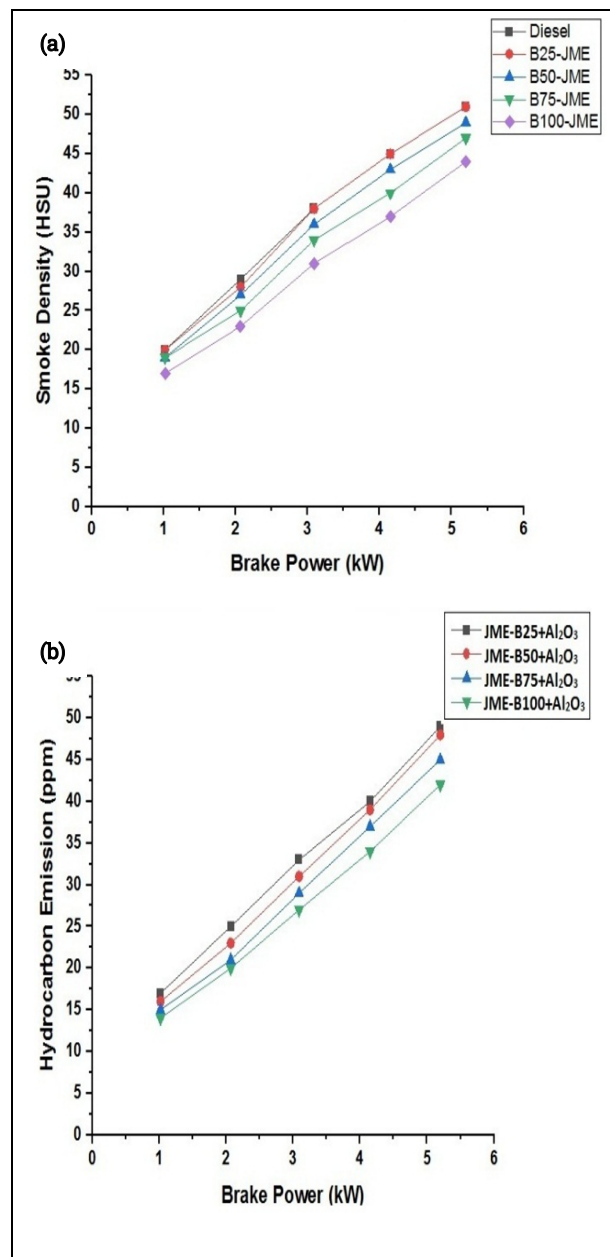


**Fig. 7: Variation of SD with BP for (a) Standard test fuels and (b) Advanced test fuels**

Biodiesel blends demonstrated a significant reduction in smoke emissions. B25 showed a 1% change at this load point (50.4 HSU), while B100 exhibited a substantial 13.7% reduction (44 HSU), highlighting the soot suppressing effect of fuel bound oxygen. The addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles dramatically enhanced this benefit. B25 with nanoparticles produced 44 HSU, a

13.7% reduction from neat B25. The smoke density of B100 with nanoparticles was 38 HSU, a 13.6% further reduction. The nanoparticles act as an oxidation catalyst, ensuring more complete combustion of soot precursors, thereby drastically curbing smoke formation (Sajin *et al.* 2021). This catalytic oxidation is a key mechanism by which metal oxide nanoparticles reduce particulate emissions (Senger *et al.* 2023).

## 7.5 Carbon Monoxide (CO) Emission

Carbon monoxide is a toxic product of incomplete combustion, formed when there is insufficient oxygen to convert all carbon in the fuel to carbon dioxide. The significant oxygen content in biodiesel aids in oxidizing CO to CO<sub>2</sub> (Shaafi *et al.* 2015). Fig. 8 (a) and 8 (b) show the correlation among brake power and CO emission for standard and advanced test fuels.

The graph confirms that CO emissions decrease with higher biodiesel blends. At maximum load, conventional fuel emitted 0.101 (% by volume). At similar load, the blend B25 resulted in the CO emission of 0.099 (% by volume), which is 2% less when compared with the value of conventional fuel, while B100 showed a 17.8% reduction by revealing a CO emission of 0.083 (% by volume). The incorporation of Al<sub>2</sub>O<sub>3</sub> nanoparticles led to a further decrease in CO emissions. For B25 with nanoparticles, the emission of CO was 0.085% (% by volume), which is 14.1% less than that of neat B25. For B100 with nanoparticles, CO dropped to 0.071 (% by volume). The catalytic effect of the nanoparticles provides additional oxidation sites, ensuring complete oxidation of CO, thereby minimizing its emission. The oxygen buffering capacity of nanoparticles like Al<sub>2</sub>O<sub>3</sub> plays a pivotal role in this enhancement.

## 7.6 Hydrocarbon (HC) Emission

Unburnt fuel during combustion is indicated by hydrocarbon emissions. Similar to CO, HC emissions are a direct consequence of incomplete combustion. The relatively high oxygen content of biodiesel and cetane number promote more complete combustion, reducing HC. Fig. 9 (a) and 9 (b) represent the correlation among

brake power and HC emission for standard and advanced test fuels.

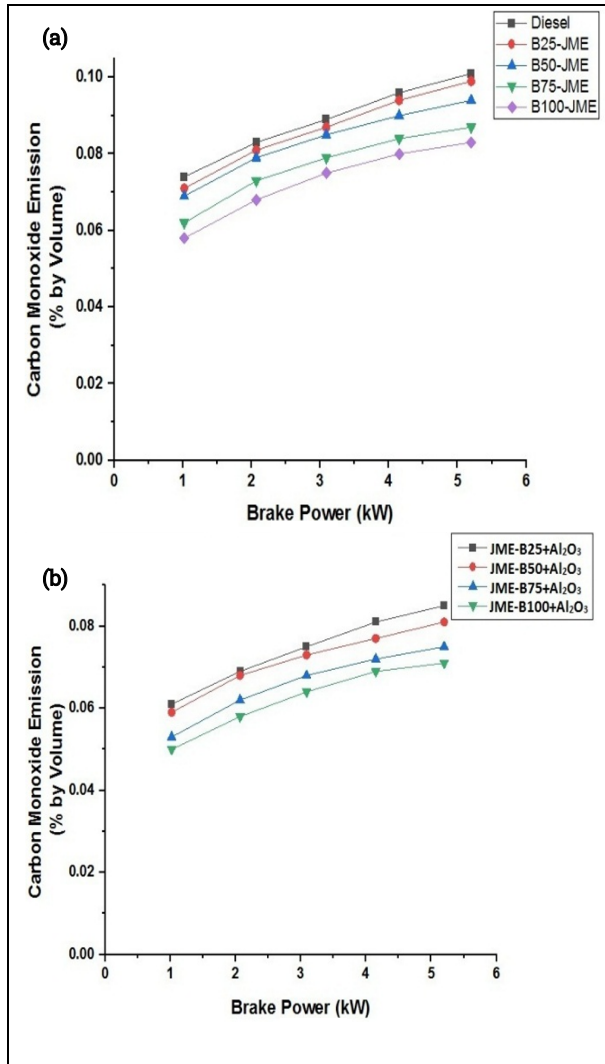


**Fig. 8: Variation of CO emission with BP for (a) Standard test fuels and (b) Advanced test fuels**

The data illustrates a clear reduction in HC emissions with the use of biodiesel. At maximum load, conventional fuel produced 59 ppm of HC. B25 showed a 1.7% reduction (58 ppm), while B100 showed a more significant 15.3% reduction (50 ppm). The addition of nanoparticles further enhanced this positive trend. B25 with nanoparticles emitted 49 ppm of HC, a 15.5% reduction when compared with neat B25. B100 with nanoparticles recorded 42 ppm, a 16.0% reduction. The Al<sub>2</sub>O<sub>3</sub> nanoparticles enhance the combustion process by providing a surface for more rapid and complete fuel oxidation, effectively minimizing the escape of unburned hydrocarbons. The improved combustion efficiency

attributed to nanoparticles is a consistent finding across multiple studies.

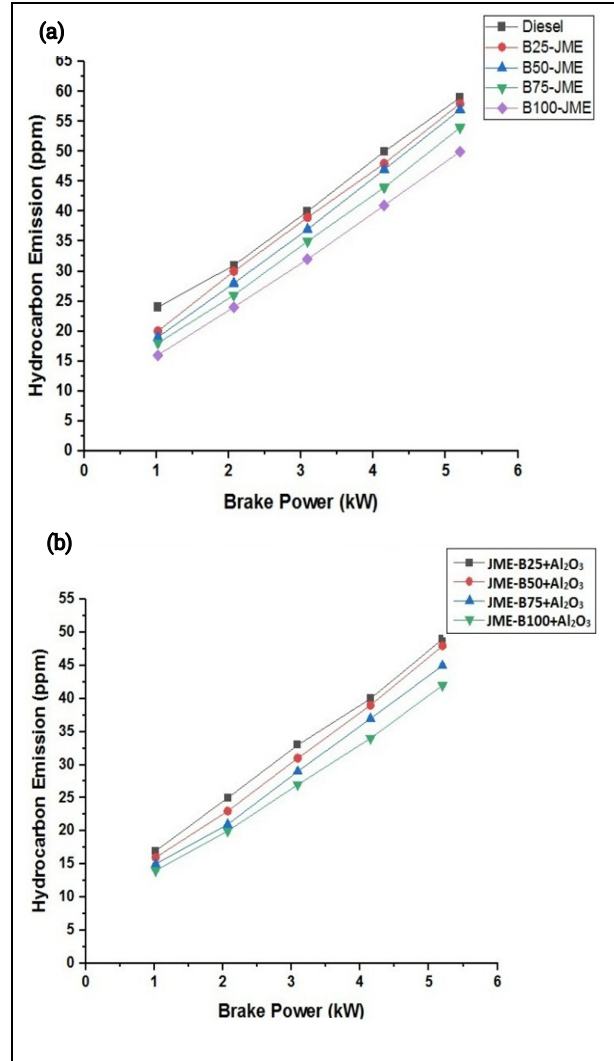


**Fig. 9: Variation of HC emission with BP for (a) Standard test fuels and (b) Advanced test fuels**

## 7.7 Oxides of Nitrogen (NO<sub>x</sub>) Emission

Oxides of nitrogen are formed primarily at high temperatures through the oxidation of atmospheric nitrogen. The NO<sub>x</sub> emission trend is complex and often higher for biodiesel due to factors like increased oxygen concentration and advanced injection timing. Fig. 10 (a) and 10 (b) show the correlation among brake power and NO<sub>x</sub> emission for standard and advanced test fuels. Contrary to the trends of other emissions, NO<sub>x</sub> was found to increase with biodiesel concentration. At maximum load, conventional fuel emitted 802 ppm of NO<sub>x</sub>. B25 and B100 emitted 820 ppm and 887 ppm of NO<sub>x</sub>, which is

2.2% and 10.6% high when compared with conventional fuel.

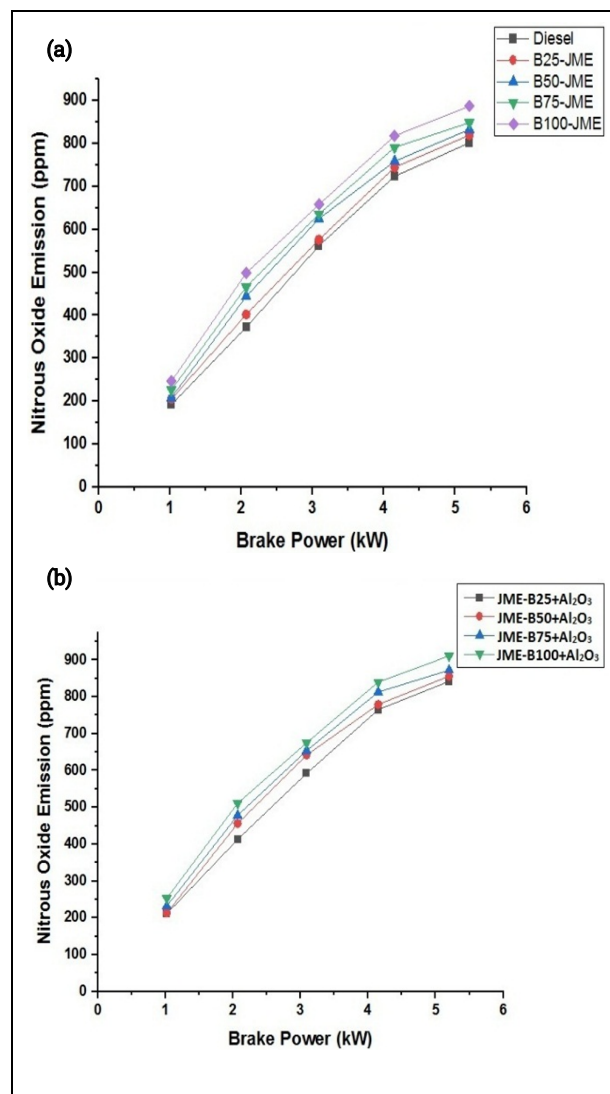


**Fig. 10: Variation of NO<sub>x</sub> emission with BP for (a) Standard test fuels and (b) Advanced test fuels**

This is due to the fuel bound oxygen promoting higher in-cylinder temperatures. The addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles resulted in a further increase in NO<sub>x</sub>. B25 with nanoparticles produced 842 ppm, a 2.7% increase over the neat form. B100 with nanoparticles reached 911 ppm, a 2.7% increase over the neat form. This is attributed to the nanoparticles role in enhancing combustion efficiency and peak cylinder temperatures, which, while beneficial for other emissions, exacerbates the NO<sub>x</sub> formation (Sharifianjazi *et al.* 2023). This correlation between reduced HC, CO and increased NO<sub>x</sub> with nanoparticle addition is a challenge documented in the literature (Vellaiyan *et al.* 2019). In common practice, Al<sub>2</sub>O<sub>3</sub> is a substance that possesses a high heat capacity,

the addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles results in an increase in the amount of NO<sub>x</sub>. The considerable improvement in fuel atomization and vaporization results in a combustion that is both more rapid and intense. Because of this, the high temperature environment is created, which provides the ideal circumstances for the exponential emission of NO<sub>x</sub>.

## 8. CONCLUSION

This study quantifies performance and emission behavior of jatropha methyl ester and its blends with and without Al<sub>2</sub>O<sub>3</sub> nanoparticles. Biodiesel use reduced engine performance and increased NO<sub>x</sub>, with B100 showing a 30% rise in BSFC and an 11.1% drop in BTHE, while lowering HC by 15.3%, CO by 17.8%, and smoke by 13.7%. Addition of Al<sub>2</sub>O<sub>3</sub> nanoparticles improved combustion, increasing BTHE of B25 by 2.2%, reducing BSFC by 2.9%, and further reducing smoke (13.7%), CO (14.1%), and HC (15.5%). NO<sub>x</sub> increased by 2.7% for both B25 and B100 with nanoparticles. B25 with Al<sub>2</sub>O<sub>3</sub> provides near-diesel performance with substantial reductions in HC, CO, and smoke, confirming the catalytic activity of Al<sub>2</sub>O<sub>3</sub> in jatropha biodiesel blends.

## ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Department of Mechanical Engineering, Jayalakshmi Institute of Technology, for providing the necessary resources and infrastructure to conduct this research.

## FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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