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Enhancing the Performance and Emission Profile of B25 Jatropha Biodiesel in a Diesel Engine Using a Cerium Oxide Nanoadditive

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Abstract

This study outlines the performance and emission features of a diesel engine fuelled with jatropha methyl ester (JME) blends and their enhancement with cerium oxide (CeO_2) nanoparticles. Performance analysis revealed that higher biodiesel blends showed a reduction in brake thermal efficiency (BTHE), while the B25 blend exhibited identical performance as that of conventional fuel. At maximum load, the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTHE) of conventional fuel were 0.257 kg/kWh and 32.06%, while for B25 they were 0.280 kg/kWh and 32.04%, respectively. B25 outperformed other biodiesel blends in performance metrics. The addition of CeO_2 nanoparticles improved the BTHE of B25, and at maximum load, it was 32.42%. In emissions, B25 demonstrated a superior profile compared to conventional fuel, significantly reducing the emission of carbon monoxide (CO) by 34%, unburned hydrocarbons (HC) by 35%, and smoke density by over 30% when doped with nanoparticles. At maximum load, the NO_X emission of conventional fuel and B25 was found to be 802 ppm and 820 ppm. The inclusion of CeO_2 significantly enhanced the performance with a reduction in exhaust emissions, except for the emission of NOx, affirming B25 with CeO_2 as an optimum fuel blend.

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1. INTRODUCTION

Global energy security and environmental sustainability have become a serious threat in recent years. Due to significant efficiency, the diesel engine has become a primary source in the sectors of energy and transportation. In contrast, the exhaust emissions of similar engine including nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC), pose a serious threat to the environment. Concurrently, the limited nature of petroleum reserves and their negative impacts on the environment have intensified the search for viable, renewable, and cleaner alternative fuels [1]. In recent days, biodiesel has emerged as one of the most promising alternatives. Biodiesels can be derived from renewable biological sources through the process of transesterification; biodiesel is renewable, biodegradable, and non-toxic [2]. Among the various available non-edible feedstocks, jatropha curcas has gained considerable attention [3]. Its ability to thrive on marginal and arid lands, without competing with food crops, makes it a sustainable and economically viable source for biodiesel production [4]. Jatropha Oil Methyl Ester (JME) exhibits fuel properties comparable to conventional diesel, allowing it to be used in

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existing diesel engines with little or no modification. Several research investigations have documented that the jatropha biodiesel, when utilized as fuel, lowers the exhaust emissions, including PM, CO, and HC, due to its significant oxygen concentration, which facilitates better combustion [5]. Furthermore, the relatively high density, viscosity, and lower calorific value of JME result in poor performance features when compared to conventional fuel [6]. To address these challenges, the incorporation of appropriate nanoadditives was found to be an effective approach [7]. Cerium oxide (CeO_2) nanoparticles typically act as oxygen buffers, promoting oxidation and combustion and thereby reducing CO and HC emissions, while suppressing the formation of NOx [8]. Furthermore, its catalytic effect enhances the cetane number, resulting in better combustion, which can improve BTE and reduce BSFC [9]. Only a few studies have examined the performance and emission characteristics of JME with nanoadditives [10]. The present research intends to conduct a detailed experimental analysis to evaluate the performance and emission features of a single-cylinder diesel engine fuelled with JME with and without nanoparticles. The present work also intends to outline the impact of cerium oxide nanoparticles on key parameters such as BTE, BSFC, and the emissions of NOx, HC, CO, and smoke.

2. JATROPHA AS FEEDSTOCK

Non-edible feedstocks, such as jatropha seeds, have become a focal point of biofuel research. This plant tends to thrive on marginal land and therefore cannot compete with agricultural crops. The seeds of this plant are used as a feedstock for biodiesel production due to their high oil content and cost-effectiveness. The seeds of Jatropha are found to contain 30% oil by weight. Fig. 1 shows the seeds of Jatropha.

Fig.1. Seeds of jatropha

3. MATERIAL AND METHODS

Jatropha seeds were collected from the local market; those found to contain impurities were cleaned, washed with clean water, and dried in the shade for 3 days. Then, with the help of a screw press expeller, the oil was expelled from pure form seeds. This machine applies relatively high pressure to crush the kernels, forcing out the crude oil and leaving behind a seed cake. The neat derived oil is found to be highly dense and viscous with an unpleasant odour. However, this crude Jatropha oil in its raw form is not suitable for diesel engines. Its most significant drawbacks are its high viscosity and density, which can damage the fuel system [11]. To address these limitations, the neat oil is subjected to an appropriate chemical process; among the available approaches, transesterification is the simplest, most conventional, and most cost-effective [12].

3.1. Transesterification

The optimal combination of the catalyst, alcohol, and reaction circumstances is crucial to the effectiveness of transesterification-based biodiesel generation. This chemical approach is designed to reduce the viscosity of vegetable oils by breaking down their triglyceride structure into smaller, more volatile monoalkyl ester molecules. To start the reaction at feasible temperatures, a homogenous alkaline catalyst is essential. Parameters such as the alcohol-to-oil molar ratio are particularly crucial, as an excess of alcohol shifts the reaction equilibrium towards ester production, thereby enhancing the final yield. The optimal reaction rate and mass transfer between the reactant phases are ensured by appropriate temperature and blending optimisation. Fig. 2 shows a photograph of the batch reactor employed in the present work.

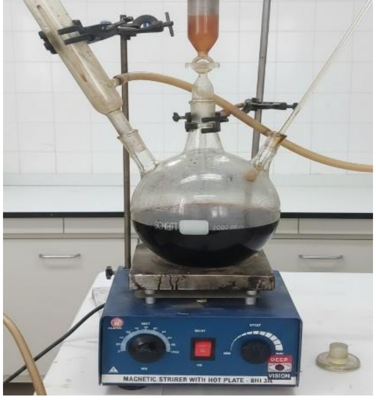


Fig. 2. Photograph of the reactor

In this experimental study, a combination of methanol and sodium hydroxide (NaOH) was utilized to catalyze the transesterification of jatropha oil. A molar ratio of 1:6 (oil to methanol) was maintained to provide high conversion efficiency. The process was consistently carried out at 60°C with a stirring speed of 200 rpm over a 2-hour period to maintain reaction homogeneity and temperature uniformity. Post-reaction, the mixture was left undisturbed, resulting in distinct layers of biodiesel and glycerol, leveraging their difference in density. This methodology successfully yielded approximately 80% jatropha methyl ester. The physicochemical properties of conventional fuel and jatropha biodiesel are presented in Table 1.

Table 1. Physicochemical properties of conventional fuel and jatropha biodiesel

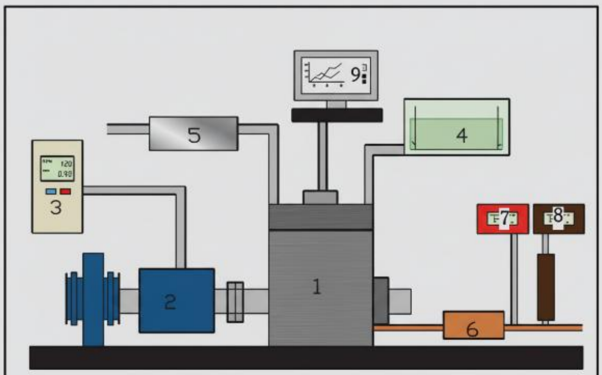
Property	Diesel	Jatropha biodiesel
Density (kg/m^3)	826	884
Kinematic viscosity (40 ^oC, mm^2/s)	2.8	4.5
Flash Point (^oC)	56	138
Fire Point (^oC)	67	158
Calorific Value (kJ/kg)	43000	37227
Specific gravity	0.83	0.88
Cetane Number	47	50

3.2. Test Fuels Employed

A graded series of fuel samples was meticulously prepared for the experimental study to analyse the effect of increasing biodiesel concentration. The fuels consisted of pure baseline diesel (B0) and four distinct jatropha biodiesel blends: B25, B50, B75, and B100, where the number indicates the biodiesel volumetric percentage. To create these blends, the requisite volumes of jatropha biodiesel and conventional diesel were measured and combined. A magnetic stirrer was then used to agitate the mixture for 20 minutes, ensuring a homogeneous and stable solution. Once blended, each fuel variant was stored in a separate, clearly identified plastic container to ensure traceability and preserve its properties until testing.

3.3. Test Setup

A reliable test engine setup, anticipated for accurate and consistent data collection, served as the base for the present study. Its primary component was a water-cooled Kirloskar diesel engine with a displacement volume determined by its 87.5 mm bore and 110 mm stroke. It was rated for 5.2 kW of power and was configured to run at a constant 1500 rpm. The setup used an AG 10/ED 1 electrical dynamometer for applying a regulated load ranging from zero to maximum in discrete 20% steps. To measure the tailpipe emissions of the test engine, the exhaust line was equipped with an AVL di gas 444 exhaust gas analyzer, capable of measuring emissions such as hydrocarbons (HC) and carbon monoxide (CO), and a smoke meter to measure smoke opacity. The experiment was performed in two distinct phases. The initial phase involved a comparative fuel analysis, where the test engine was operated with conventional fuel, and the performance and emission outcomes were taken as standard reference data against its operation on various blends of Jatropha biodiesel. This comparative analysis aimed to determine the optimum blend. In the subsequent phase of investigation, the identified optimum biodiesel blend was doped with 50 ppm of cerium oxide nanoparticles. The primary objective of this phase was to conduct a direct comparison of the test engine behaviour with and without the nanoparticle additive. The schematic arrangement of the test setup is depicted in Fig. 3.



1-Diesel engine, 2-Eddy current dynamometer, 3-Dynamometer panel, 4-Fuel tank, 5-Air box, 6-Exhaust manifold, 7-Exhaust gas analyzer, 8-Smoke meter, 9-Computer with DAQ

Fig. 3. Schematic arrangement of test setup

4. RESULTS AND DISCUSSION

4.1. Brake Specific Fuel Consumption

The analysis of Brake Specific Fuel Consumption (BSFC) provides critical insight into the engine's efficiency in converting the chemical energy of the fuel into useful mechanical work. The correlation between BSFC and BP for standard and advanced fuel is depicted in Figs. 4 (a) and (b).

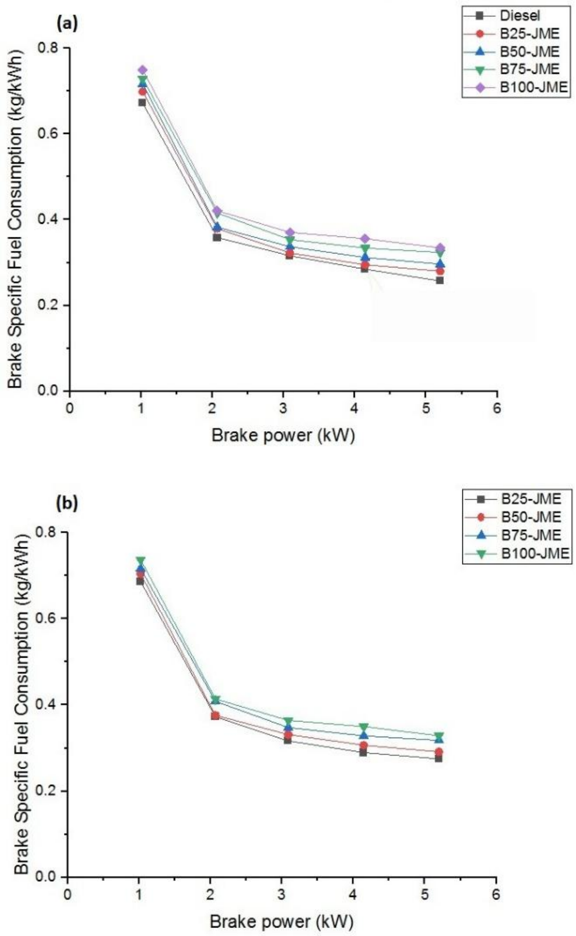


Fig. 4. BSFC Vs BP (a) for standard fuel (b) for advanced fuel

The results, as illustrated graphically in Fig. 4, reveal a significant influence of both fuel blending and nanoparticle addition on BSFC. Higher BSFC of the Jatropha biodiesel blends compared to conventional diesel was observed across the entire load spectrum. At maximum load, the BSFC for conventional fuel was recorded as 0.257 kg/kWh, whereas B25 exhibited a BSFC of 0.280 kg/kWh. This constitutes an 8.21% increase in fuel consumption for the B25 blend relative to baseline fuel. This elevation in BSFC for the biodiesel blend is a well-documented phenomenon and can be primarily attributed to the lower calorific value and higher density and viscosity of jatropha methyl ester (JME) compared to mineral diesel [13]. The relatively high density of biodiesel blends results in enhanced BSFC because the engine consumes relatively high fuel to deliver rated output [14]. The introduction of Cerium Oxide (CeO_2) nanoparticles, however, addressed this drawback [15]. The BSFC for the B25+CeO_2 blend decreased to 0.29 kg/kWh at the same 75% load. This represents a 3.87% reduction compared to the neat B25 blend. The improvement can be directly correlated to the role of CeO_2 in promoting more complete combustion [16]. The incorporation of cerium oxide resulted in a BSFC similar to that of conventional fuel, addressing the compromise in performance while retaining the environmental benefits of biodiesel [17].

4.2. Brake Thermal Efficiency (BTHE)

A significant measure of the engine's capacity to transform the chemical energy of fuel into mechanical work is the braking thermal efficiency. The data reveal that BTHE is highly dependent on both the fuel blend and the applied load. For all tested fuels, BTHE increases with an increase in brake power, reaching a maximum at the highest load. Figs. 5 (a) and (b) show the correlation between brake power and BTHE for standard and advanced fuel.

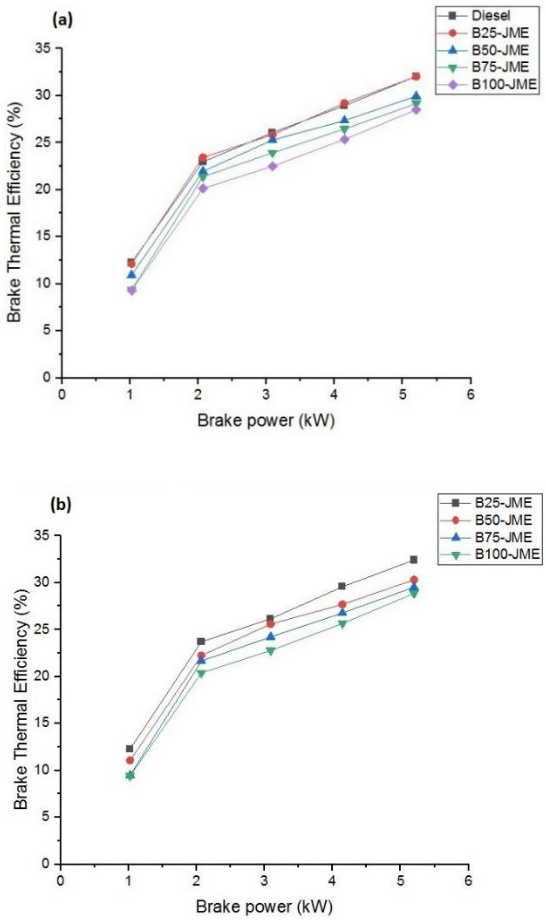


Fig.5. BTHE Vs BP (a) for standard fuel (b) for advanced fuel

A detailed comparison shows that conventional fuel exhibited the highest BTHE across all load conditions. The B25-JME blend resulted in BTHE identical to that of conventional fuel, with a marginal reduction. However, with an increase in biodiesel concentration in the blends, the BTHE was found to decline, with B100 showing a reduction of about 11% compared to conventional fuel. This is primarily due to the lower calorific value and higher viscosity of biodiesel blends [18]. The BTHE of B25-JME with nanoparticles (B25-JME+CeO_2) showed an improvement in BTHE. This is attributable to the catalytic action of cerium oxide, promoting more complete combustion.

4.3. Exhaust Gas Temperature (EGT)

Exhaust gas temperature is an indicator of heat energy lost through the exhaust and is influenced by fuel combustion quality. The data indicate a clear trend of increasing EGT with rising engine load for all test fuels. Figs. 6 (a) and (b) show the correlation between brake power and EGT for standard and advanced fuel.

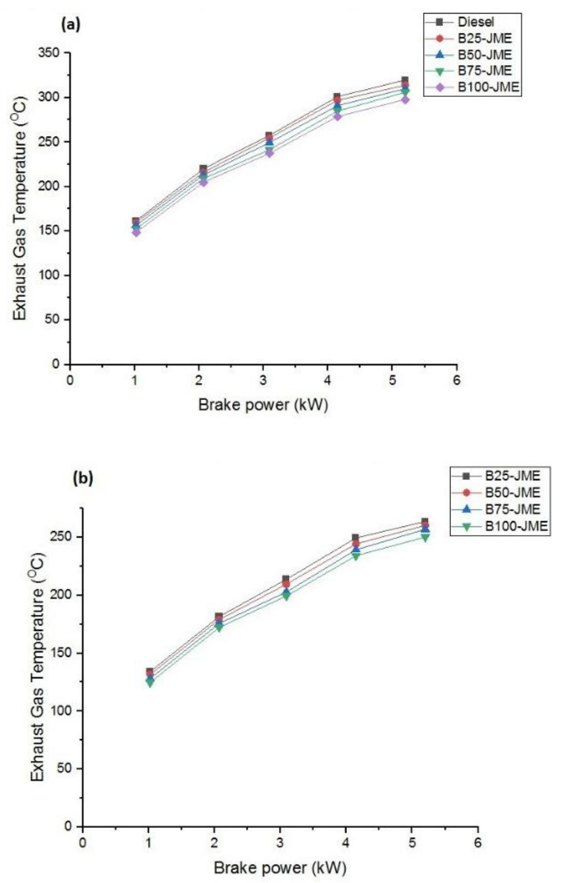


Fig.6. EGT Vs BP (a) for standard fuel (b) for advanced fuel

Comparative analysis reveals that conventional fuel recorded the highest EGT values across the entire load spectrum. The biodiesel blends exhibited progressively lower EGT with increasing JME concentration; B100-JME showed an average reduction of about 7% compared to diesel. The most profound effect was observed with the addition of cerium oxide nanoparticles, which significantly reduced EGT for all biodiesel blends [19]. The B25-JME+CeO_2 blend exhibited an average EGT reduction of approximately 16% compared to standard B25-JME and about 17% compared to diesel. This substantial decrease is a direct consequence of the nanoparticles' role as oxygen donors, which facilitates the oxidation of soot and unburned hydrocarbons and lowers the exhaust-gas temperature.

4.4. Smoke Density (SD)

Particulate matter from incomplete combustion can be precisely determined by smoke density. The results demonstrate that smoke opacity increases with engine load for all tested fuels. Figs. 7 (a) and (b) show the correlation between brake power and smoke density for standard and advanced fuel.

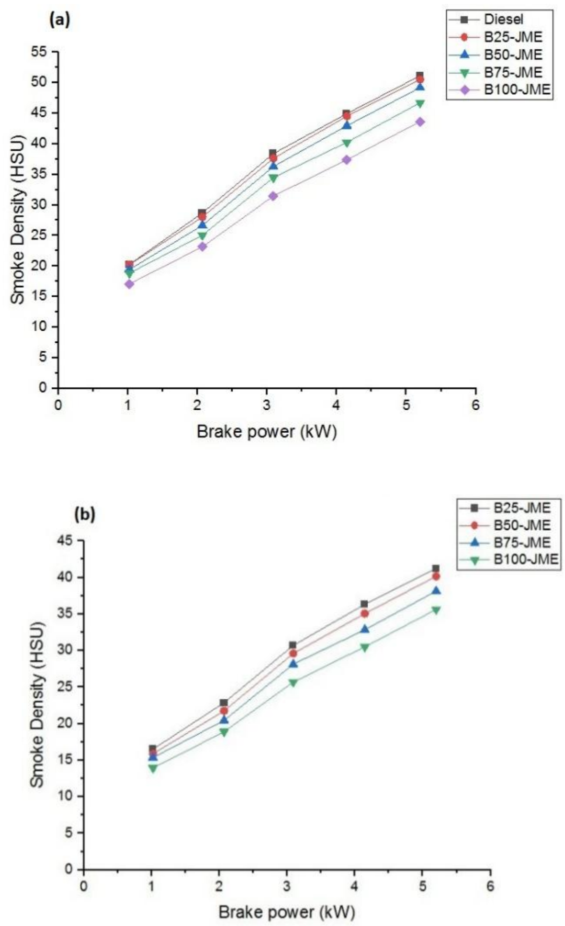


Fig.7. SD Vs BP (a) for standard fuel (b) for advanced fuel

The data indicate a favourable trend for biodiesel, where smoke density consistently decreased as the proportion of JME in the blend increased [20]. B100-JME produced approximately 14% less smoke on average compared to conventional fuel, owing to the oxygen content in the biodiesel molecule that promotes a more complete combustion of the fuel. The incorporation of cerium oxide nanoparticles further enhanced this beneficial effect. The catalytic oxidation properties of CeO_2 led to a drastic reduction in smoke emissions [21]. For the B25-JME+CeO_2 blend, smoke density was reduced by an average of 18% compared to the standard B25-JME blend and by over 30% compared to baseline diesel at peak load.

4.5. Carbon Monoxide (CO) Emission

Carbon monoxide emissions are a product of incomplete combustion, typically resulting from insufficient oxygen or inadequate combustion temperature. The recorded CO emissions for all fuels increased with engine load. Figs. 8 (a) and (b) show the correlation between brake power and CO emission for standard and advanced fuel.

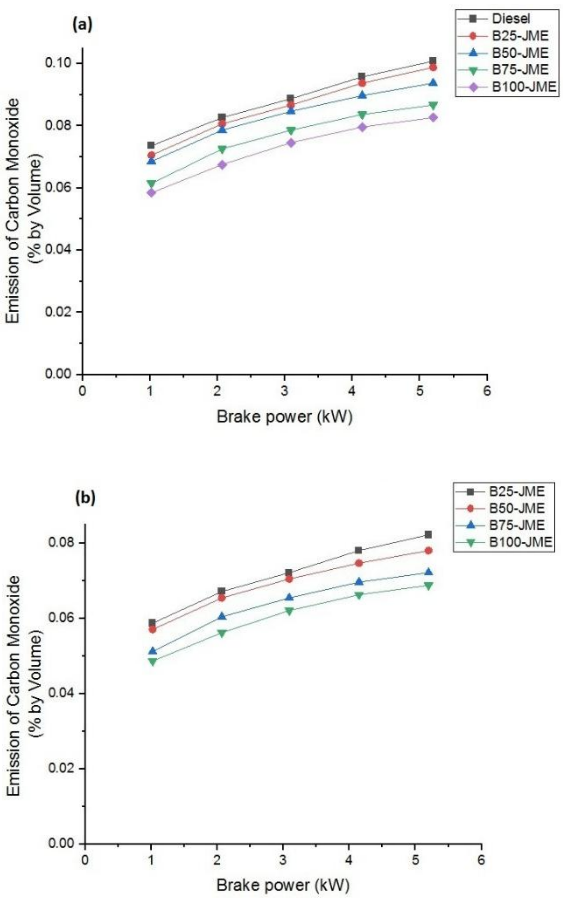


Fig. 8. Emission of CO Vs BP (a) for standard fuel (b) for advanced fuel

A clear benefit of biodiesel utilization is evident in the reduction of CO emissions [22]. The inherent oxygen content in JME promotes more complete oxidation of C to CO_2, leading to lower CO levels. B100-JME exhibited an average reduction of 18% in CO emissions compared to diesel. The addition of cerium oxide nanoparticles led to a further significant reduction in CO [23]. The B25-JME+CeO_2 blend showed an average CO reduction of 20% compared to the standard B25-JME blend and a 34% reduction compared to diesel at maximum load. This is primarily due to the oxygen buffering capacity of CeO_2, which supplies active oxygen for the oxidation of CO to CO_2.

4.6. Hydrocarbon (HC) Emission

Fuel that has partially burned and discharged from the cylinder is referred to as unburned hydrocarbon emissions. As with CO, HC emissions increased with engine load across all tested fuels. Figs. 9 (a) and (b) show the correlation between brake power and HC emission for standard and advanced fuel.

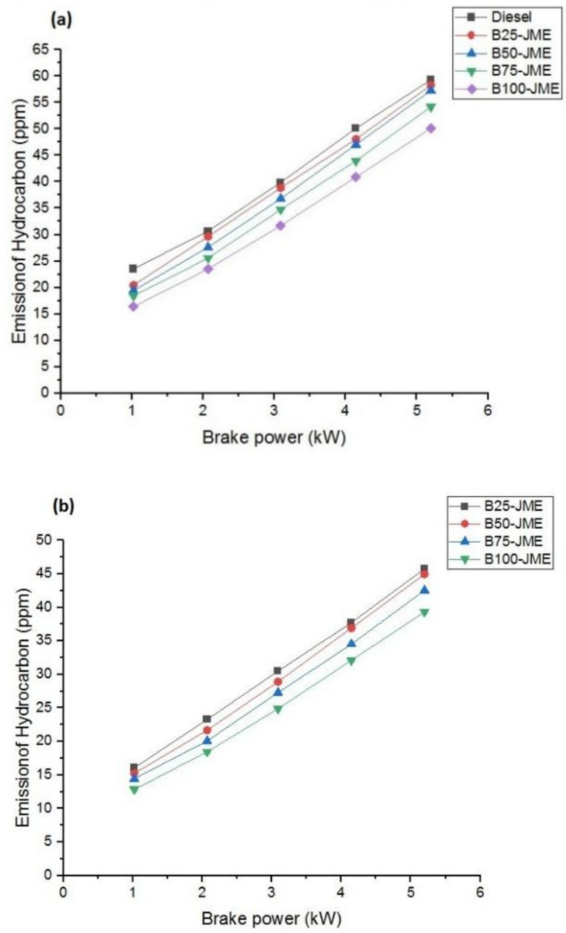


Fig. 9. Emission of HC (a) for standard (b) for advanced fuel

The graph results show a substantial reduction in HC emissions with biodiesel use. B100-JME resulted in an average HC reduction of approximately 15% compared to conventional fuel, due to the fuel-bound oxygen enabling more complete combustion [24]. The introduction of cerium oxide nanoparticles significantly reduced HC formation. The catalytic activity of CeO_2 ensures the oxidation of unburned hydrocarbons in the combustion chamber and exhaust port [25]. The B25-JME+CeO_2 blend achieved an average HC reduction of about 20% compared to standard B25-JME and over 35% compared to conventional diesel fuel at maximum load, highlighting its role as an effective combustion catalyst.

4.7. Oxides of Nitrogen (NOx) Emission

Oxides of nitrogen formation are a temperature-dependent phenomenon, primarily occurring at peak combustion temperatures. The data shows a consistent increase in NOx emissions with engine load for all fuels, as higher loads lead to elevated in-cylinder temperatures. Figs. 10 (a) and (b) show the correlation between brake power and NOx emission.

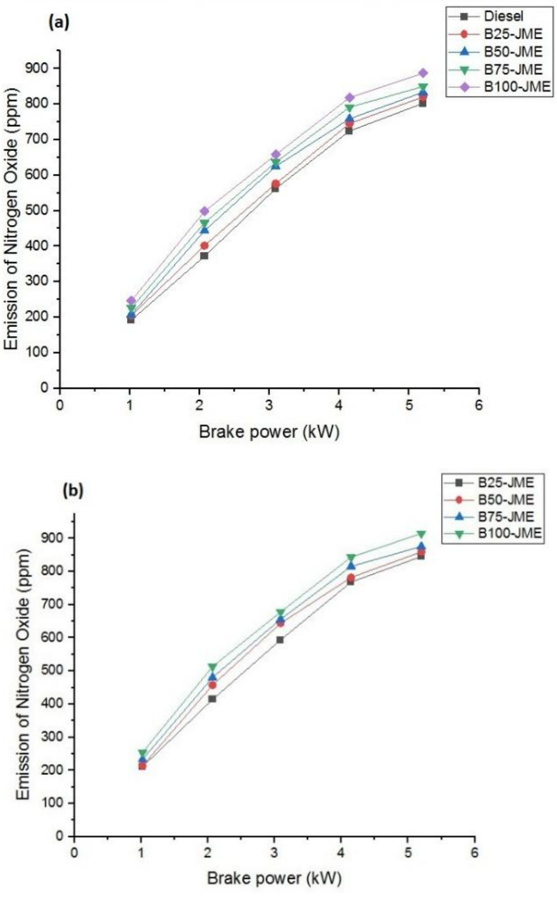


Fig. 10. Emission of NO_X (a) for standard (b) for advanced fuel

In contrast to other emissions, NOx levels were found to be higher for biodiesel blends compared to diesel [26]. B100-JME produced approximately 10% higher NOx than diesel on average. The increase in NO_X emissions of biodiesel blends is due to the presence of significant oxygen molecules that react with the nitrogen of drawn air and form NO_X. The addition of cerium oxide nanoparticles, while beneficial for other parameters, further increased NOx emissions [27]. The B25-JME+CeO_2 blend showed a 3-5% increase in NOx over standard B25-JME. This is due to the fact that the nanoparticles enhance the rate of combustion, leading to higher local temperatures that favour NOx formation, highlighting the existing compromise between biodiesel and NOx.

5. CONCLUSION

This comprehensive investigation outlined the following conclusions. JME biodiesel exhibits a brake thermal efficiency (BTHE) deficit relative to conventional diesel, which increases with biodiesel concentration. B100 shows an 11% lower efficiency than conventional fuel. The B25 blend performed remarkably identically to conventional fuel in terms of BSFC and BTHE. At maximum load, the BSFC of conventional fuel and B25 were found to be 0.257 kg/kWh and 0.280 kg/kWh, while at similar load, for similar fuels, the BTHE were found to be 32.06% and 32.04%. The blend B25 outperformed in terms of BSFC and BTHE when compared with the other blends. Compared to conventional fuel, B25 decreased the emission of carbon monoxide (CO) by 18%, unburned hydrocarbons (HC) by 15%, and smoke density by 14%. The addition of cerium oxide nanoparticles with B25 revealed 34% reduction in CO, 35% in HC emission, and over 30% in smoke when compared to the conventional fuel. The study also confirms the challenge of NOx emissions with biodiesel. B25 produces about 10% higher NOx than conventional fuel. The NO_X emission of B25 with and without CeO_2 is found to be 820 ppm and 845 ppm. Inclusion of CeO_2 further enhanced the NO_X emission by 5% and 2.9% when compared with the conventional fuel and its neat form. Featuring performance almost identical to conventional fuel and substantial reductions in CO, HC, and smoke emissions, the B25-JME blend with cerium oxide nanoparticles emerges as an excellent fuel substitute, with only a minimal increase in NOx.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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