Malaysian Journal of Chemistry, 2025, Vol. 27(3), 530-542
(Special Issue: *International Conference on Sustainable Materials and Technologies, ICSMT 2025*)

Influence of Al_2O_3 and CeO_2 Nanoparticle-Enriched Waste Cooking Oil Blends on Performance and Emissions of a CI Engine

Vennimalai, M. and Shaisundaram, V. S.*
Department of Mechanical Engineering, Vels Institute of Science, Technology and Advanced Studies (VISTAS), Chennai
*Corresponding Author mail id (e-mail: saiswastik23@gmail.com)

The increasing need for green fuels, requires the use of waste based biodiesels with improved fuel properties. The present research work examine the impact of aluminum oxide (Al_2O_3) and cerium oxide (CeO_2) nanoparticles on a single cylinder compression ignition (CI) engine operating with waste cooking oil biodiesel blends. The nanoparticles, in different concentrations, were mixed in biodiesel and stirred into the biodiesel via ultrasound to reach homogeneity and stability. Engine runs were performed with varying load conditions for BTE, BSFC, NOx, CO, HC, and smoke opacity. The results reveal that the combustion efficiency is enhanced upon addition of nanoparticles to the biodiesel blends, which also enhances the BTE while slightly decreasing the BSFC. Significantly the CO and HC emissions decreased, whereas the NOx emission slightly increased. At 25% full load, the highest braking thermal efficiency for B20 was attained by adding 70 ppm of aluminum oxide nanoparticles along with 10% exhaust gas recirculation. The braking specific fuel consumption of the nanoparticles is decreased when an aluminum oxide concentration of 70 parts per million is used with 10% exhaust gas recirculation and 25% at full load. Hydrocarbon and nitrous oxide emissions were decreased at 25% full load by adding 60 ppm of cerium oxide nanoparticles along with 10% exhaust gas recirculation.0.06 ppm of hydrocarbons and 4 ppm of nox are released. The study concludes that Al_2O_3 and CeO_2 additives can effectively enhance biodiesel performance, supporting their potential in cleaner diesel engine applications.

Keywords: Biodiesel; nano additives; exhaust gas recirculation; emission; performance

Received: January 2025; Accepted: May 2025

The global demand for energy and the rising concerns over environmental pollution have driven extensive research into alternative and sustainable fuel sources. Biodiesel, a renewable and biodegradable fuel derived from vegetable oils and animal fats, has gained significant attention as a viable substitute for conventional diesel. But it also has its own disadvantages such as low calorific value, high viscosity and high nitrogen oxide emissions. require engine alterations in order to improve combustion efficiency and emissions. Among potential solution, adding metal oxide nanoparticles as fuel additives and applying EGR technology are considered as new concepts. Metal oxide nanoparticles, such as alumina (Al_2O_3) and ceria (CeO_2), have recently focused considerable attention due to their capability to enhance the biodiesel physicochemical properties. Al_2O_3 nanoparticles serve as combustion catalysts and result in better atomization, enhanced surface area for reaction, and superior thermal conductivity. When mixed with Biodiesel and used EGR, Al_2O_3 nanoparticles lead to better values of the brake thermal efficiency (BTE), reduced level of unburnt hydrocarbon (HC)and CO emissions and better engine operation.

Also, CeO_2 Nanoparticles have high capacity to store oxygen, which is useful for promoting fuel and soot particle oxidation for lowering particulate matter (PM) and carbon deposit formation. CeO_2 nanoparticles effectively reduce NO_x emissions by catalyzing the burning process with no loss of the degree of combustion efficiency. When used together with the biodiesel and EGR for a cleaner and efficient combustion, the CeO_2 nanoparticles, also used, optimize the NO_x and the particulate emissions trade-off. The effects of 10% (by volume) of Al_2O_3 and CeO_2 nanoparticle-prosperous biodiesel in combination with EGR on the combustion, performance and emission of a diesel engine are described. The results of this study will shed light on the possibility of nanotechnology–EGR, incombination, as potential promising technologies for advancement of biodiesel as an environmentally friendly and sustainable alternative fuel. The nano-additives of diesel–biodiesel blends influence on the fuel stability, performance, and emission of diesel engine. These nanoparticles act as combustion modifiers due to the effective fuel atomization, better heat release and lower brake specific fuel consumption. Metal-based catalyst (both as bulk

†Paper presented at the International Conference on Sustainable Materials and Technologies (ICSMT 2025)

and nanoparticles) such as cerium oxide (CeO_2) and aluminium oxide (Al_2O_3) are quite important for demobilising emissions like NOx, CO, HC and PM [1]. Addition of alumina nano-additives in biodiesel-diesel blends for enhanced combustion and reduced pollutants in EGR equipped diesel engine.

Nanocatalysts, such as Al_2O_3 nanoparticles, improve fuel-air mixture and chemistry resulting into improved combustion efficiency [2]. Cerium oxide nanosized particles and lemongrass are mixed with biodiesel. The determination of the diesel engine is now being considered [3]. A 50 ppm Ce-ZnO nanoparticles could reduce the inorganic species such as CO and CENxOy by acting in biodiesel [4]. Enhanced brake thermal efficiency with reduced CO and NOx emissions have been achieved using aluminum oxide nanoparticles as additives in biodiesel. [5, 6] Performance of diesel after addition of two nanoparticles, viz. CeO2 and Al_2O_3, in biodiesel is evaluated. Alternative diesel fuel is considered a research gap [7]. This work explores the effect of Sr-doped ZnO nanoparticles as an additive in RC biodiesel-diesel blends on modified CRDI diesel engine. Performance, combustion and emission parameters were studied. The findings demonstrated that adding nanoparticles enhanced the combustion, reduced emissions and increased engine efficiency. The present work demonstrates the promise of Sr@ZnO nanoparticles as a potential catalyst for enhancement of the utilization of biodiesel for sustainable energy applications [8] When metallic nanoparticles are added to bio-diesel, nitrogen oxide levels increase by 0.7%, leading to better engine efficiency and better combustion [9]. Graphite nanoparticles are heterogeneous in the biodiesel sample. It will increase the pressure at cylinder peak and reduces NO_x by 0.6%. Adding CeO_2 to be mixed with Biodiesel will decrease the hydrocarbon and NO_x by 0.62% [10-11]. The combustion and the Nox emission can be optimized by adding antioxidants [12]. This research studies aluminum oxide (Al_2O_3) nanoparticles and cerium oxide (CeO_2) nanoparticles in biodiesel blend on diesel engine retrofitted with exhaust gas recirculation (EGR). The fuel properties are improved by adding nanoparticles, which is beneficial to atomization and combustion efficiency. Better burning is associated with higher BTE, but lower BSFC. The catalytic capability of CeO_2 and better oxidation of unburned hydrocarbon lead to lower HC and CO emission. The presence of nanoparticles (Al_2O_3) results in increased heat transfer and combustion stability. Both EGR and nanoparticles have the potential to decrease NO_x emissions, while maintaining the performance. The results showed a remarkable decrease of particulate and soot formation. Life of the engine is prolonged through carbon deposit and wear minimization [13]. It also results in the reduced ignition delay and the improved operability. Results support viability of nanoparticle-activated biodiesel for cleaner combustion. This will drive sustainable fuel use in diesel engines. The present work is a promising alternative for decreasing the emissions and without affecting the engine performance.

Despite the growing interest in alternative fuels for compression ignition (CI) engines, especially biodiesel derived from waste cooking oil (WCO), several limitations remain unaddressed in the current literature. Many existing studies have explored the use of WCO as a sustainable fuel, yet they often report drawbacks such as poor combustion efficiency, higher emissions of NO_x and particulate matter, and reduced engine performance compared to conventional diesel [14-16]. While the addition of metal oxide nanoparticles like Al_2O_3 and CeO_2 has been investigated for their catalytic and combustion-enhancing properties, most research focuses on isolated nanoparticle types or lacks comprehensive evaluation under real engine operating conditions, such as the implementation of exhaust gas recirculation (EGR). Furthermore, limited studies have systematically assessed the combined effect of dual nanoparticles and EGR in WCO-diesel blends [17-19]. This creates a critical research gap in understanding the synergistic influence of these additives on combustion behaviour, emission profiles, and overall engine performance. In addition, the simultaneous optimizations for the concentrations of nanoparticle and EGR rate have not been widely studied, especially for the practical engine. In this study, the effect of blending of WCO with diesel and simultaneous addition of Al_2O_3 and CeO_2 nanoparticles on performance and emission behaviour of CI engine with EGR is explored. This method brings a new combination of fuel treatment and emission control together, which can provide a comprehensive solution to enhancing combustion performance and reducing emission pollution [20-21]. The results are to provide important information for the development of the cleaner and more efficient alternative fuel systems to CI engines.

MATERIALS AND METHODS

Preparation of Biodiesel

In order to improve fuel properties and reduce environmental pollution, the biodiesel is blended with petroleum diesel based biodiesel blending ratios. 17 Biodiesel is obtained from transesterification of triglycerides from oils or fats to fatty acid methyl esters (FAME) with glycerin as a side product [22-24]. This is the transesterification of triglycerides with some alcohol (usually methanol), in the presence of a catalyst such as potassium hydroxide (KOH) or sodium hydroxide (NaOH).

In the present work waste cooking oil (WCO) was collected from a local hotel in Tamil Nadu, India and filtered to separate impurities. As the viscosity of WCO is quite high only one method could be used to transform it in a suitable fuel for typical biodiesel applications, i.e., transesterification. 500 mL of filtered

WCO were mixed with 125 mL of methanol and 3 g of KOH. The reaction was performed at 60°C for 60 min using magnetic stirring for perfect mixing and reaction control. After the reaction, the mixture was kept at rest in a separating funnel for 24 h to scavenge glycerine-separated (which was at bottom because of higher density). The upper layer of biodiesel was washed several times with water to remove remaining impurities [25-26].

Following biodiesel production, various ratios of conventional diesel were blended with biodiesel to evaluate their suitability for engine applications. Common biodiesel blends, such as B5 (5% biodiesel, 95% diesel), B10 (10% biodiesel, 90% diesel), and B20 (20% biodiesel, 80% diesel), are widely used in diesel engines without requiring modifications. Higher blends, such as B50 and B100, offer increased renewable content but may necessitate adjustments to engine components and fuel systems [27-28]. The blending process involved accurately measuring the required volumes of biodiesel and diesel fuel, followed by thorough mixing to ensure homogeneity. The prepared blends were analysed for key fuel properties, including viscosity, density, flash point, cetane number, and calorific value, to assess their performance characteristics. Storage conditions and oxidation resistance were also assessed by determination of the stability of the fuel.

Biodiesel blends have a beneficial impact on fuel lubricity, which result in reduced wear on engine parts, contributing to reduced carbon monoxide (CO), hydrocarbon (HC), sulphur oxides (SO_x) and particulate matter (PM) emissions. But increasing the amount of biodiesel also affects cold flow performance and can cause gelling of the fuel in cold weather. The mixtures were screened to optimize performance properties, and to maintain compatibility with the current fuel infrastructure. This process guarantees the use of a consistent method to make and test biodiesel blends and advances cleaner fuel options which have a small impact on the environment and optimal performance in every engine. Figure 1 and Figure 2 shows the biodiesel samples.

Preparation of Biodiesel Blend with Aluminium Oxide Nanoparticle

Al_2O_3 nanoparticles inthe present investigation were supplied from Nano Lab, Jamshedpur, India, having a particle size between 30–50 nm and purity of 99.5%. Ultrasonic dispersion method was employed to homogeneously disperse the catalyst into the biodiesel blend. Sonication is a reliable tool to achieve a stable suspension of nanoparticles in the fuel to avoid agglomeration and to mix uniformly. The particle dispersion was sonicated for 30 min for each of the fuel blends and this time was enough for the nanoparticles to get dispersed homogeneously in the fuel matrix. Biodiesel properties have been presented in Table 1.

The base fuel was B20 biodiesel blend (80% diesel and 20% biodiesel). Al_2O_3 nanoparticles were blended with biodiesel at 25 ppm, 50 ppm and 75 ppm with the neat biodiesel to analyse the influence of the nanoparticles on fuel properties, combustion and emissions. The mixes were sonicated at the ultrasonicator to ensure the nanoparticles were uniformly distributed in the fuel. As uniform dispersion of nanoparticles is critical to the combustion qualities, performance and emissions of the fuel, this preparation process is crucial.

The modified biodiesel blends were tested in a diesel engine, performances like combustion, brake fuel consumption and emissions were evaluated at constant speed and engine load. Key performance parameters such as engine efficiency, brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), emissions (CO, CO_2, NOx and PM) were monitored and measured. These experimental studies were conducted to investigate the effect of particle concentration on the engine performance and combustion behaviour.

Figure 1. Raw Waste Cooking oil.

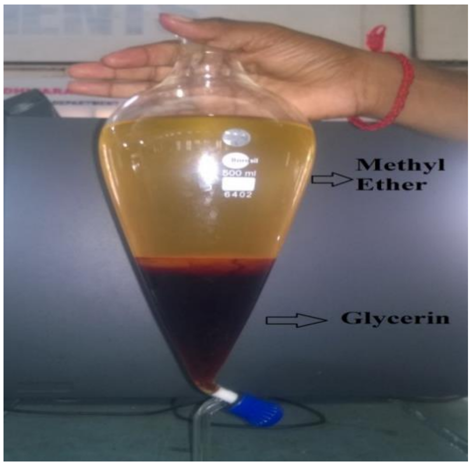

Figure 2. Waste Cooking oil Biodiesel.

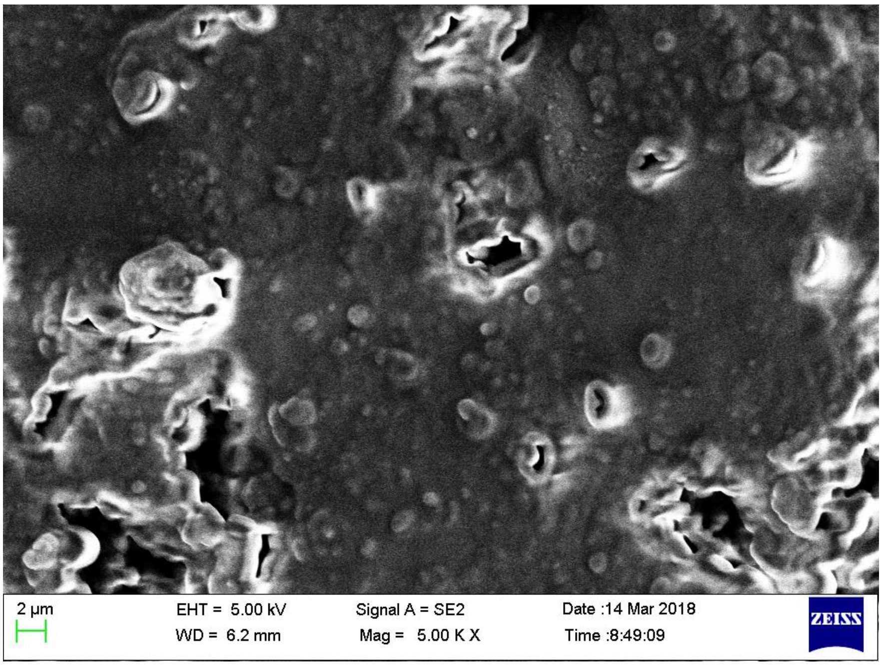

Figure 3. SEM image of nano additives.

Preparation of Biodiesel Blend with Cerium Oxide Nanoparticle

The B20 formulation (20% biodiesel, 80% diesel) was used in this study as it contained a low concentration of biofuel suitable for testing. The cerium oxide nanoparticles (30-50 nm) with 99.5% purity were obtained from an authentic supplier. The effects of various nanoparticle ratios on the fuel quality were also tested by adding such nanoparticles to the B20 bio-diesel in the range of 20 ppm, 50 ppm, 70 ppm. Ultrasonic dispersion was used to obtain uniform distribution of CeO_2 nanoparticles in biodiesel. The use of the ultra-sonication technique to stabilize and homogenize the suspensions is well established. Nanoparticles-50 (0.1% CeO_2/1 L B20 on board) (Table 7): Each application involved mixing the amount of CeO_2 nanoparticles indicated in the table into 1 liter of B20 biodiesel in ultrasonic processor during 30 minute. This technique would provide a uniform dispersion of the nanoparticles in the fuel thereby preventing agglomeration of the particles and achieving a uniform mixture. The same steps were repeated for each concentration (20 ppm, 50 ppm and 70 ppm) to obtain three different fuel blends.

The experiments were performed on a four stroke, single cylinder, naturally aspirated direct injection (DI) diesel engine. An eddy current dynamometer was attached to the engine to load and sense it in the testing process. Figure 3 SEM image of nano additives. The image usually exhibits randomly distributed nanoparticles, but some are present in aggregation in the biodiesel support. These nanoparticles improves the fuel quality by higher combustion efficiency, lower pollutants and fuel stability. In the SEM we have high resolution imaging, which enables us to analyze the size, the shape and agglomeration. Characterizing these features is important for getting insights into the interaction of nanoparticles with biodiesel, which is critical to the design of formulations and their performance. The system was equipped with required sensors to monitor crank-angle variation, fuel line pressure, and combustion pressure. Pressure-crack angle diagrams were generated by computer-integrating these data. The arrangement is described in Figure 4. A separate panel box also contained gauges to monitor temperatures, load environment, fuel flow and airflow. The testing apparatus was composed of a panel box that has a hardware interface, a process indicator, a manometer, a fuel measuring device, fuel and air flow detection transmitters, and an airbox for monitoring and acquisition of accurate data.

"Engine Soft," an Engine Performance Analysis program built on LabVIEW, was used to assess the engine's performance and allowed for real-time monitoring. Manual fuel flow measurement was done using a digital timer and a regular burette. A pressure transducer and a crank angle encoder were utilized to measure and record the in-cylinder gas pressure and the corresponding crank angle, enabling detailed analysis of combustion characteristics. Variations in combustion temperature were analyzed using reference temperature data from a thermometer mounted on the exhaust pipe. Exhaust emissions, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and hydrocarbons (HC), were measured using a five-gas AVL Digas analyzer to assess the environmental impact of the biodiesel blends. Engine performance data may be collected, stored, and analyzed thanks to the automated data gathering system. Diesel fuel was used to start the engine, then a combination of diesel and biodiesel, and finally a blend of diesel, biodiesel, and alumina (Al_2O_3) nanoparticles.

The performance and emissions characteristics of the engine were evaluated in terms of fuel consumption rate, air intake rate, exhaustion composition, and combustion quality, during steady-state operation for the load change from no-load to full load. In order to warm up the engine and to stabilize the system, each load level was logged after 15 mins running. The temperature of the lubricating oil was measured to avoid overheating. Measurement reproducibility was checked by repeating the experiment 2–3times for each load condition before data evaluation. These engineered nanoparticles can be purchased from commercial vendors or prepared in the laboratory, such as by laser ablation, high-pressure carbon monoxide (HiPCO) process, arc discharge and chemical vapor deposition (CVD) process. Examples include carbon buck balls (fullerenes), carbon nanotubes, (CNTs), metal nanoparticles (e.g., gold), metal oxides (e.g., titanium dioxide) and quantum dots.

The current work investigates the effect of alumina (Al_2O_3) and ceria (CeO_2) nanoparticles as additives in a biodiesel-diesel blend on engine, combustion, and emission parameters. The use of ultra-sonication is necessary to disperse the nanoparticles homogenously in the fuel, to avoid agglomeration and to achieve a good mixing quality. The findings of this study offer an encouraging perspective for the application of nanoparticle injected as fuel additives in diesel engines.

Influence of Nanoparticle with EGR

Nitrogen oxide (NOx) emissions are lowered via exhaust gas recirculation (EGR) by sending part of the exhaust back to the combustion chamber. This method reduces the formation of NOx by lowering peak combustion temperatures. This article studied the impacts of biodiesel doped with aluminum oxide (Al_2O_3) nanoparticles in EGR conditions. Al_2O_3 nanoparticles also act to improve combustion by improving fuel atomization, increasing thermal conductivity and acting as a catalyst in oxidizing reactions. In addition to the preservation of combustion efficiency and reduction in particulate matter emissions, EGR also serves to improve NOx reduction. Similarly, at EGR conditions, cerium oxide (CeO_2) nanoparticle blended biodiesel was also examined. CeO_2 nanoparticles are oxygen suppliers, thus can promote complete combustion and minimize carbon deposition. Their catalytic action assists in the oxidation of soot, thereby lowering emissions of CO and HC. EGR and CeO_2 nanoparticles complement each other in achieving both lowered NOx emission and improved combustion stability. The findings of this investigation are expected to shed light on the synergistic impacts of the injection of biodiesel-nanoparticle blend and EGR on the engine performance, emissions and combustion behavior.

Figure 4. Experimental Setup.

Al_2O_3 NPs enhance thermal conductivity and atomization of the fuel, thereby increasing combustion efficiency. They promote oxidation and reduce particulate matter (PM) formation by acting as catalysts. It also controls the NOx emissions while keeping the combustion stability in combination with the EGR. Nevertheless, due to the incomplete combustion, the excess EGR can produce greater emissions of HC and CO. CeO_2 NPS are oxygen donors that may improve oxidation and decrease carbon deposition. Their catalysis activity promotes soot oxidation, which notably reduces PM and HC emissions. With EGR together, CeO_2 nano materials act to suppress reduction in oxygen supply, thus maintaining stable combustion efficiency and lowering Nox at the same time.

RESULTS AND DISCUSSIONS

Brake Thermal Efficiency

The relationship between brake power and brake thermal efficiency (BTE) is illustrated in the figure 5. While higher concentrations of Al_2O_3 demonstrate an improvement in BTE, the results indicate that all Al_2O_3-blended biodiesel formulations exhibit higher BTE values compared to conventional diesel. The blend's aluminum oxide nanoparticles may be the cause, as they function as an oxygen buffer and encourage longer, more thorough burning, both of which boost efficiency. When 75 ppm of aluminum oxide nanoparticles were added to B20, the highest brake thermal efficiency was 24.95% at full load. It was discovered that the BWCO/50 AONP + 50 MWCNT nano-fuel produced notable outcomes, including a minimum ignition delay of 9 and a brake thermal efficiency (BTE) of 30.65%, in-cylinder pressure of 58.36 bar, and heat release rate of 38.38 J/kg.

This chart shows the impact of different concentrations of a B20 biodiesel blend (25 ppm, 50 ppm, and 75 ppm) compared to regular diesel fuel on engine performance, specifically brake power and brake thermal efficiency. The numbers 1 through 5 likely represent different engine load conditions. Looking at brake power, all fuels see an increase as load increases. The B20 blend at 50 ppm appears to produce the highest power output, even slightly exceeding diesel in some cases, suggesting an optimal blend concentration. The 75 ppm concentration appears to be the sweet spot in this experiment, maximizing both power and efficiency. Further research could explore the reasons behind this optimal concentration and investigate the long-term effects of these blends on engine performance and emissions.

The addition of CeO_2 nanoparticles significantly improved the BTE of the B20 biodiesel blend, with the 50 ppm blend showing the most balanced and optimal performance is shown in figure 6. The improvement can be attributed to the catalytic role of CeO_2, which promotes better fuel oxidation, enhanced flame propagation, and reduced ignition delay. The superior thermal efficiency observed in nanoparticle-enriched blends suggests a promising approach to improving biodiesel performance in diesel engines.

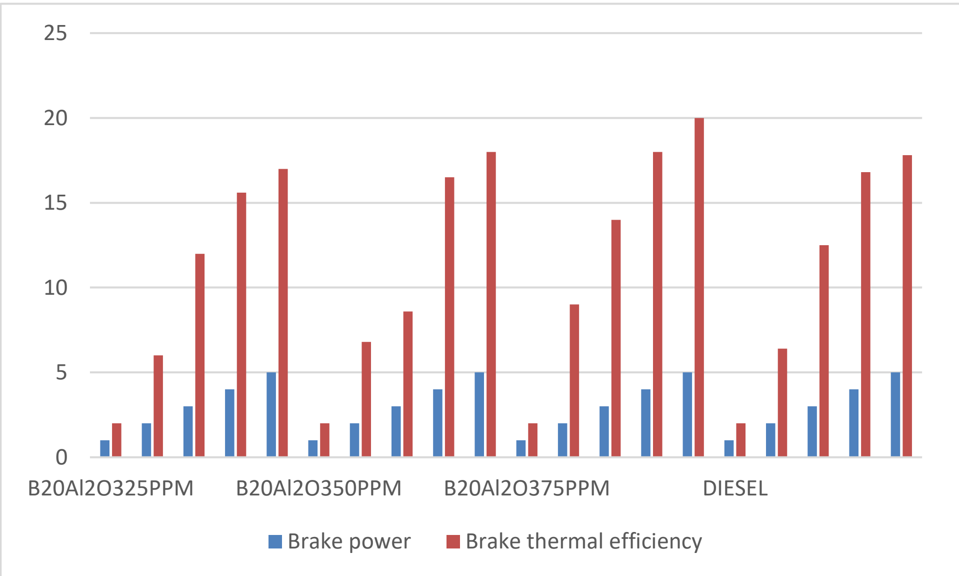

Figure 5. Brake Power vs Brake Thermal Efficiency.

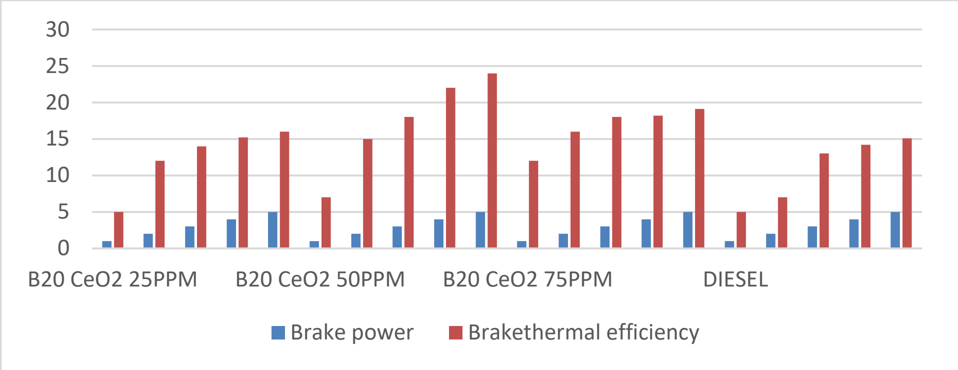

Figure 6. Brake Power vs Brake thermal Efficiency.

However, while the 75 ppm blend showed higher BTE than diesel and B20 without nanoparticles, the diminishing returns at higher power outputs suggest that excessive nanoparticle concentration may not necessarily translate into proportional efficiency gains. Further studies focusing on the long-term stability and potential deposit formation due to nanoparticle usage are recommended to optimize fuel formulations for practical applications. Cerium oxide nanoparticles improve brake thermal efficiency and aid in the elimination of hydrocarbons 16.

Brake Specific Fuel Consumption

The variation of brake specific fuel consumption (BSFC) with brake power for different dosing levels of aluminium oxide (Al_2O_3) nanoparticles blended with B20 biodiesel is illustrated in Figure 7. The results indicate that the inclusion of Al_2O_3 nanoparticles significantly influences fuel consumption due to their role in enhancing combustion efficiency. The results indicate that both neat biodiesel and the BDWFO20 biodiesel blend, with and without nano additives, exhibit higher thermal efficiency compared to conventional diesel fuel. Additionally, the engine fueled with BDWFO100, BDWFO20, BDWFO20 with AN, and BDWFO20 with AN as an additive in the biodiesel blend demonstrated improvements in brake-specific energy consumption (BSEC) by approximately 10%, 3.6%, 16%, and 8%, respectively, compared to neat diesel fuel.

Among the tested blends, $B20Al_2O_3$ (75 ppm) exhibited the lowest BSFC, recorded at 0.4926 kg/kW-hr, demonstrating improved energy conversion efficiency. This reduction in fuel consumption can be attributed to the catalytic role of Al_2O_3 nanoparticles, which promote better atomization, enhance air-fuel mixing, and facilitate complete combustion. Additionally, the high surface area of nanoparticles accelerates heat release, reducing ignition delay and improving thermal efficiency. As the dosing level of nanoparticles increased beyond 75 ppm, a slight increase in BSFC was observed. This could be due to nanoparticle agglomeration at higher concentrations, which may hinder effective dispersion and lead to inconsistent combustion characteristics.

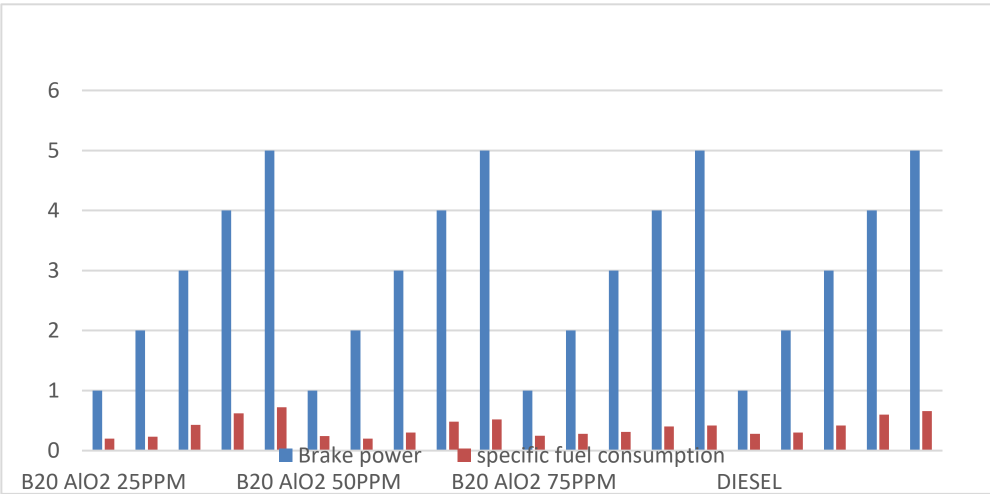

Figure 7. Brake Power vs Brake Specific fuel consumption.

Overall, the incorporation of Al_2O_3 nanoparticles at an optimal concentration (75 ppm) in B20 biodiesel enhances combustion performance by reducing fuel consumption. This improvement suggests that nanoparticle-assisted biodiesel blends can serve as a viable alternative for enhancing engine efficiency and promoting sustainable fuel utilization

The BSFC rose slightly with increasing the dosage of the nanoparticles above 75 ppm. Such behaviour is possibly attributed to agglomeration of the nanoparticles in the higher concentrations and impeded dispersion, so that higher standard deviation values are produced in combustion of the nanofuels. In general, the use of Al_2O_3 nanoparticles at an optimum concentration (75 ppm) has a positive impact on the combustion of B20 biodiesel, thereby reducing fuel consumption. This benefit indicates that FNP-AEDM blends can be a potential alternative to improve engine performance and advocate sustainable fuel usage.

Figure 8 BSFC of biodiesel and their blends with CeO_2 nanoparticles (25, 50 and 75 PPM) and diesel It has been observed that the BSFC of biodiesel is increased as compared to diesel due to increase in bio viscosity. BSFC values of the blends of CeO_2 25 PPM with B20 showed an increase from 2 to 6.5 kg/kWh, with the increase of the brake power. At this concentration the B20 CeO_2 50 PPM blend manifested an improved and a more steady slightly lower BSFC range (2.5 - 5.2 kg/kWh) which may have indicated a better fuel combustion efficiency. The B20 CeO 2 75 PPM showed the minimum BSFC (1.6–2 kg/kWh) which is attributed to better fuel consumption and efficiency that is believed to be attributed to the catalytic action of CeO 2 nanoparticles on the combustion.

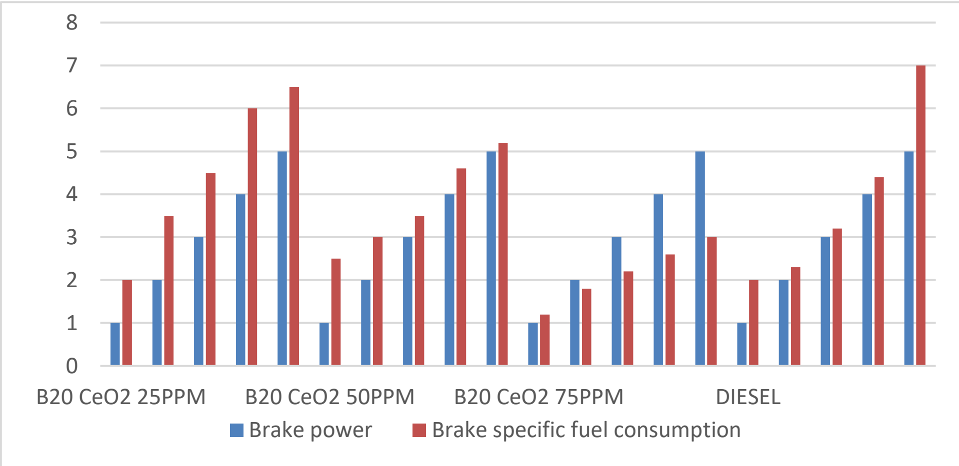

Figure 8. Brake Power vs Brake Specific fuel consumption

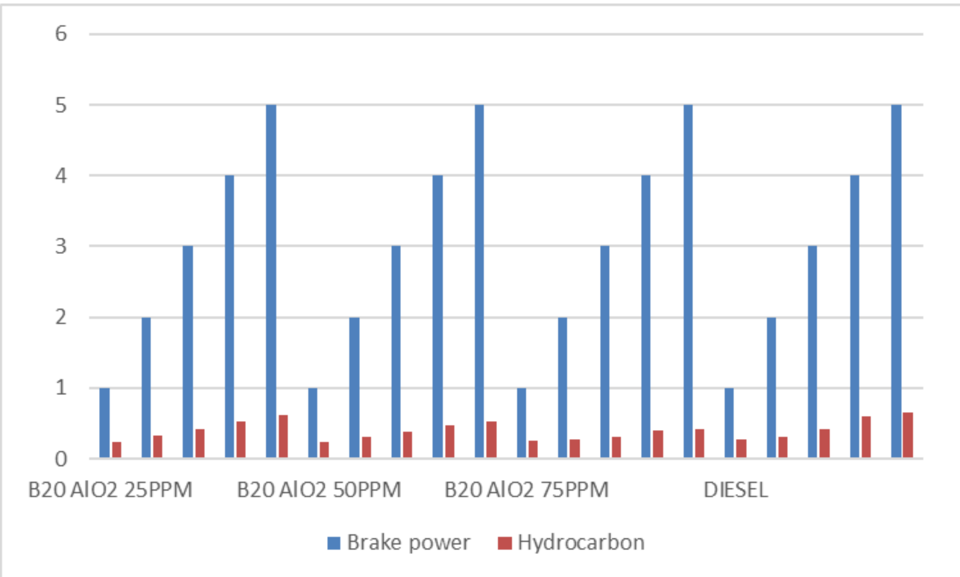

Figure 9. Brake Power vs Hydrocarbon.

Hydrocarbon

Figure 9 shows the correlation between braking power (BP) and hydrocarbon (HC) emissions for different aluminium oxide (AlO_3) nanoparticle concentrations mixed with B20 biodiesel. A distinct pattern emerges from the data: HC emissions fall with increasing AlO_3 nanoparticle concentration. At 25 ppm, 50 ppm, and 75 ppm, the HC emissions for B20AlO_3 blends were measured at 0.50, 0.40, and 0.32 units, respectively. The reduction in HC emissions can be attributed to the enhanced oxygen content introduced by the Al_2O_3 nanoparticles. The presence of these nanoparticles promotes more complete combustion, thereby reducing the formation of unburned hydrocarbons. This finding aligns with previous studies, which have reported that the addition of metal oxide nanoparticles to biodiesel blends improves combustion efficiency and reduces HC emissions. The transesterfication process of biodiesel produces methyl ester.

Furthermore, the catalytic properties of Al_2O_3 nanoparticles facilitate better atomization and mixing of the air-fuel mixture, leading to more efficient combustion processes. This results in a decrease in HC emissions as the nanoparticle concentration increases. However, it is essential to determine the optimal nanoparticle dosing level, as excessive concentrations may lead to agglomeration, potentially hindering combustion efficiency.

The hydrocarbon (HC) emissions for B20 biodiesel blends with varying CeO_2 nanoparticle concentrations (25 PPM, 50 PPM, and 75 PPM) were analyzed across different brake power levels (1-5 kW) and compared with conventional diesel is shown in figure 10. Diesel exhibited the highest HC emissions, ranging from 0.3 to 0.72 g/kWh, indicating incomplete combustion. The B20 CeO_2 25 PPM and 50 PPM blends showed a reduction in HC emissions, with values peaking at 0.62 g/kWh and 0.4 g/kWh, respectively. The B20 CeO_2 75 PPM blend demonstrated the lowest HC emissions (0.23–0.48 g/kWh), highlighting improved combustion efficiency due to the catalytic effect of CeO_2 nanoparticles. The decrease in HC emissions with increasing nanoparticle concentration suggests enhanced oxidation reactions, promoting cleaner combustion. Overall, the B20 CeO_2 75 PPM blend proved most effective in reducing hydrocarbon emissions, making it a promising alternative for sustainable diesel engine applications. Engine load vibration reduction of 32.57%, 86.88 engine load conditions, and a 27.68% biofuel blend.

Oxides of Nitrogen

Figure 11 shows how nitrogen oxide (NO_x) emissions and braking power (BP) relate to different amounts of aluminum oxide (Al_2O_3) nanoparticles mixed with B20 biodiesel. According to the findings, when compared to regular diesel fuel, all nano-blended biodiesel samples show greater NO_x emissions. At 25 ppm, 50 ppm, and 75 ppm, NO_x emissions for B20Al_2O_3 blends were measured at 8, 7, and 5.2 units, respectively.

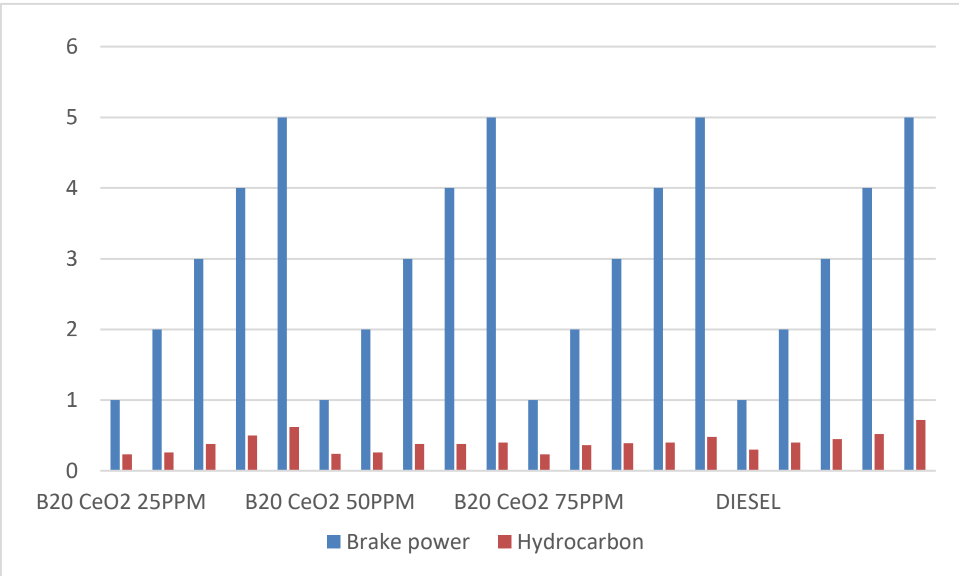

Figure 10. Brake Power vs Hydrocarbon.

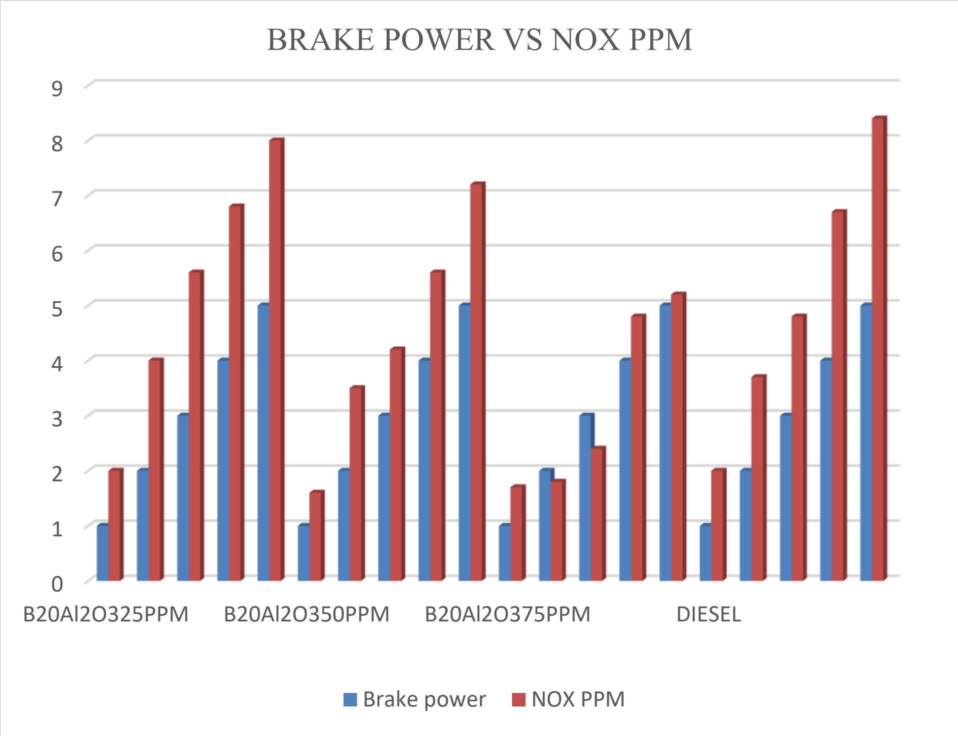

Figure 11. Brake Power Vs Nitrous Oxide.

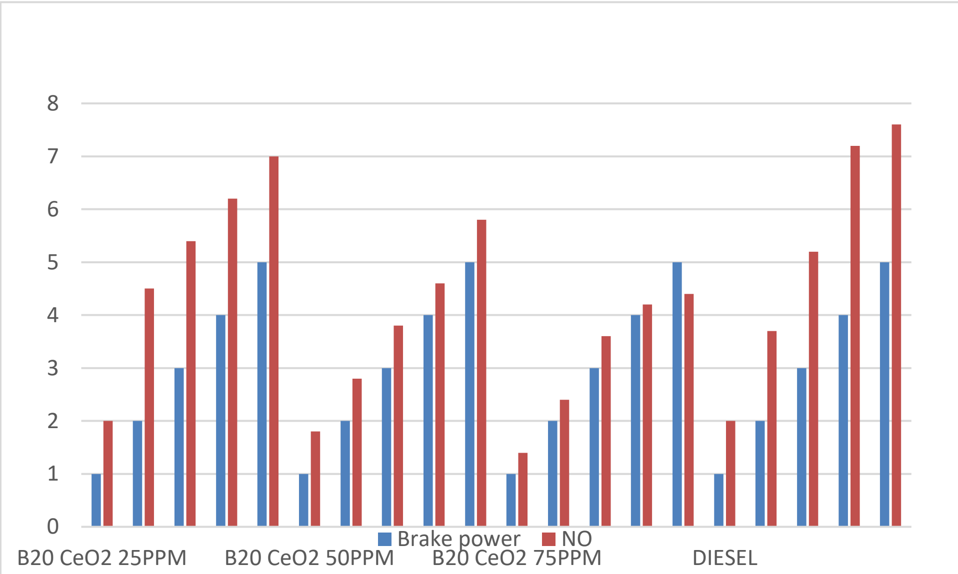

Figure 12. Brake Power vs Nitrousoxide.

The elevated NO_x emissions can be attributed to the role of Al_2O_3 nanoparticles in enhancing the combustion process. The improved combustion efficiency leads to higher in-cylinder temperatures, which, in turn, promote the formation of NO_x. This phenomenon aligns with findings from previous studies, which have reported that the addition of metal oxide nanoparticles to biodiesel blends can result in increased NO_x emissions due to elevated combustion temperatures. Carbon monoxide (CO), unburnt hydrocarbons (HC), and smoke emissions exhibited a slight reduction compared to conventional diesel fuel. The lowest nitrogen oxide (NOx) emissions were observed with aluminum oxide (Al_2O_3) nanoparticle-blended mahua methyl esters. Additionally, the aluminum oxide nanoparticle-infused methyl ester demonstrated higher in-cylinder gas pressure and an increased heat release rate.

Interestingly, as the concentration of Al_2O_3 nanoparticles increases from 25 ppm to 75 ppm, a decreasing trend in NO_x emissions is observed. This reduction may be due to the catalytic properties of Al_2O_3 nanoparticles, which enhance combustion efficiency and reduce the residence time of high-temperature gases in the combustion chamber, thereby limiting NO_x formation. However, it is essential to balance the concentration of nanoparticles to optimize both performance and emission characteristics.

The Nox vs. BP emission is displayed in the Figure 12. When compared to diesel, all of the values for nano-blended biodiesel are greater. Because of the significant function that nanoparticles play in combustion, which raises the cylinder temperature and causes Nox to develop. The Nox emissions for B20 CeO_2 25ppm, B20 CeO_2 50ppm, and B20 CeO_2 75ppm were 8, 7 and 5.2 respectively, Incorporation of CO notably reduces hydrocarbon and NOx emissions. The findings of this study indicate a reduction in brake-specific fuel consumption and emission levels, along with an improvement in brake thermal efficiency.

Carbon Monoxide

The CO emission versus BP is displayed in the Figure 13. Better combustion results from the oxygen in nanoparticles, which lowers carbon monoxide levels. For B20 Al_2O_3 25 ppm, B20 Al_2O_3 50 ppm, and B20 Al_2O_3 75 ppm, the corresponding carbon monoxide emissions were 8.6, 7.86, and 6.2.

The CO emission versus BP is displayed in the figure 14. Better combustion results from the oxygen in nanoparticles, which lowers carbon monoxide levels. For B20 CeO_2 25 ppm, B20 CeO_2 50 ppm, and B20 CeO_2 75 ppm, the corresponding carbon monoxide emissions were 6, 4.86, and 4.2. Hence CO emissions slowly reduced when aluminum oxide nanoparticles were blended with biodiesel. This may be combustion improvement due to adding Al_2O_3.

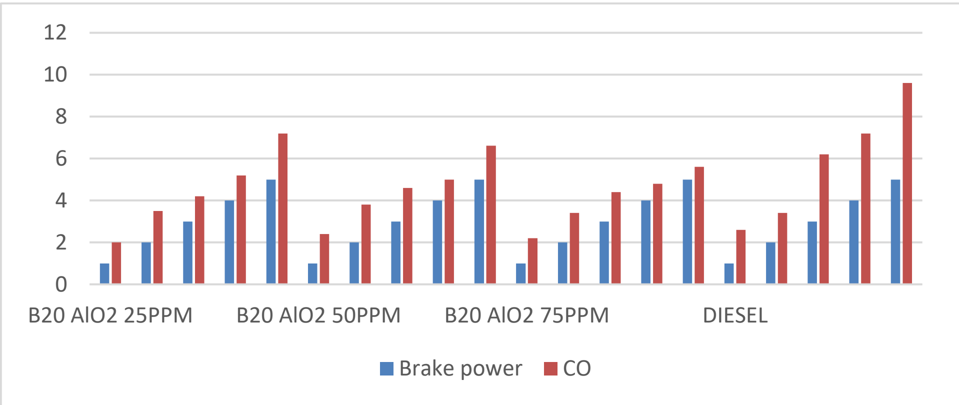

Figure 13. Brake Power vs Carbon Monoxide.

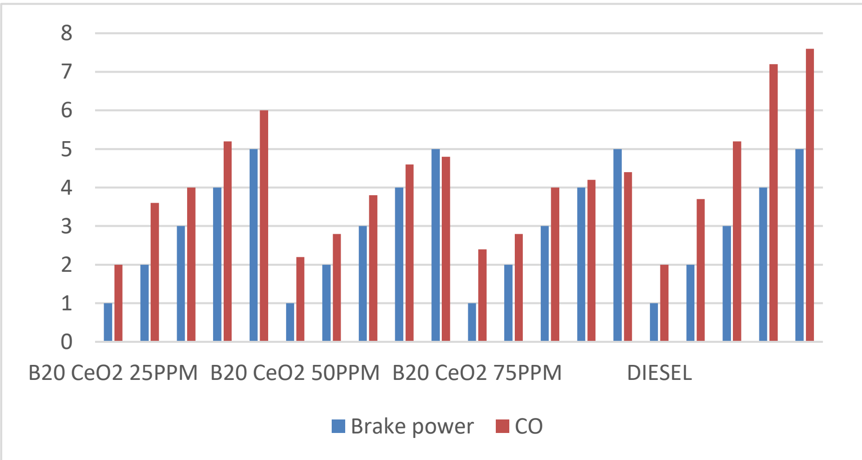

Figure 14. Brake Power vs Carbonmonoxide.

Table 1. Properties for various nanoparticle with biodiesel.

Parameter	Al_2O_3 Nano particle + B20 Biodiesel +10% EGR	CeO_2 Nano Particle+ B20 Biodiesel + 10%EGR	Better Option
Brake Thermal Efficiency	20%	24%	CeO_2
BSFC	0.49 kg/kW-hr	0. 32 kg/kW-hr	CeO_2
Hydrocarbon Emissions	0.32 ppm	0.38 ppm	Al_2O_3
Carbon Monoxide (CO)	6.2 ppm	4.2 ppm	CeO_2
Nitrous Oxide (NOx)	6.7 ppm	6.2 ppm	CeO_2

CONCLUSION

The study on aluminium oxide (Al_2O_3) and cerium oxide (CeO_2) nanoparticle-blended biodiesel with Exhaust Gas Recirculation (EGR) demonstrates significant improvements in combustion characteristics and emission reductions. The addition of nanoparticles enhances oxygen availability, leading to better combustion efficiency and reduced hydrocarbon (HC) and carbon monoxide (CO) emissions. The lowest HC and CO emissions were recorded at 75 ppm nanoparticle concentration. However, NO_x emissions were initially higher due to increase in-cylinder temperatures but showed a decreasing trend with higher nanoparticle concentrations, likely due to improved combustion stability. The cerium oxide blend exhibited better CO reduction than aluminium oxide. Overall, nano-additive biodiesel blends offer a promising approach to reducing harmful emissions while maintaining engine performance. Further optimization of nanoparticle dosage and EGR rates can enhance emission control.

REFERENCES

1. Soudagar., Manzoore Elahi M. (2018) the effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance, and emission characteristics. *Energy Conversion and Management*, **178**, 146–177.

2. Praveen, Lakshmi Narayana Rao and Balakrishna Banavathu (2018) Effect of alumina nano additives into biodiesel-diesel blends on the combustion performance and emission characteristics of a diesel engine with exhaust gas recirculation. *Environmental Science and Pollution Research*, **25**, 23294–23306.

3. Perumal Venkatesan, E., Kandhasamy, A., Sivalingam, A., Kumar, A. S., Ramalingam, K., Joshua, P. J. T., and Balasubramanian, D. (2019) Performance and emission reduction characteristics of cerium oxide nanoparticle-water emulsion biofuel in diesel engine with modified coated piston. *Environmental Science and Pollution Research*, **26**, 27362–27371.

4. Hussain, Fayaz (2020) Enhancement in combustion, performance, and emission characteristics of a diesel engine fueled with Ce-ZnO nanoparticle additive added to soybean biodiesel blends. *Energies*, **13**, 4578.

5. Allami, H. A., Nayebzadeh, H. and Rahmanivahid, B. (2024) Utilizing alpha alumina as a fuel additive to enhance the performance and reduce emissions of a diesel engine. *Fuel*, **371**, 132011.

6. Ronaghi, T. B., Fotovat, F. and Zamzamian, S. A. H. (2024) Enhancing Cerium Oxide Nanoparticle Stability in Diesel–Biodiesel Blends via Alumina Nanoparticle Amalgamation. *Waste and Biomass Valorization*, **15(11)**, 6107–6120.

7. Mofijur, M. (2024) Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics. *Energy Conversion and Management: X*, **21**, 100515.

8. Shaisundaram, V. S., Chandrasekaran, M., Mohan Raj, S. and Muraliraja, R. (2020) Investigation on the effect of thermal barrier coating at different dosing levels of cerium oxide nanoparticle fuel on diesel in a CI engine. *International Journal of Ambient Energy*, **41(1)**, 98–104.

9. Hosseinzadeh-Bandbafha, Homa (2023) Applications of nanotechnology in biodiesel combustion and post-combustion stages. *Renewable and Sustainable Energy Reviews*, **182**, 113414.

10. Shaisundaram, V. S., Saravanakumar, S., Balambica, V., Sendil Kumar, D., Chandrasekaran, M., Muraliraja, R. and Asres, Y. (2022) Effects of thermal barrier coating using various dosing levels of aluminium oxide nanoadditive fuel on

diesel in compressed ignition engine. *Journal of Nanomaterials*, **2022(1)**, 8355098.

11. Uslu, Samet and Mehmet Celik (2023) Response surface methodology-based optimization of the amount of cerium dioxide (CeO2) to increase the performance and reduce emissions of a diesel engine fueled by cerium dioxide/diesel blends. *Energy*, **266**, 126403.

12. Sathish, T. (2023) Enhanced waste cooking oil biodiesel with Al_2O_3 and MWCNT for CI engines. *Fuel*, **333**, 126429.

13. Thamarai Kannan, B. (2022) Use of waste fish oil biodiesel blended with aluminum oxide nanoparticle in IC engines: an experimental on performance, combustion, and emission study. *Scientific Reports*, **12.1**, 12930.

14. Puchakayala, Hema Chandra (2023) Maximizing the potential of biodiesel through nanoparticle assistance: A review of key factors affecting performance and emissions. *Sustainable Energy Technologies and Assessments*, **60**, 103539.

15. Rastogi, P. M. (2020) Sustainability of aluminum oxide nanoparticles blended mahua biodiesel to the direct injection diesel engine performance and emission analysis. *Pollution*, **6.1**, 25–33.

16. Shaisundaram, V. S., Chandrasekaran, M., Shanmugam, M., Padmanabhan, S., Muraliraja, R. and Karikalan, L. (2021) Investigation of Momordica charantia seed biodiesel with cerium oxide nanoparticle on CI engine. *International Journal of Ambient Energy*, **42(14)**, 1615–1619.

17. Arockiasamy, P. (2025) Analysis of diesel engine performance using blends of tamarind biodiesel and nanoparticle mixtures. *Petroleum Science and Technology*, 1–17.

18. Osama Khan (2023) Multi-objective optimization of diesel engine performance, vibration, and emission parameters employing blends of biodiesel, hydrogen and cerium oxide nanoparticles with the aid of response surface methodology approach. *International Journal of Hydrogen Energy*, **48(56)**, 21513-21529.

19. Shaisundaram, V. S. (2021) Investigation of Tamarind Seed Oil biodiesel with aluminum oxide nanoparticle in CI engine. *Materials Today Proceedings*, **37**, 1417–1421.

20. Vairamuthu, G. (2016) Experimental investigation on the effects of cerium oxide nanoparticle on Calophyllum inophyllum (Punnai) biodiesel blended with diesel fuel in DI diesel engine modified by nozzle geometry. *Journal of the Energy Institute*, **89(4)**, 668–682.

21. Modi, V., Rampure, P. B., Shetty, S. K., Nagaral, M., Naik, N., C. K., MGM, J. and Alam, S. (2025) Nano-Enhanced Dairy Scum Biodiesel Blends: Unleashing the Power of Aluminium Oxide for Sustainable and Efficient Engine Performance. *Journal of Thermal Science*, **34(1)**, 283–302.

22. Prabu, A. (2024) Exploring the impact of aluminum oxide nanoparticles on waste transformer biodiesel blend under variable injection timing. *Sustainable Energy Research*, **11(1)**, 19.

23. Sharma, A., Pali, H. S., Kumar, M., Singh, N. K., Rahim, E. A., Singh, Y. and Gupta, N. K. (2024) Effect of α-aluminium oxide nano additives with Sal biodiesel blend as a potential alternative fuel for existing DI diesel engine. *Energy and Environment*, **35(2)**, 663–691.

24. Sabarish, R., Jenoris Muthiya, S., Anandan, B., Sathis Kumar, D., Manideep, B., Sekar, P. and Elumalai, P. V. (2025) The Role and Impact of Al_2O_3 Additive on the Performance of the Diesel Engine Operated by JFO Along with Its Measures of Combustion and Emissions. *Energy Science and Engineering*.

25. Sudarsanam, M. and Jayaprabakar, J. (2024) Effect of alumina and bio-based calcium Oxide nano additives on reduction of emissions and performance improvement in a common rail direct injection diesel engine fueled with B20 blend of waste cooking oil biodiesel. *Energy Technology*, **12(5)**, 2301107.

26. Damian, C. S., Devarajan, Y., Raja, T. and Jayabal, R. (2024) A comprehensive review of biomass pyrolysis for hydrogen production in India. *Process Safety and Environmental Protection*, **190**, 646–662.

27. Chandran, J., Manikandan, K., Ganesh, R. and Baskar, S. (2022). Effect of nano-material on the performance patterns of waste cooking biodiesel fuelled diesel engine. *International Journal of Ambient Energy*, **43(1)**, 2226–2230.

28. Veeraraghavan, S. M., Kaliyaperumal, G., Dillikannan, D. and De Poures, M. V. (2024) Influence of Hydrogen induction on performance and emission characteristics of an agricultural diesel engine fuelled with cultured Scenedesmus obliquus from industrial waste. *Process Safety and Environmental Protection*, **187**, 1576–1585.