

Impact of alumina nanoparticles and lanthanum zirconate coating on the Performance, combustion and emission characteristics of diesel engine functioned with terminalia cattappa seed oil

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Nomenclature

| | |
|--------------------------------|--|
| Al ₂ O ₃ | Aluminum oxide |
| B100 | Pure Terminalia catappa oil |
| B20 | 20% Terminalia catappa oil + 80% Diesel |
| BP | Brake Power (kW) |
| BSFC | Brake Specific Fuel Consumption (kg/kW.hr) |
| BTE | Brake Thermal Efficiency (%) |
| CO | Carbon Monoxide (vol %) |
| D100 | Diesel |
| DI | Direct Injection |
| HC | Hydrocarbon (ppm) |
| HRR | Heat Release Rate (kJ/m ³ deg.) |
| NaOH | Sodium Hydroxide |
| NO _x | Nitrogen Oxide (ppm) |
| PM | Particulate matters |
| TC | Terminalia catappa oil |

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Abstract

This study investigated the potential of biofuels as sustainable alternatives to petroleum based source in CI engines, through focus about biodiesel derived from *Terminalia catappa* seed oil. This study aims to enhance the performance and emission characteristics of diesel engines by utilizing biodiesel derived from *Terminalia catappa* seed oil, in combination with aluminum oxide (Al_2O_3) nanoparticles and lanthanum zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$) thermal barrier coatings. The objectives include evaluating fuel properties, analyzing engine performance, and comparing emissions across different fuel blends and coating conditions. Four fuel variants were examined: pure diesel, pure *Terminalia catappa* biodiesel, a 20% biodiesel–80% diesel blend, and a nanoparticle-enhanced version of the same blend. Key fuel characteristics—density, calorific value, viscosity, Cetane number, and flash point—were measured. Engine performance was assessed using brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), heat release rate, and peak cylinder pressure. The nanoparticle-blended biodiesel, used in a coated engine, showed a 10% reduction in BSFC and a 6.4% increase in BTE compared to diesel. Emissions were significantly reduced: CO by 43%, HC by 13.8%, and smoke opacity by 10%. These results demonstrate the potential of combining biodiesel with additives and thermal coatings for cleaner and more efficient diesel engine operation.

Keywords: Diesel engine; Bio-diesel; Terminalia catappa oil; Thermal barrier; Lanthanum Zirconate; Nanoparticles

1. Introduction

The environmental impact of diesel engines, widely used for transportation and industrial applications, has spurred significant interest in finding alternative fuels and methods to reduce emissions (Allasi et al. 2023; Dhana Raju et al. 2022; Venkatesh et al. 2021). Diesel engines produce high levels of pollutants such as nitrogen oxides (NO_x), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO), which contribute to environmental degradation and adverse health effects. (Rajesh et al. 2022a; Rajesh et al. 2022b; Ding et al., 2024). Moreover, such emissions hinder efforts toward sustainable development goals and carbon emission efficiency, particularly in rapidly industrializing nations (Zhang et al., 2024; Imran et al., 2025). As a result, there has been a global push toward developing renewable and environmentally friendly biofuels to substitute conventional fossil fuels (Hojati et al. 2020; Saheban Alahadi et al. 2017; Shirneshan et al. 2014).

The *Terminalia catappa* tree, commonly known as the tropical almond, Indian almond, or beach almond, is a large, deciduous tree native to the tropical regions of Asia, Africa, and the Pacific. The tree can grow up to 35 meters tall and produces edible fruits that are almond-like in flavor, lending it the common name Indian almond (Sundararaju Perinbakannan et al. 2022; Muthukrishnan et al. 2022). The fruit of the *Terminalia catappa* tree is an oval drupe with a fibrous outer layer and a hard, woody shell. Within this shell is a single edible seed, often referred to as the kernel. These seeds are rich in oil, typically containing around 50%–60% oil by weight (Menkiti et al. 2015; Janporn et al. 2015), which makes them an excellent source for oil extraction. This oil is gaining recognition for its various potential applications, particularly in biofuel production, due to its fatty acid composition and high energy content.

Dos Santosa et al. (2008) characterized *Terminalia Catappa* (TC) oil for biodiesel applications. They extracted oil from TC kernels with a yield of approximately 49% by mass. The fatty acid composition of TC oil was found to resemble that of conventional oils used in biodiesel production. Using methanol and a conventional catalyst, they transesterified the crude oil to produce biodiesel. The resulting biodiesel met acceptable physicochemical standards for use in diesel engines, suggesting TC oil as a viable feedstock. Adewuyi et al. (2011) conducted further research on TC oil biodiesel production. Utilizing a two-step reaction process, they pretreated the oil with 2% sulfuric acid in methanol before performing transesterification with KOH as the catalyst. This method yielded biodiesel with an ester content above 97% and low phosphorus levels (<1 ppm). The biodiesel met European (EN 14214) and American (ASTM D6751-07b) fuel standards, reinforcing the potential of TC oil as a valuable biodiesel feedstock.

Iha et al. (2014) expanded on previous studies by comparing biodiesel produced from TC oil with *Carapa guianensis* (CG) oil, another species native to the Amazon and Brazilian coastline. This research aimed to promote biodiesel production that avoids food crop competition and supports rainforest preservation. Their findings confirmed that the physicochemical properties of biodiesel derived from both TC and CG oils met acceptable diesel engine standards, offering an economically promising alternative to fossil fuels. Sani et al. (2018) extracted TC oil through mechanical pressing and solvent extraction, achieving a high oil yield of 56.3%. They characterized the oil's properties, such as acid value, viscosity, and moisture content, using standard analytical methods. A two-stage esterification and transesterification process was employed to produce biodiesel. The biodiesel blends (B6, B10, and B20) produced from TC oil met ASTM D6751 and D7467 standards. This study confirmed that blending TC biodiesel with conventional diesel results in a fuel that complies with industry standards.

Muhammada et al. (2018) explored an innovative approach by using a CaO catalyst derived from snail shells to transesterify TC oil extracted with n-hexane. They analyzed the fuel properties of the resulting biodiesel, which included notable fatty acids such as hexadecanoic acid and 9,12-octadecadienoic acid. The biodiesel yield was 73.6% at optimal conditions of 60 °C and a reaction time of 120 minutes. Critical fuel properties, including density, pour point, and flash point, conformed to ASTM standards, underscoring TC oil's potential as a biodiesel feedstock. Ogbeide et al. (2021) focused on both the biodiesel potential and the additional applications of TC oil. The physicochemical properties of the biodiesel, such as specific gravity, flash point, and saponification value, met ASTM D6751 standards.

Research over the years has established *Terminalia catappa* oil as a viable biodiesel feedstock, showing compatibility with international fuel standards. Biodiesel from TC oil exhibits desirable fuel properties such as acceptable viscosity, flash point, and acid value, which conform to ASTM and EN standards. Consequently, *Terminalia catappa* oil presents a promising, multi-functional bioresource for sustainable energy and industrial applications. Research on tamarind seed biodiesel blends (Raju et al., 2020) and novel biodiesel sources (Subramani et al., 2019) provides additional benchmarks for evaluating the suitability of *Terminalia catappa* oil.

Despite many characterization studies are available in literature about TC biodiesel, the performance studies on diesel engine using TC biodiesel was not seen. Hence, there exists a research gap to focus on the performance, combustion and emission characteristics of diesel engine via TC. Further, to augment performance of TC in diesel engines, innovative solutions such as additives as well as thermal barrier coatings (TBCs) are toward be implemented. Venu et

al. (2019) explored the influence of TiO_2 nano-additives, revealing enhanced performance metrics.

Alumina (Al_2O_3) nanoparticles, when used as fuel additives, offer enhanced combustion efficiency due to their catalytic properties, which promote faster and more complete fuel oxidation, potentially lowering emissions and improving fuel economy (El-Seesy et al. 2018; Hosseini et al. 2017). The production of alumina nanoparticles typically involves methods such as sol-gel synthesis and chemical vapor deposition, which are energy-intensive and generate chemical waste that requires careful management. Similarly, lanthanum zirconate coatings are often produced via plasma spraying, which, while effective for high-temperature applications, consumes significant energy and generates by-products. The disposal of these materials poses challenges, particularly for alumina nanoparticles, which may exhibit environmental persistence and potential toxicity if not properly managed. Studies on the lifecycle assessment of such materials highlight the importance of adopting sustainable production methods and recycling strategies to mitigate their environmental footprint (Venu et al. 2022). While this study focuses on the performance characteristics of these materials, future work will aim to explore their lifecycle impacts in greater detail.

In parallel, TBCs such as lanthanum zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$) have been investigated for their ability to retain warmth inside burning chamber, which be able to enhance thermal effectiveness and reduce unburned hydrocarbon emissions. Lanthanum zirconate, in particular, is known in favor of excellent thermal steadiness, inferior thermal conductivity, plus resistance to elevated-temperature oxidation, building it promising choice in favor of TBCs (Mathivanan et al. 2024; Cihan et al. 2020) When used together, alumina nanoparticles and lanthanum zirconate coatings

may synergistically improve the combustion and emission characteristics of biodiesel-fueled diesel engines.

This study aims to evaluate the impact of alumina along with lanthanum zirconate TBC on performance diesel engine fueled through *Terminalia catappa* seed oil biodiesel. By investigating this combined approach, the study seeks to provide insights into optimizing biodiesel use in diesel engines, potentially contributing to cleaner and more efficient engine technology.

This study bridges a key research gap by evaluating *Terminalia catappa* biodiesel in diesel engines while uniquely integrating alumina additives plus lanthanum zirconate heat resistance layer aiming to boost combustion, effectiveness, and emissions. This dual-modification approach offers a novel, sustainable pathway for advanced biodiesel utilization in engine applications.

2. Materials and methods

2.1 *Terminalia catappa* seed preparation

Terminalia catappa fruit was collected from the *Terminalia catappa* tree growing in the local area of farm land situated Madurai, Tamilnadu, India. Fruits contained flesh at outer layer, hard inner shell and seed similar to groundnut at the inside of hard shell. Flesh was soft layer, eatable, which was removed manually. Hard shell was broken by hammer and seed was taken out. Collected seeds were dried under sunlight in cleaned surface for 10 days. Dried seeds were processed into powder form by grinding it using the mechanical grinder and preserved in airtight chamber to avoid moisture absorption

2.2 Terminalia catappa oil preparation

Terminalia catappa oil was extracted from its seed powder using Soxhlet extractor (Soxtron, semi, rectangle shape). The powders were mixed with solvent (hexane) and allowed to dissolve about 10 hours. The residue was separated from the oil and solvent solution. Finally, the oil and solvent solution was heated to evaporate the solvent. The pure oil was collected.

2.3 Biodiesel production

<Figure 1>

<Table 1>

Biodiesel was generated from Terminalia catappa oil through a transesterification process carried out in a reactor (Capacity: 3KL, Pressure: 10 kg). Figure 1 illustrates each step involved in biodiesel production. First, oil (1 litre) was warmed 65 °C. NaOH (14 g) in solution form disintegrated in 180 ml methanol was then added to the heated oil in the reactor. The mixture was vigorously stirred using a magnetic stirrer at 600 rpm for one hour to ensure thorough mixing. Mixture was permitted at surrounding temperature (30 °C) after allowing reaction. Finally, relocated in separatory funnel (8 hours). During this period, glycerin settled at the bottom due to gravity. Finally, the methyl esters (biodiesel) and glycerin were separated through filtration.

Terminalia catappa biodiesel was characterized to understand the different properties of biodiesel as detailed in the Table 1.

2.4 Biodiesel blending

<Figure 2>

<Table 2>

<Table 3>

Biodiesel blends were prepared by simple blending method. Firstly, the diesel was poured in the blending container and then biodiesel was added with it gently. This mixture was stirred well about 20 minutes and kept at room temperature for 30 minutes. The dispersion of alumina nanoparticles into the biodiesel was achieved through a sonication procedure, with the characteristics of the nanoparticles detailed in Table 2. Figure 2 shows the SEM image of alumina nanoparticles. Utilizing an ultrasonicator, the Al_2O_3 (50 ppm) particles were dispersed within biodiesel medium. To ensure homogeneity, the dispersion process endured for approximately 45 minutes, facilitating a well-mixed blend.

The dispersion stability of the nano-biodiesel blend was evaluated under static storage conditions at ambient temperature ($25 \pm 2^\circ\text{C}$) in sealed glass containers. The blend remained visually stable for up to 92 hours (~ 3.8 days), with no visible signs of sedimentation or phase separation during this period. This short-term stability assessment indicates good initial dispersion of nanoparticles; however, further studies with extended storage durations (e.g., 30 to 90 days) under variable climatic conditions are necessary to establish long-term fuel stability.

The different fuel blends prepared in this investigation is detailed in Table 3. Nanoparticles improve the wear performance of engine components when used with biodiesel, but their formulation, concentration, and dispersion must be optimized to avoid adverse effects.

Long-term durability studies are critical for realizing their full potential in practical applications (Bala Prasad et al. 2020).

2.5 Thermal barrier coating

<Figure 3>

<Table 4>

Figure 3(a) shows the thermal barrier coating process. Lanthanum Zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$) thermal layer was applied over engine components by plasma spray principle (Venu et al. 2019; Domakonda et al. 2019). Lanthanum Zirconate powder of 99.8% purity and 30–50 μm particle range was used. Parameters for the coating process, including specific settings for spray distance, plasma temperature, feed rate, and other relevant conditions, are provided in detail in Table 4. These carefully controlled parameters ensure a high-quality and durable coating, essential for the thermal insulation and wear resistance required in engine applications. Figure 3(b) shows the image of coated piston

2.6 Experimental

<Figure 4>

<Table 5>

The experimental investigation was carried out using a single-cylinder, four-stroke, water-cooled diesel engine. Initially, tests were performed using D100 (pure diesel) and B100 (pure Terminalia catappa biodiesel) on an uncoated engine. Subsequent tests were conducted

with B20 fuel (20% biodiesel and 80% diesel) under both coated and uncoated engine conditions. The specifications of the engine are provided in Table 5, and Figure 4 shows the actual photograph of the experimental test setup, including the engine, eddy current dynamometer, and emission measurement instruments.

Before testing, the engine was allowed to warm up at idle speed for 30 minutes using D100 fuel to stabilize the operating conditions. During testing, the engine was run at a constant speed of 1500 rpm, and loads ranging from 0 to 10 kg were applied incrementally using the eddy current dynamometer. Fuel consumption and air intake were measured, while temperatures were recorded using calibrated K-type thermocouples. Emissions were monitored using an AVL 437C Smoke Meter and an AVL 437 DUO Gas Analyzer to measure CO, HC, and NO_x.

To prepare the nanoparticle-enhanced blend (B20ALC), alumina (Al₂O₃) nanoparticles were accurately weighed (50 mg for 1 liter of fuel) using a high-precision analytical balance. The nanoparticles were then dispersed into the B20 blend using an ultrasonic bath sonicator for 45 minutes to ensure uniform distribution. Stability tests confirmed that the nanoparticle dispersion remained homogeneous for up to 92 hours without noticeable sedimentation.

Each experimental run was repeated three times under the same conditions to ensure repeatability and reliability. All instruments were calibrated prior to testing, and uncertainty analysis was performed as reported in Section 2.7.

2.7 Uncertainty analysis

<Table 6>

Error bars are used to indicate the uncertainty associated with each measurement. A comprehensive uncertainty analysis for equipment and measured parameters are presented in Table 6(a) and Table 6(b) respectively. The uncertainties in Table 6(b) indicate reliable measurements, with low values for critical parameters like fuel mass flow rate ($\pm 0.02\%$) and brake power ($\pm 0.51\%$), ensuring accurate performance evaluation. The $\pm 1\%$ uncertainty in brake thermal efficiency reflects careful error propagation, confirming confidence in experimental results under controlled conditions and calibrated instrumentation.

3. Results and discussion

3.1 Brake specific fuel consumption

<Figure 5>

Figure 5 depicts association amid Brake BSFC along with BP for a diesel engine running on Terminalia catappa seed oil blended with alumina nanoparticles. The findings indicated that pure diesel (D100) had smallest BSFC than biodiesel blends. Higher BSFC in B20 and B100 blends was credited to lower calorific values (Table 1) compared to D100, necessitating more fuel to achieve the same output (Mathivanan et al. 2024). Additionally, the higher viscosity of the bio-fuels (Table 1) resulted in suboptimal air-fuel mixing plus incomplete burning, supplementary rising BSFC. Alike trends were observed with Elkelawy et al. (2021). BSFC was also observed to decrease with increasing BP, likely due to enhanced vortex plus improved burning efficiency, matching through the findings of Srihari et al. (2017) and Can et al. (2017).

B20C established inferior BSFC than B20 because of augmented cylinder temperatures plus improved burning resulting from thermal barrier effect of the coating. This effect retained heat within the cylinder, advancing more competent firing and thereby reducing BSFC. Furthermore, the B20ALC blend showed a further decrease in BSFC when compared to both B20 and B20C. This improvement was likely due to the inclusion of alumina nanoparticles, whose oxygen content aided combustion, leading to lower BSFC values (Pandian et al., 2017; Caliskan et al., 2017). At full load, B20ALC accomplished smallest BSFC, recorded at 0.18 kg/kW.hr, marking 10% lessening than D100. These findings were consistent with Sivakumar et al. (2018), who presented 0.34 kg/kW.hr BSFC for Pongamia oil with Al_2O_3 , stressing positive concerning nanoparticles on heat transfer efficiency.

3.2 Brake thermal efficiency

<Figure 6>

Figure 6 presents BTE results of a DI engine functioning on Terminalia catappa seed oil blended with alumina nanoparticles. The results indicated that BTE augmented through BP because of better firing and bargain BSFC (Chelliah et al. 2024). B100 demonstrated inferior BTE than D100, mainly due to its lower calorific value. However, the B20 blend demonstrated a higher BTE than B100, benefiting from an optimal diesel-to-biodiesel ratio. Notably, B20C exhibited the highest BTE among all fuels. Thermal layer reduced energy dissipation, leading to enhanced disintegration and volatilization, which in turn improved combustion and energy extraction from the fuel. This resulted in B20C showing superior BTE compared to supplementary fuel blends, matching through Krishnamani et al. (2016), who found that a coated engine using rapeseed oil achieved better BTE than an uncoated engine. Additionally, B20ALC

surpassed B20C in BTE due to the introduction of alumina nanoparticles. These nanoparticles improved atomization, facilitating fuel evaporation and combustion, and provided efficient heat transfer, further boosting combustion and BTE. The findings showed that B20ALC reached a BTE of 33%, marking a 6.4% increase over D100, under full load conditions. Al-Kheraif et al. (2021) similarly found that CI engine fueled by Candle nut-Soap nut with Al_2O_3 nanoparticles achieved better BTE because of better firing supported by nanoparticles.

3.3 Carbon monoxide

<Figure 7>

Figure 7 presents carbon monoxide (CO) outflow from DI engine powered by blends of Terminalia catappa seed oil with alumina nanoparticles. As BP increased, CO emissions also rose because of advanced fuel contribution (Senniangiri et al. 2024). Across all BP levels, D100 displayed the highest CO emissions in comparison to biofuel blends such as B100, B20, and B20C. This reduction in CO emissions for biofuels was attributed to the oxygen content in biofuels, which promoted the conversion of CO to CO_2 . Among the biofuels, B100 had advanced CO outflow than B20, primarily due to elevated viscosity, which caused unfinished burning plus, consequently, more CO formation. Conversely, B20C exhibited lower CO emissions than B20. This decrease was linked to the elevated cylinder temperature achieved with B20C, enhancing fuel combustion and dipping CO outflow. The accumulation of alumina to B20C further contributed to a significant reduction in CO emissions. This improvement was due to the combined oxygen content from the nanoparticles and the biofuel, which supported complete combustion, thereby lowering CO emissions. Notably, B20ALC achieved a low CO emission of 0.051 vol% under full load, marking reductions of 43% compared to D100. Similarly, Raju et al.

(2021) observed a reduction in CO emissions to 0.26 vol% in a diesel engine using mango seed oil with Al_2O_3 nanoparticles, underscoring the beneficial impact of nanoparticles on emission control.

3.4 Hydrocarbon

<Figure 8>

Figure 8 illustrates the hydrocarbon (HC) expel commencing a DI engine functioned through blends of Terminalia catappa seed oil and alumina nanoparticles. The data revealed that HC outflow augmented by higher BP, since the engine demanded additional fuel, resulting in a richer fuel mixture and incomplete combustion under higher loads. This unfinished burning contributed to elevated HC outflow. D100 created elevated HC outflow than biofuel alternatives, such as B100 and B20, which emitted less due to the oxygen content in biofuels that promoted more complete combustion. Among these biofuels, B20 showed even lower HC emissions than B100, likely by inferior viscosity, which improved burning competence. B20C demonstrated the lowest HC emissions of all because of thermal layer that minimized energy dissipation and raised cylinder temperatures, thus enhancing combustion and reducing HC outflow. Accumulation of alumina to B20C led to even further reductions in HC emissions. This reduction was credited by supplementary oxygen from nanoparticles, which promoted more efficient firing. Under full load, B20ALC achieved a hydrocarbon emission level of 31 ppm, representing a reduction of 13.8% compared to D100. Correspondingly, research by Tamilvanan et al. (2019) on CI engines with Tamanu oil and copper nanoparticles reported an HC emission level of 52 ppm, emphasizing the nanoparticles function in augmenting combustion efficiency in addition to dipping HC outflow.

3.5 Smoke opacity

<Figure 9>

Figure 9 displays the smoke opacity measurements for a direct injection engine fueled with Terminalia catappa seed oil combined with alumina nanoparticles. Results indicated that smoke opacity rose with increasing BP, which could be attributed to better-off fuel-air combination required at advanced BP stage. This richer mixture and incomplete combustion led to increased smoke formation. D100 exhibited the highest smoke outflow in relation to biofuel blends like B100 as well as B20. The oxygen content in these biofuels supported more absolute burning, resulting in abridged smoke expel. B100 had lowest smoke outflow since of higher oxygen presence compared toward B20. When comparing B20, B20C showed a further reduction in smoke opacity. The thermal coating enhanced combustion by minimizing heat loss, thus lowering smoke emissions in B20C relative to B20. The blend with nanoparticles, B20ALC, showed the lowest smoke opacity, reaching 45%, which is 10% lower than D100. The presence of nano-additives improved combustion by accelerating the fuel evaporation rate, thus enhancing combustion efficiency and minimizing smoke formation.

3.6 Nitrogen oxide

<Figure 10>

Figure 10 illustrates the NO_x emissions from a CI engine fueled by Terminalia catappa seed oil blended with alumina nanoparticles. At lower BP, NO_x emissions were lower, while at higher BP, NO_x emissions rose, primarily due to increased cylinder temperatures because of more fuel deliver on elevated loads. D100 had lowest NO_x emissions, whereas B100 produced higher NO_x levels due to incomplete combustion, leading to increased NO_x formation as

unburned nitrogen reacted with oxygen. B20 showed reduced NO_x emissions compared to B100 because it contained a smaller proportion of biofuel in the blend. Comparing NO_x emissions from B20C and B20, the B20C showcased advanced NO_x outflow because of greater cylinder heat from lower heat denial in layered engine. Emissions from B20ALC were higher than those from B20C and B20. The addition of alumina nanoparticles contributed to amplified fuel vaporization, combustion charge, warmth discharge, plus drive out gas temperature, which collectively caused augment toward NO_x expel. In this study, B20ALC showed a peak NO_x emission of 702 ppm.

3.7 Peak cylinder pressure

<Figure 11>

Figure 11 presents the crest cylinder pressure consequences for CI engine fueled with a blend of Terminalia catappa seed oil and alumina nanoparticles. The D100 fuel exhibited higher peak cylinder pressure than both B100 plus B20 because of D100's better burning uniqueness arising because of advanced calorific worth and inferior viscosity than biofuels. Increased crest cylinder pressure noted with D100 could be credited to a larger portion of energy being fired throughout premixed burning stage (Gad et al. 2022). Biodiesel blends tend to produce lower pressures than diesel because of lowered fuel use in pre-blended stage and reduced detonation delay. The primary contributor to elevated crest cylinder pressure of D100 was the larger amount of fuel consumed in this initial combustion stage. The B20 blend demonstrated advanced cylinder pressure in relation to B100, probable due to its more efficient combustion relative to B100. Additionally, the B20C blend (with coating) showed increased cylinder pressure in relation to B20 because of enhanced cylinder temperature provided by thermal layer, which

promotes supplementary complete burning. Finally, B20ALC blend exhibited the highest peak cylinder pressure, attributed to advancement in heat discharge pace, heat transfer capability, in addition to vaporization pace due to presence of alumina nanoparticles. In this study, B20ALC achieved a maximum crest cylinder pressure of 75 bar.

3.8 Maximum heat release rate

<Figure 12>

Figure 12 displays Heat Release Rate (HRR) consequences for CI engine fueled with a blend of Terminalia catappa seed oil and alumina nanoparticles. D100 fuel demonstrated advanced HRR than both B100 plus B20, largely because of advanced calorific value, which supports supplementary resourceful burning and consequently releases better heat power. In contrast, biofuels such as B100 plus B20 have inferior calorific values and higher viscosities than D100, factors that tend to reduce combustion efficiency and result in lower heat release. Additionally, B20C showcased a advanced HRR in relation to B20. The coating helps retain more heat within the cylinder, decreasing thermal loss to the surroundings, which increases cylinder temperature and enhances combustion efficiency. Thus, the coated engine configuration showed an improved HRR over the uncoated setup. Moreover, the results showed an increase in HRR for B20ALC, likely due to the presence of nanoparticles that promote better atomization, vaporization, and overall combustion efficiency. In this study, B20ALC achieved a peak HRR of 73 kJ/m³ deg, indicating its enhanced performance.

3.9 Comparative results

<Table 7>

The table 7 presents the performance and emissions outcomes of a diesel engine operated at full load (3.5 kW brake power) using different types of biodiesel (B20 blend). Among the biodiesel types studied, *Terminalia catappa* seed oil achieved the BTE of 30%, along with small BSFC of 0.22 kg/kW.hr, and moderate emissions with 0.07 vol% CO, 686 ppm NO_x, 33 ppm HC, and 47% smoke opacity. Algae biodiesel, as reported by Subramaniam et al. (2020), demonstrated a lower BTE of 26% and BSFC of 0.3 kg/kW.hr, but achieved the lowest CO emissions (0.03 vol%) and relatively low NO_x (380 ppm), HC (15 ppm), and a smoke opacity of 60%. Tamarind seed oil, examined by Harun Kumar et al. (2020), showed a BTE of 29% but recorded the highest NO_x emissions (1700 ppm) and a smoke opacity of 40%, with 0.07 vol% CO and 75 ppm HC.

Other biodiesels, such as cotton seed oil and linseed oil, displayed varying emission characteristics. Cotton seed oil, as studied by Yesilyurt et al. (2020), showed the lowest BTE (18%) and high smoke opacity (71%). Linseed oil, tested by Uyumaz et al. (2020), achieved a BTE of 29% and NO_x emissions of 570 ppm. *Jatropha* seed oil, analyzed by Gad et al. (2021), demonstrated a moderate BTE (25%) with the lowest smoke opacity (30%). *Prosopis Juliflora* biodiesel, as reported by Duraisamy et al. (2023), exhibited a BTE of 29%, high NO_x emissions (1300 ppm), CO emissions of 0.35 vol%, and a smoke opacity of 55%. Lastly, coffee husk biodiesel, studied by Emma et al. (2022), presented a BTE of 28%, CO emissions of 0.45 vol%, NO_x emissions of 900 ppm, HC emissions of 50 ppm, and a smoke opacity of 46%.

This comparative analysis revealed the variability in performance and emissions among different biodiesel sources, highlighting Terminalia catappa seed oil, algae, and Jatropha seed oil as promising options for balancing efficiency and emissions.

<Table 8>

The outcomes presented in Table 8 demonstrate the performance and emission characteristics of diesel engines operating with various biodiesel blends (B20) combined with different nanoparticles under full load conditions (BP = 3.5 kW). These results highlight the influence of biodiesel feedstock and nanoparticle type on engine efficiency and emissions.

Among the biodiesel blends tested, Terminalia catappa seed oil with Al_2O_3 nanoparticles achieved the highest BTE at 33%, indicating superior energy conversion efficiency. This could be attributed to the enhanced combustion properties provided by the Al_2O_3 nanoparticles, such as improved atomization and heat transfer characteristics. In contrast, parsley biodiesel with TiO_2 nanoparticles exhibited the lowest BTE at 24%, suggesting less efficient combustion, possibly due to differences in biodiesel composition or nanoparticle interaction.

The BSFC values reflect the fuel required to produce a unit of power. Terminalia catappa seed oil with Al_2O_3 demonstrated the lowest BSFC at 0.18 kg/kW.hr, highlighting its efficiency in fuel utilization. Conversely, algae and avocado biodiesel blends, both with Al_2O_3 and SnO_2 nanoparticles, recorded higher BSFC values of 0.29 kg/kW.hr. These higher BSFC values may be attributed to differences in the calorific value of the biodiesel blends or incomplete combustion characteristics.

CO emissions were lowest for avocado biodiesel with Al_2O_3 nanoparticles (0.028 vol%), signifying effective combustion. In comparison, Simarouba biodiesel with graphene nanoparticles recorded the highest CO emission (0.2 vol%), likely due to incomplete oxidation of carbon in the fuel. NO_x emissions were highest for Simarouba biodiesel with graphene nanoparticles (1150 ppm), potentially due to the elevated combustion temperatures associated with graphene's thermal conductivity. Conversely, avocado biodiesel with Al_2O_3 produced the lowest NO_x emissions (521 ppm), indicating a lower peak combustion temperature. Avocado biodiesel recorded the highest HC emissions (73 ppm), suggesting incomplete combustion. Terminalia catappa seed oil with Al_2O_3 nanoparticles achieved the lowest HC emissions (31 ppm), indicating improved combustion efficiency due to nanoparticle catalysis. Smoke opacity, an indicator of particulate emissions, varied significantly among the biodiesel blends. Terminalia catappa seed oil with Al_2O_3 nanoparticles demonstrated relatively low smoke opacity (45%), whereas Simarouba biodiesel with graphene recorded the highest smoke opacity (75%). The high smoke opacity with graphene could be attributed to its particle agglomeration or incomplete combustion of the biodiesel.

The current study's findings on Terminalia catappa seed oil with Al_2O_3 nanoparticles stand out in terms of efficiency and reduced emissions. It consistently achieved higher BTE, lower BSFC, and minimized emissions of CO, HC, and smoke opacity compared to other blends. This suggests that Al_2O_3 nanoparticles effectively enhance combustion processes and mitigate pollutant formation. On the other hand, biodiesel blends such as Simarouba with graphene nanoparticles exhibited poorer emission performance, highlighting the need for optimization in nanoparticle formulation and dispersal. The results underline the critical role of nanoparticle type and biodiesel feedstock in influencing diesel engine performance and emissions. Terminalia

catappa seed oil with Al_2O_3 nanoparticles emerged as a promising combination for achieving improved engine efficiency and reduced environmental impact.

3.10 Economic and environment feasibility of alumina nanoparticles and lanthanum zirconate coating

While the primary focus of this study was on improving engine performance and emission characteristics using nano-biodiesel and thermal coatings, the economic viability of the proposed modifications is also critical for real-world application.

Al_2O_3 nanoparticles were used at a concentration of 50 ppm, resulting in an approximate cost of \$0.006 per liter of fuel, a negligible increase considering the associated improvements in combustion and emission performance. The lanthanum zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$) thermal barrier coating, applied via plasma spraying, incurs a one-time cost of \$80–\$120. Literature suggests a coating service life of 500–1000 hours (Cihan et al. 2020; Mathivanan et al. 2024), providing extended durability and thermal efficiency gains that can reduce long-term engine wear and fuel consumption.

These findings suggest that the combined use of low-dose nano-additives and thermal barrier coatings is economically justifiable, especially in applications requiring high engine efficiency and lower emissions.

Alumina (Al_2O_3) nanoparticles, despite their catalytic advantages in combustion enhancement, may pose potential ecological risks. Literature indicates that their small size enables environmental persistence, and their inhalation or leaching into soil or water bodies may

lead to toxic effects in aquatic organisms and disruption of microbial ecosystems. Although Al_2O_3 is considered less toxic than other engineered nanomaterials, its bioaccumulation in aquatic species and sedimentation in ecosystems warrants careful handling and disposal protocols.

Lanthanum zirconate coatings contain rare earth elements, which raise sustainability and toxicity concerns associated with rare earth mining and material disposal. Lanthanum-based compounds may pose moderate environmental hazards during production and end-of-life, including soil contamination or air emissions from wear or flaking of coatings during engine operation.

We recognize the concern that nanoparticles can be released into the atmosphere during fuel handling, combustion, or disposal. Although in this study the Al_2O_3 particles were tightly suspended within the fuel medium and no airborne particle release was detected during operation, this aspect needs further investigation under long-term operational conditions, especially regarding emission residues and filter trapping efficiency.

4. Conclusion

This research investigated the impact of Terminalia catappa seed oil biodiesel blended with alumina nanoparticles and thermal coatings on the performance, emissions, and combustion behavior of a diesel engine. The main findings of the study are summarized as follows:

- At full load, the B20ALC blend recorded the lowest BSFC 0.18 kg/kW.hr, which depicts a 10% drop in relation to D100. This improvement was attributed toward better burning efficiency, facilitated by oxygen content in alumina nanoparticles.

- For BTE, B20ALC achieved a value of 33% at full load, marking a 6.4% increase over D100. This boost in efficiency was due to declined warmth loss, upgraded fuel fragmentation and gasification, and healthier burning performance.
- In provisions of outflow, B20ALC demonstrated a considerable reduction in CO, reaching 0.051 vol% at full load, 43% lower than D100. Additionally, HCs were reduced to 31 ppm, a 13.8% decrease compared to D100. These reductions could be attributed to the oxygen content in both the biofuel and nanoparticles, which supported more complete combustion. The engine's thermal coating further contributed to lower HC and CO emissions by maintaining higher cylinder temperatures, promoting better combustion.
- B20ALC also exhibited the lowest smoke opacity at 45%, 10% lower than D100, owing to improved heat retention and enhanced fuel evaporation, which resulted in more efficient combustion.
- Finally, B20ALC demonstrated a higher peak cylinder pressure (75 bar) in addition to heat release rate ($73 \text{ kJ/m}^3 \cdot ^\circ\text{C}$) compared to D100, reflecting the improvements in combustion efficiency streamlined by addition of alumina particles.

The study highlights the superior performance of the B20ALC blend (80% diesel, 20% biodiesel, alumina nanoparticles) in a coated diesel engine, achieving 10% lower BSFC, 6.4% higher BTE, 43% CO reduction, 13.8% HC reduction, 10% less smoke opacity, and enhanced combustion with higher peak pressure (75 bar) and heat release. In summary, the addition of alumina nanoparticles and thermal coatings to Terminalia catappa seed oil biodiesel significantly enhanced engine performance, fuel efficiency, and emission reduction, creating it a capable alternative energy in favor of diesel engines.

The findings of this study hold international significance, particularly for countries striving to reduce reliance on fossil fuels and improve air quality. The integrated use of *Terminalia catappa* biodiesel with alumina nanoparticles and lanthanum zirconate TBCs provides a scalable solution adaptable to diverse geographic and economic contexts. This approach can support global energy sustainability goals by offering cleaner combustion alternatives in both developing and developed nations, especially where biodiesel feedstocks and waste materials are underutilized.

5. Recommendations for Future Studies:

- Examine the prolonged impact of biodiesel blends enhanced with nanoparticles on engine longevity and component wear.
- Carry out comprehensive life cycle analyses to assess the environmental implications of using alumina nanoparticles and thermal barrier coatings, from their manufacturing and operational use to their disposal.
- Investigate the potential of combining alternative additives with advanced thermal barrier layers to further improve combustion efficiency and exhaust characteristics.
- Perform experimental evaluations under diverse load and speed scenarios to gain deeper insights into engine performance and combustion dynamics.
- Lifecycle assessments (LCA) of nanoparticles and coatings from synthesis to disposal.
- Ecotoxicological studies examining nanoparticle interaction with air, soil, and water environments.
- Emission residue characterization, especially post-combustion particulate analysis to detect potential nanoparticle presence in exhaust systems.

- Safety protocols for handling, storage, and disposal of nanoparticle-blended fuels.

Declarations

Ethics approval

This material is the authors' own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Conflicts of interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication

Author's contribution

P. Venkatesh: Planning, execution of research, plotting of results and manuscript preparation

B. Kumaragurubaran: Planning, execution and manuscript preparation

J. Bensam Raj: Materials collection, experimental facility and manuscript preparation

C. Ramesh Kumar: Data processing, software handling and manuscript preparation

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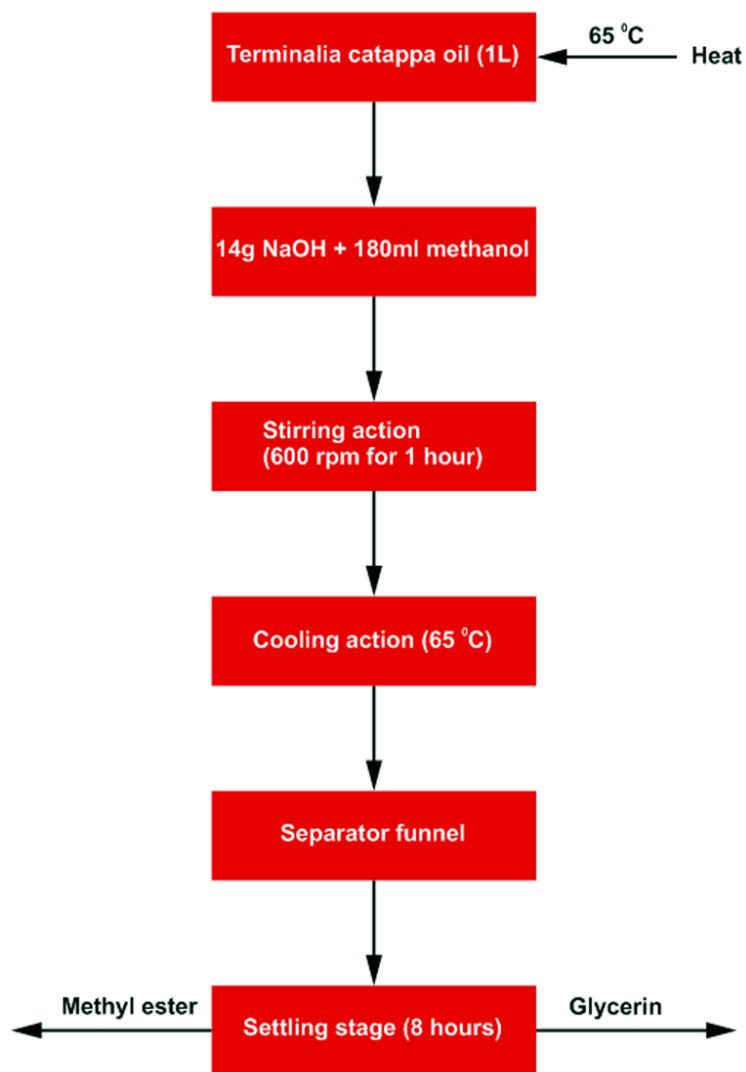


Figure 1 Biodiesel production steps

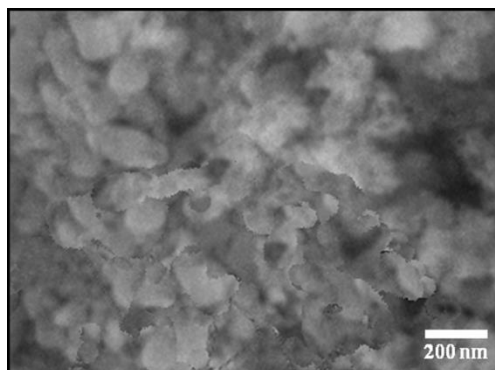


Figure 2 SEM image of alumina nanoparticles

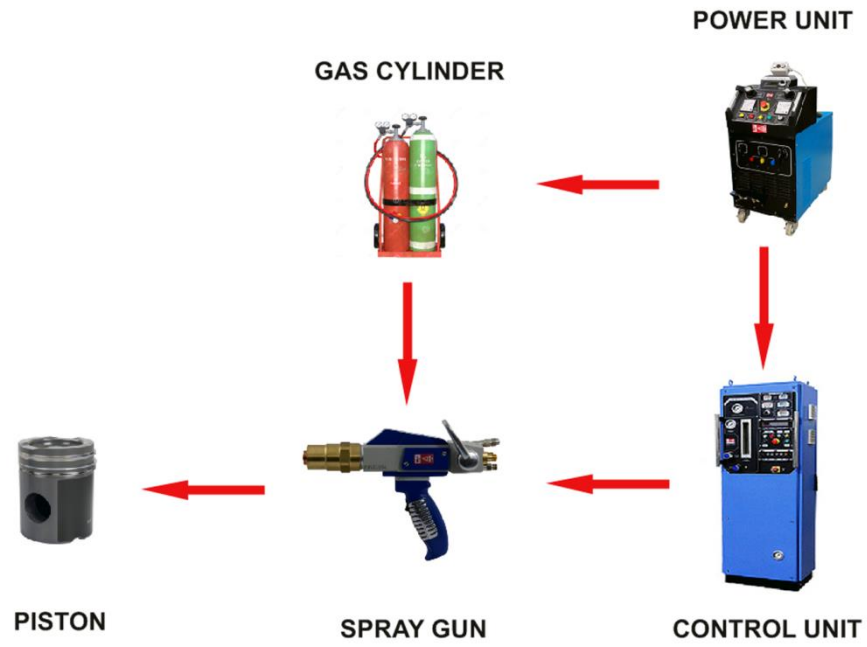


Figure 3(a) Thermal barrier coating process

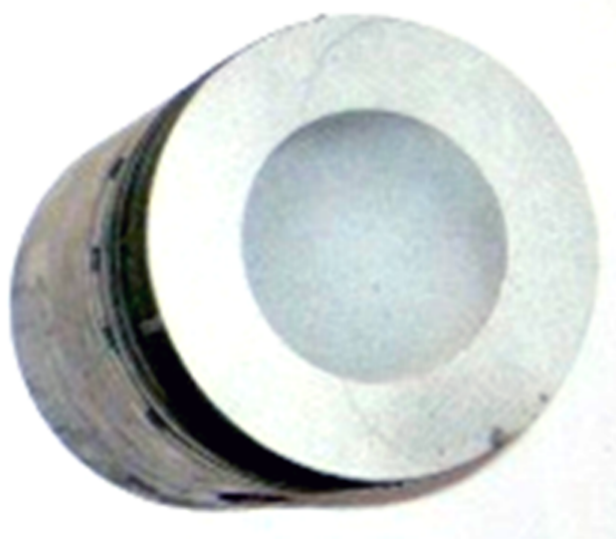


Figure 3 (b) Coated pistons

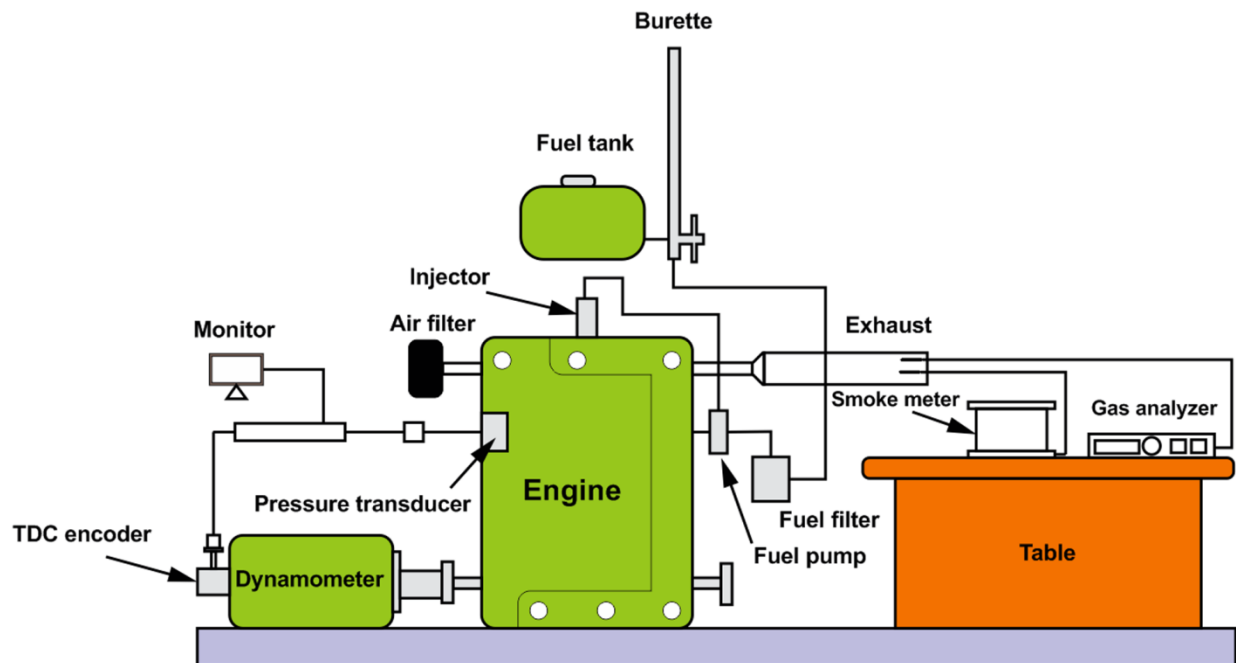


Figure 4(a) Schematic representation of experimental setup



Figure 4(b) Photo of experimental setup

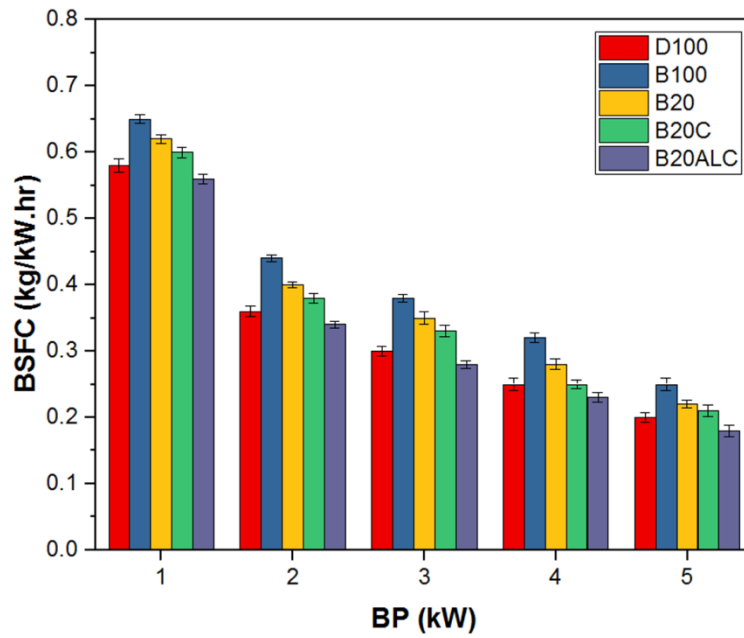


Figure 5 BSFC outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

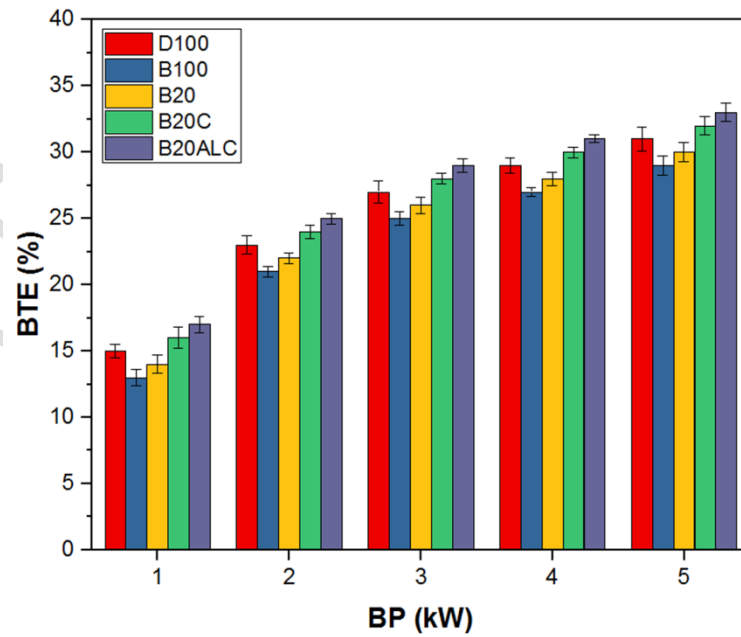


Figure 6 BTE outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

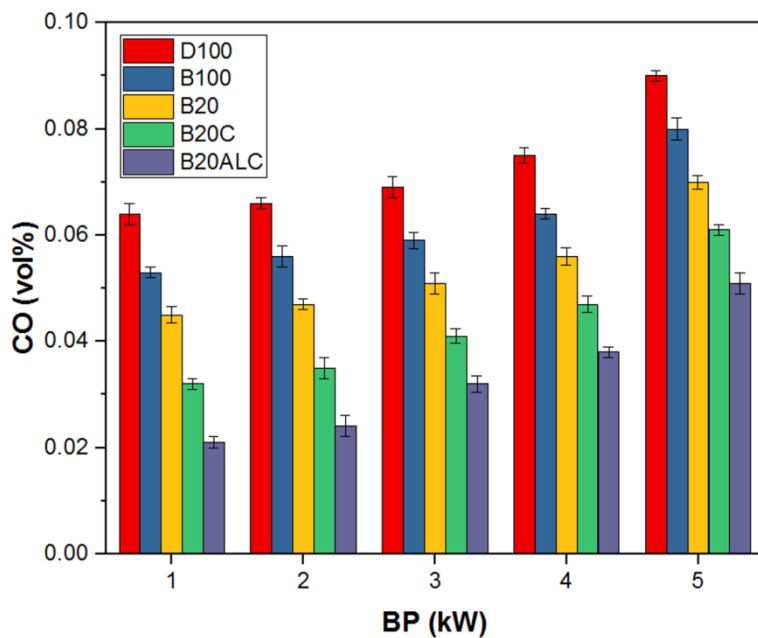


Figure 7 CO outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

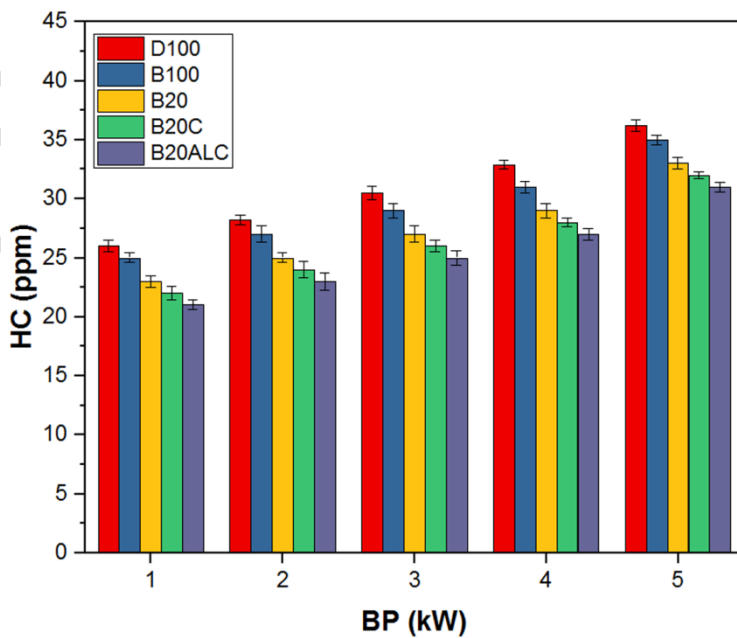


Figure 8 HC outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

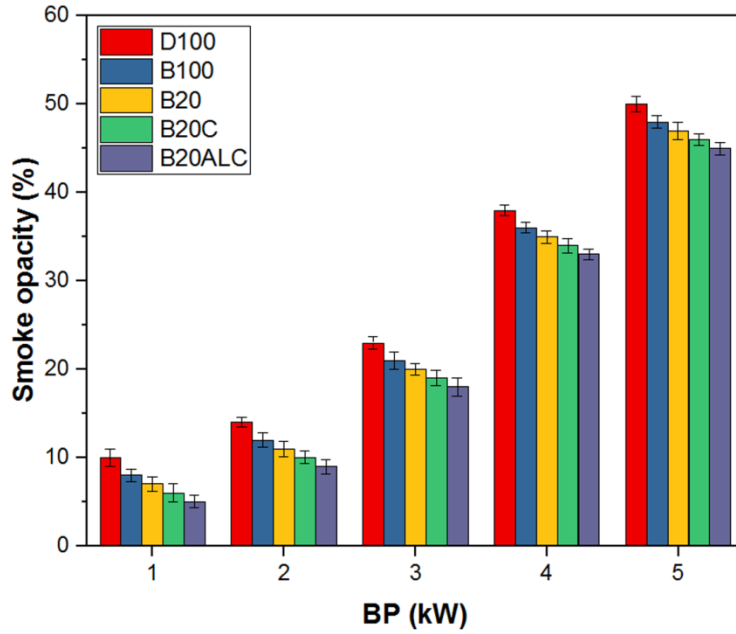


Figure 9 Smoke opacity outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

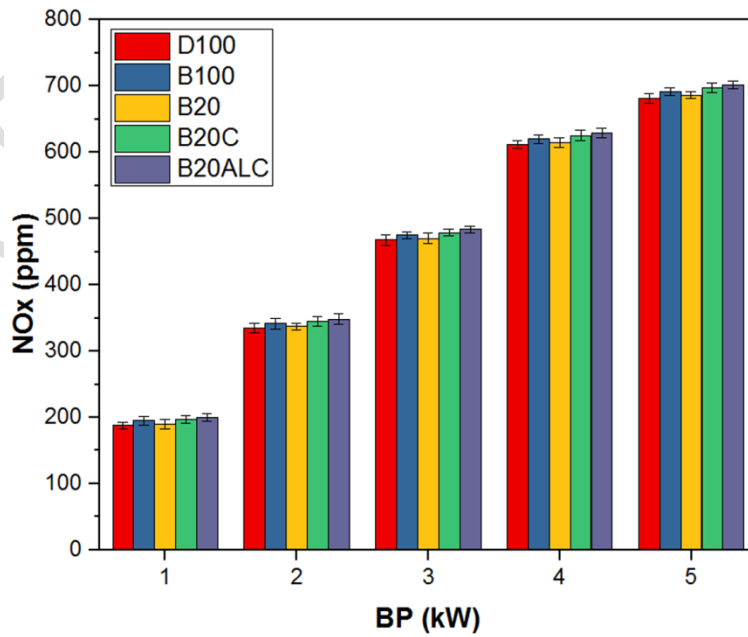


Figure 10 Nitrogen oxide outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

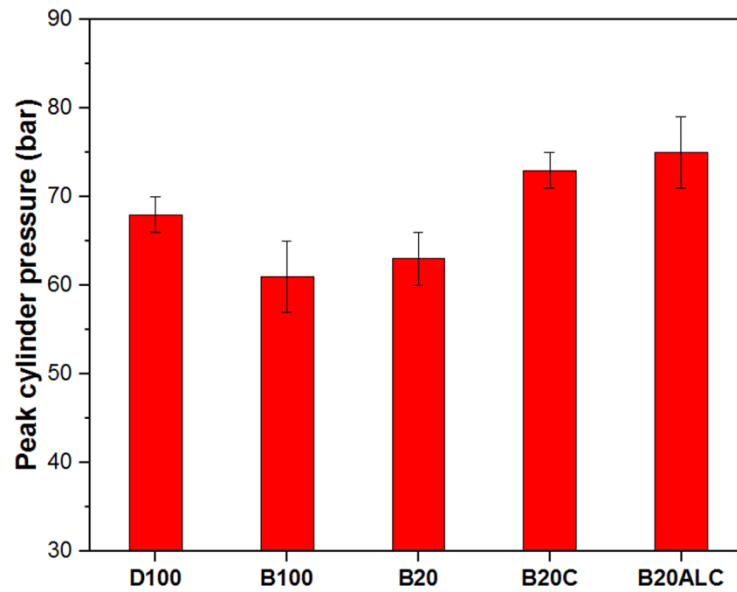


Figure 11 Peak cylinder pressure outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

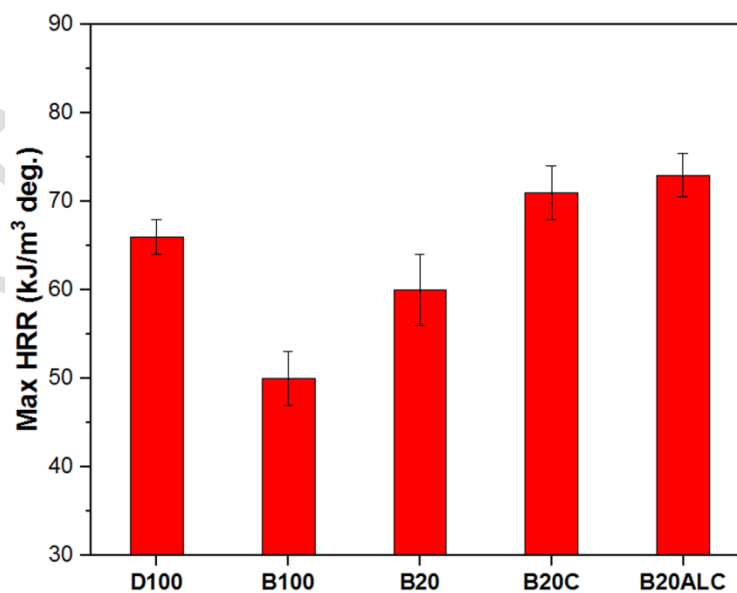


Figure 12 Maximum heat release rate outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

Table 1(a) Testing methods for fuel properties

| Fuel properties | Method |
|------------------------|---------------|
| Density | ASTM D4052 |
| Viscosity | ASTM D445 |
| Cetane number | ASTM D613 |
| Flash point | ASTM D976 |
| Fire point | ASTM D976 |
| Calorific value | ASTM D240 |

Table 1(b) Properties of fuels

| Properties | D100 | B100 | B20 | B20 + Al₂O₃ |
|---|-------------|-------------|------------|--|
| Density (kg/m ³) at 15 °C | 828 | 872 | 847 | 852 |
| Viscosity (mm ² /s) at 40 °C | 3 | 4.32 | 3.71 | 3.83 |
| Cetane number | 50 | 55 | 52 | 54 |
| Flash point (°C) | 53 | 153 | 85 | 81 |
| Calorific value (KJ/kg) | 44680 | 43122 | 39010 | 39265 |

Table 2 Characteristics of Al₂O₃ nanoparticles

| Property | Al ₂ O ₃ nanoparticles |
|------------------------------|--|
| Size (nm) | 50 - 100 |
| Shape | Spherical |
| Density (g/cm ³) | 2.6 |
| Thermal conductivity (W/mK) | 30 |
| Melting point (°C) | 2050 |

Table 3 Fuel blends used

| Fuels | Blending details | Coating condition |
|--------|---|-------------------|
| D100 | 100% diesel | No |
| B100 | 100% Terminalia catappa oil | No |
| B20 | 80% diesel + 20% Terminalia catappa oil | No |
| B20C | B20 | Yes |
| B20ALC | B20 + 50 ppm Al ₂ O ₃ | Yes |

Table 4 Parameters maintained while coating (Mathivanan et al. 2024)

| Parameters | Values |
|--------------------------------|---------|
| Distance of spray | 130 mm |
| Intensity of arc current | 660 A |
| Flow rate of carrier gas | 4 slpm |
| Hydrogen (Secondary) flow rate | 16 slpm |
| Argon gas (Primary) flow rate | 30 slpm |

Table 5 Engine's parameters

| Description | Details |
|-------------------|------------------------------------|
| Engine type | 1 cylinder, 4-stroke, water cooled |
| Compression ratio | 17.5 |
| Bore × stroke | 87.5 mm × 110 mm |
| Maximum power | 5.2 kW |
| Capacity | 661 cm ³ |

| | |
|-------------------|------------------------|
| Injector pressure | 220 kg/cm ² |
| Injection timing | 23 ° BTDC |
| Injection type | Direct |
| Speed | 1500 |
| Dynamometer | Eddy current |

Table 6(a) Equipment uncertainty particulars

| Parameters | Range | Accuracy | Uncertainty (%) |
|-------------|--------------|-----------|-----------------|
| Pressure | 0 to 110 bar | ± 0.1 bar | ±0.1 |
| Temperature | 0 to 900 °C | ± 1 ° C | ±0.1 |
| Crank angle | - | ± 1 ° | ±0.2 |
| Load | 0 to 100 kg | ±0.1 kg | ±0.2 |

| | | | |
|-----------------|-----------------|---------------|------------|
| Smoke | 0 to 100% | $\pm 1\%$ | ± 1 |
| NO _x | 0 to 5000 ppm | ± 10 ppm | ± 0.01 |
| HC | 0 to 100000 ppm | ± 20 ppm | ± 1 |
| CO | 0 to 10% | $\pm 0.02 \%$ | ± 0.2 |

Table 6(b) Measured parameters uncertainty particulars

| Measured variable | Uncertainty (%) |
|---------------------------------|-----------------|
| Mass flow rate of air | ± 0.52 |
| Mass flow rate of fuel | ± 0.02 |
| Brake power | ± 0.51 |
| Brake specific fuel consumption | ± 1.2 |
| Brake thermal efficiency | ± 1 |

Table 7 Outcomes of diesel engine operated with different biodiesel at full load (BP = 3.5 kW) for B20 blend

| Biodiesel | BTE (%) | BSFC (kg/kW.hr) | CO (vol%) | NOx (ppm) | HC (ppm) | Smoke opacity (%) | Reference |
|-----------------------------|--------------------|----------------------------|----------------------|----------------------|---------------------|------------------------------|---------------------------|
| Terminalia catappa seed oil | 30 | 0.22 | 0.07 | 686 | 33 | 47 | Current study |
| Algae | 26 | 0.3 | 0.03 | 380 | 15 | 60 | Subramaniam et al. (2020) |
| Tamarind seed oil | 29 | 0.325 | 0.07 | 1700 | 75 | 40 | Harun Kumar et al. (2020) |
| Cotton seed oil | 18 | 0.5 | Nil | Nil | Nil | 71 | Yesilyurt et al. (2020) |
| Linseed oil | 29 | 0.3 | Nil | 570 | Nil | Nil | Uyumaz et al. (2020) |
| Jatropha seed oil | 25 | Nil | Nil | Nil | Nil | 30 | Gad et al. (2021) |
| Prosopis Juliflora | 29 | Nil | 0.35 | 1300 | 70 | 55 | Duraisamy et al. (2023) |
| Coffee husk | 28 | Nil | 0.45 | 900 | 50 | 46 | Emma et al. (2022) |
| Chlorella emersonii | 28 | Nil | 0.16 | 710 | 58 | 62 | Subramani et al. (2019) |

Table 8 Outcomes of diesel engine operated with different biodiesel added with nanoparticles at full load (BP = 3.5 kW) for B20 blend

| Biodiesel | Nano-particles | BTE (%) | BSFC (kg/kW.hr) | CO (vol%) | NO_x (ppm) | HC (ppm) | Smoke opacity (%) | Reference |
|-----------------------------|--------------------------------|----------------|------------------------|------------------|-----------------------------|-----------------|--------------------------|------------------------------|
| Terminalia catappa seed oil | Al ₂ O ₃ | 33 | 0.18 | 0.051 | 702 | 31 | 45 | Current study |
| Algae | SnO ₂ | 26 | 0.29 | 0.073 | 700 | 28 | 41 | Mathivanan et al. 2024 |
| Avocado | Al ₂ O ₃ | 25 | 0.29 | 0.028 | 521 | 73 | 48 | Rajesh Kana et al. (2022) |
| Parsley | TiO ₂ | 24 | 0.25 | - | - | - | - | Bitire et al. (2023) |
| Mahua | TiO ₂ | 26 | - | - | 185 | 45 | - | Sarma et al. (2023) |
| Simarouba | Graphene | 25 | - | 0.2 | 1150 | 65 | 75 | Paramashivaiah et al. (2018) |