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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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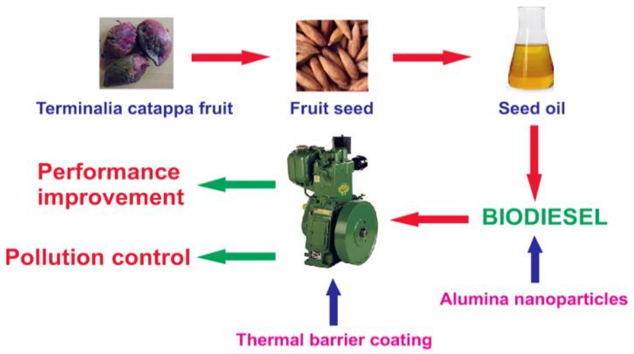
Graphical abstract



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 ($La_2Zr_2O_7$) 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 (NOx), 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 ($La_2Zr_2O_7$) 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.

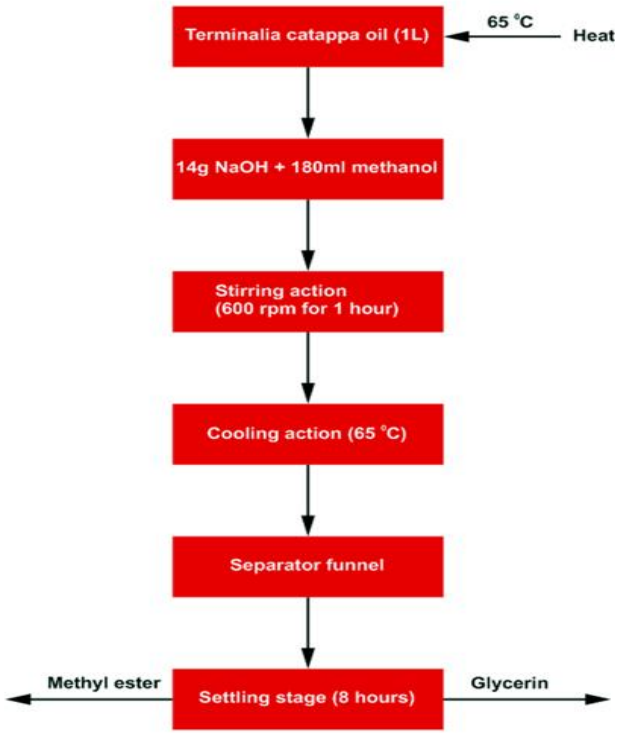


Figure 1. Biodiesel production steps

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*

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**.

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 + Al_2O_3
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

2.4. Biodiesel blending

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.

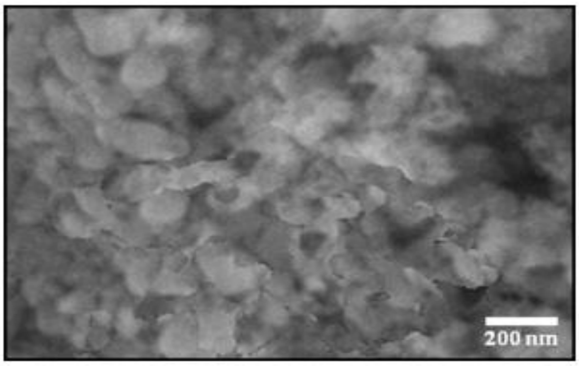


Figure 2 SEM image of alumina nanoparticles

The dispersion stability of the nano-biodiesel blend was evaluated under static storage conditions at ambient temperature (25 ± 2 °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.

Table 2. Characteristics of Al_2O_3 nanoparticles

Property	Al_2O_3 nanoparticles
Size (nm)	50 - 100
Shape	Spherical
Density (g/cm^3)	2.6
Thermal conductivity (W/mK)	30
Melting point (°C)	2050

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).

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_2O_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

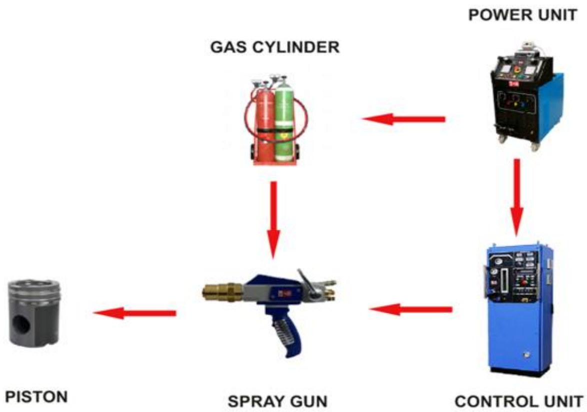


Figure 3(a). Thermal barrier coating process

Figure 3 (b). Coated pistons

2.5. Thermal barrier coating

Figure 3(a) shows the thermal barrier coating process. Lanthanum Zirconate ($La_2Zr_2O_7$) 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

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.

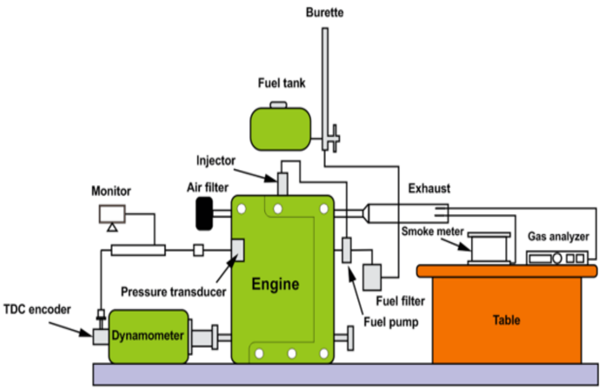


Figure 4(a). Schematic representation of experimental setup

Figure 4(b). Photo of experimental setup

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

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 NOx.

To prepare the nanoparticle-enhanced blend (B20ALC), alumina (Al_2O_3) 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

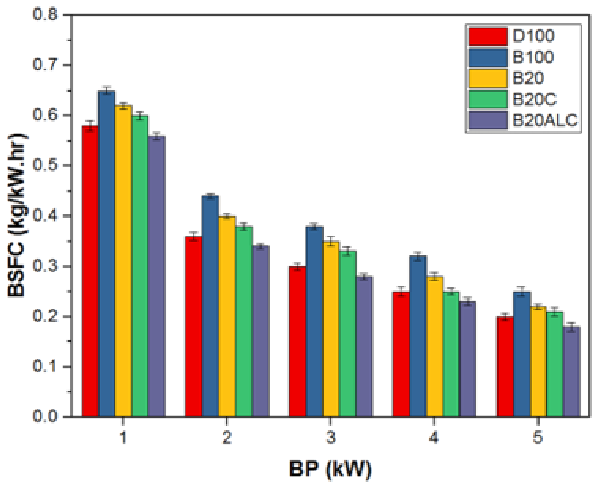


Figure 5. BSFC outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

2.7. Uncertainty analysis

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 (±0.02%) and brake power (±0.51%), ensuring accurate performance evaluation. The ±1% uncertainty in brake thermal efficiency reflects careful error propagation, confirming confidence in experimental results under controlled conditions and calibrated instrumentation.

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%	±1%	±1
NO_x	0 to 5000 ppm	± 10 ppm	±0.01
HC	0 to 100000 ppm	± 20 ppm	±1
CO	0 to 10%	±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

3. Results and discussion

3.1. Brake specific fuel consumption

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.

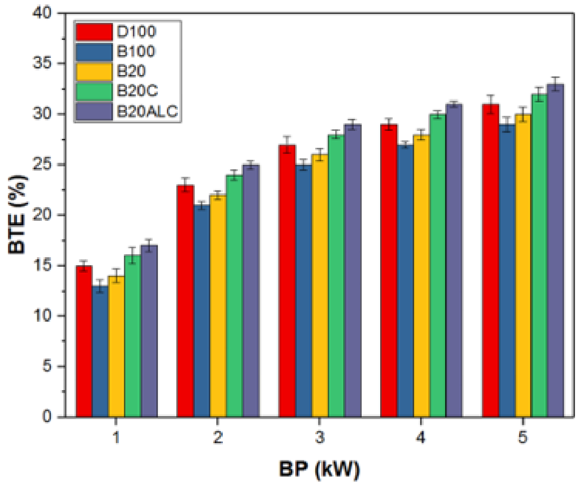


Figure 6. BTE outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.2. Brake thermal efficiency

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 volatilazation, 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.

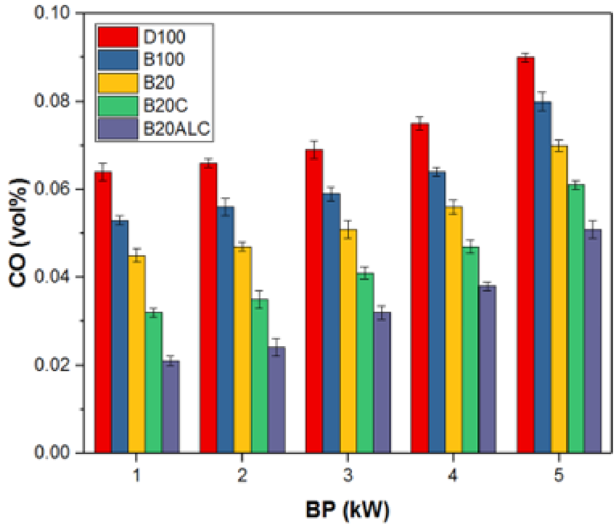


Figure 7. CO outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.3. Carbon monoxide

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.

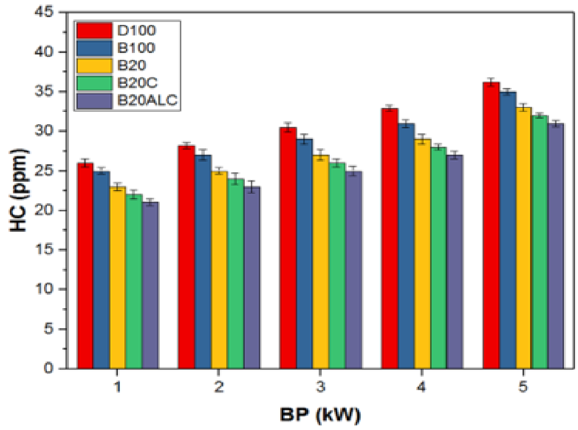


Figure 8. HC outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.4. Hydrocarbon

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 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.

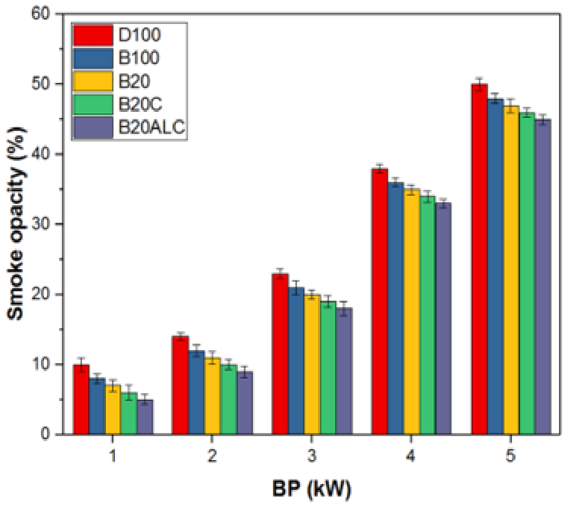


Figure 9. Smoke opacity outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

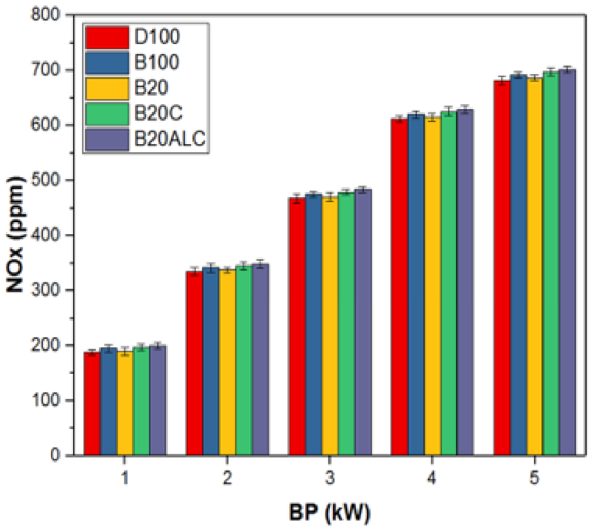


Figure 10. Nitrogen oxide outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.6. Nitrogen oxide

Figure 10 illustrates the NOx emissions from a CI engine fueled by Terminalia catappa seed oil blended with alumina nanoparticles. At lower BP, NOx emissions were lower, while at higher BP, NOx emissions rose, primarily due to increased cylinder temperatures because of more fuel deliver on elevated loads. D100 had lowest NOx emissions, whereas B100 produced higher NOx levels due to incomplete combustion, leading to increased NOx formation as unburned nitrogen reacted with oxygen. B20 showed reduced NOx emissions compared to B100 because it contained a smaller proportion of biofuel in the blend. Comparing NOx emissions from B20C and B20, the B20C showcased advanced NOx 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 NOx expel. In this study, B20ALC showed a peak NOx emission of 702 ppm.

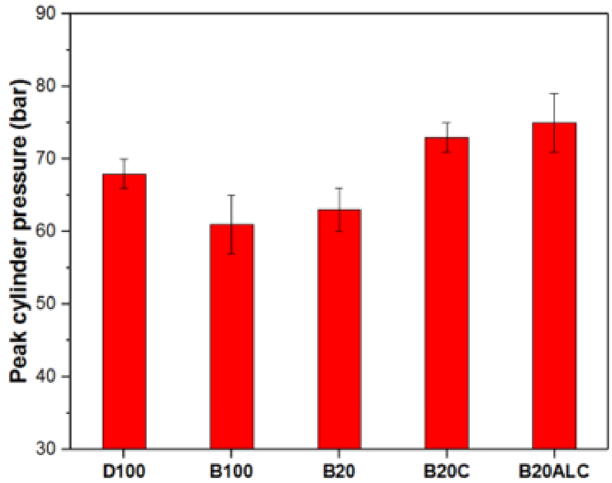


Figure 11. Peak cylinder pressure outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.7. Peak cylinder pressure

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.

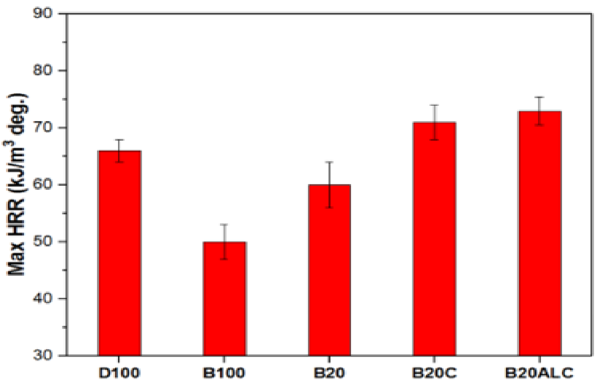


Figure 12. Maximum heat release rate outcomes of diesel engine functioned with terminalia catappa seed oil mixed with alumina nanoparticles

3.8. Maximum heat release rate

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

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 NOx, 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 NOx (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 NOx 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 NOx 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 NOx 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%, NOx 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 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)

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.

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%)	NOx (ppm)	HC (ppm)	Smoke opacity (%)	Reference
Terminalia catappa seed oil	Al_2O_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_2O_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)

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. NOx 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 NOx 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 $0.006 per liter of fuel, a negligible increase considering the associated improvements in combustion and emission performance. The lanthanum zirconate ($La_2Zr_2O_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 $kJ/m^3 \cdot °C$) 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

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Nomenclature

Al2O3	Aluminum oxide
B100	Pure Terminalia catappa oil
B20	20% Terminalia catappa oil + 80% Diesel
BP	Brake Power (kW)
BSFC (kg/kW.hr)	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency (%)
CO	Carbon Monoxide (vol %)
D100	Diesel
DI	Direct Injection
HC	Hydrocarbon (ppm)
HRR	Heat Release Rate (kJ/m3 deg.)
NaOH	Sodium Hydroxide
NOx	Nitrogen Oxide (ppm)
PM	Particulate matters
TC	Terminalia catappa oil

References

Al-Kheraif, A.A., Syed, A., Elgorban, A.M., Divakar, D.D., Shanmuganathan, R. and Brindhadevi, K. (2021). Experimental assessment of performance, combustion and emission characteristics of diesel engine fuelled by combined non-edible blends with nanoparticles. *Fuel,* **295**, 120590.

Allasi, H.L., Rajalingam, A.A., Jani, S.P. and Uppalapati, S. (2023). Influence of synthesized (green) cerium oxide nanoparticle with neem (Azadirachta indica) oil biofuel. *Bulletin of the Chemical Society of Ethiopia*, **37**(2), 477–490.

Bala Prasad, K., Meduri, O., Dhana Raju, V., Azmeera, A.K., Venu, H., Subramani, L. and Soudagar, M.E.M. (2020). Effect of split fuel injection strategies on the diverse characteristics of CRDI diesel engine operated with tamarind biodiesel. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–19.

Bitire, S.O. and Jen, T.C. (2023). An optimization study on a biosynthesized nano-particle and its effect on the performance-emission characteristics of a diesel engine fueled with parsley biodiesel blend. *Energy Reports*, 9, 2185–2200.

Caliskan H. and Mori K. (2017). Thermodynamic, environmental and economic effects of diesel and biodiesel fuels on exhaust emissions and nano-particles of a diesel engine. *Transportation Research Part D: Transport and Environment* **56**, 203–221. https://doi.org/10.1016/j.trd.2017.08.009

Can O., Ozturk E. and Yucesu SH. (2017). Combustion and exhaust emissions of canola biodiesel blends in a single cylinder DI diesel engine. *Renew Energy*, **109**, 73–82.

Chelliah, R., Krishnaswamy, H., Muthukrishnan, S. and Ramakrishnan Iyappalam, R. (2024). Influence of ZnO and TiO2 nanoparticles on the performance, combustion and emission characteristics of diesel engine fueled with okra seed bio-diesel. *Petroleum Science and Technology*, 1–17.

Cihan, Ö., Temizer, İ., Gök, M.G. and Karabaş, M. (2020). Investigation of the effect of rare earth doped La2Zr2O7 based thermal barrier coating on performance and combustion characteristics of DI diesel engine. *Surface and Coatings Technology*, **403**, 126437.

Dhana Raju, V., Nair, J.N., Venu, H., Subramani, L., M. Soudagar, M.E., Mujtaba, M.A., Khan, T.Y., Ismail, K.A., Elfasakhany, A., Yusuf, A.A. and Mohamed, B.A. (2022). Combined assessment of injection timing and exhaust gas recirculation strategy on the performance, emission and combustion characteristics of algae biodiesel powered diesel engine. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **44**(4), 8554–8571.

Ding, X., Liu, H., Zhang, J., Shen, Y. and Yang, G. (2024). Does the local government multi-objective competition intensify the transfer of polluting industries in the Yangtze River Economic Belt? *Environmental Research*, **245**, 118074.

Domakonda, V.K., Reddy, P.D. and Farooq, S. (2019). November. Effect of lanthanum zirconate thermal barrier coating on the performance and emissions of a diesel engine using biodiesel. *In IOP Conference Series: Materials Science and Engineering*, (**577**(1), 012174). IOP Publishing.

Duraisamy, B., Velmurugan, K., Venkatachalapathy, V.K., Madheswaran, D.K. and Varuvel, E.G. (2023). Biodiesel from biomass waste feedstock Prosopis Juliflora as a fuel substitute for diesel and enhancement of its usability in diesel engines using decanol. *Energy Technology*, **11**(10), 2300346.

Elkelawy, M., Etaiw, S.E.D.H., Ayad, M.I., Marie, H., Dawood, M., Panchal, H. and Bastawissi, H.A.E. (2021). An enhancement in the diesel engine performance, combustion, and emission attributes fueled by diesel-biodiesel and 3D silver thiocyanate nanoparticles additive fuel blends. *Journal of the Taiwan Institute of Chemical Engineers*, **124**, 369–380.

El-Seesy, A.I., Attia, A.M. and El-Batsh, H.M. (2018). The effect of Aluminum oxide nanoparticles addition with Jojoba methyl ester-diesel fuel blend on a diesel engine performance, combustion and emission characteristics. *Fuel*, **224**, 147–166.

Emma, A.F., Alangar, S. and Yadav, A.K. (2022). Extraction and characterization of coffee husk biodiesel and investigation of its effect on performance, combustion, and emission characteristics in a diesel engine. *Energy Conversion and Management: X*, **14**, 100214.

Gad, M.S., Aziz, M.M.A. and Kayed, H. (2022). Impact of different nano additives on performance, combustion, emissions and exergetic analysis of a diesel engine using waste cooking oil biodiesel. *Propulsion and Power Research*, **11**(2), 209–223.

Gad, M.S., El-Shafay, A.S. and Hashish, H.A. (2021). Assessment of diesel engine performance, emissions and combustion characteristics burning biodiesel blends from jatropha seeds. *Process Safety and Environmental Protection*, **147**, 518–526.

Harun Kumar, M., Dhana Raju, V., Kishore, P.S. and Venu, H. (2020). Influence of injection timing on the performance, combustion and emission characteristics of diesel engine powered with tamarind seed biodiesel blend. *International Journal of Ambient Energy*, **41**(9), 1007–1015.

Hojati, A. and Shirneshan, A., (2020). Effect of compression ratio variation and waste cooking oil methyl ester on the combustion and emission characteristics of an engine. *Energy & Environment*, **31**(7), 1257–1280.

Hosseini, S.H., Taghizadeh-Alisaraei, A., Ghobadian, B. and Abbaszadeh-Mayvan, A. (2017). Effect of added alumina as nano-catalyst to diesel-biodiesel blends on performance and emission characteristics of CI engine. *Energy*, **124**, 543–552.

Imran, M., Tufail, M., Mo, C., Wahab, S., Khan, M.K., Hoo, W.C. and Ling, Z. (2025). From resources to resilience: Understanding the impact of standard of living and energy consumption on natural resource rent in Asia. *Energy Strategy Reviews*, **57**, 101590.

Janporn, S., Ho, C.T., Chavasit, V., Pan, M.H., Chittrakorn, S., Ruttarattanamongkol, K. and Weerawatanakorn M. (2015). Physicochemical properties of Terminalia catappa seed oil as a novel dietary lipid source. *Journal of food and drug analysis*, **23**(2), 201–209.

Krishnamani S, Mohanraj T. and Kumar K.M. (2016) Experimental investigation on performance, combustion and emission characteristics of a low heat rejection engine using rapeseed methyl ester and diethyl ether. *Indian Journal of Science and Technology*, **9**(15):01–09. https ://doi.org/10.17485 /ijst/2016/v9i15 /87322

Ladele, B., Kpoviessi, S., Ahissou, H., Gbenou, J., Kpadonou-Kpoviessi, B., Mignolet, E., Hérent, M.F., Bero, J., Larondelle, Y., Quetin-Leclercq, J. and Moudachirou, M. (2016). Chemical composition and nutritional properties of Terminalia catappa L. oil and kernels from Benin. *Comptes rendus. Chimie*, **19**(7), 876–883.

Mathivanan, B., Kumaragurubaran, B., Bensam Raj, J. and Veerasigamani, M., (2024). Performance, combustion and emissions characteristics of lanthanum zirconate coated DI engine fueled with nannochloropsis algae bio-diesel containing tin oxide nanoparticles. *Petroleum Science and Technology*, 1–16.

Menkiti, M.C., Agu, C.M. and Udeigwe, T.K. (2015). Extraction of oil from Terminalia catappa L.: Process parameter impacts, kinetics, and thermodynamics. *Industrial Crops and Products*, **77**, 713–723.

Monnet, Y.T., Gbogouri, A., Koffi, P.K.B. and Kouamé, L.P. (2012). Chemical characterization of seeds and seed oils from mature Terminalia catappa fruits harvested in Côte d'Ivoire. *International Journal of Biosciences*, **10**(1), 110–124

Muthukrishnan, S., R. Iyappalam Ramakrishnan, R. Chelliah, H. Krishnaswamy, B.R. Jesuretnam, and K. Ramar. (2021). "Experimental Investigation on Thermal and Transport Properties of Indian Almond–Kenaf Hybrid Composites for Construction Applications. *Journal of Natural Fibers. Advance online publication*. doi: 10.1080/15440478.2021.1889440.

Pandian A.K., Ramakrishnan R.B.B. and Devarajan Y. (2017). Emission analysis on the effect of nanoparticles on neat biodiesel in unmodified diesel engine. *Environmental Science and Pollution Research* **24**(29), 23273–23278. https://doi.org/10.1007/s11356-017-9973-6

Paramashivaiah, B.M., Banapurmath, N.R., Rajashekhar, C.R. and Khandal, S.V. (2018). Studies on effect of graphene nanoparticles addition in different levels with simarouba biodiesel and diesel blends on performance, combustion and emission characteristics of CI engine. *Arabian Journal for Science and Engineering* **43**, 4793–4801.

Rajesh Kana, S. and Shaija, A. (2022). Performance, combustion and emission characteristics of a diesel engine using waste avocado biodiesel with manganese-doped alumina nanoparticles. *International Journal of Ambient Energy* **43**(1):1437–1444.

Rajesh, S.P., Retnam, B.S.J., Devanand, M., Lenin, A.H. and Manjunathan, A. (2022). Performance Analysis on PP blended Bio-Diesel tested on a CI Engine. *International Journal of Vehicle Structures and Systems*, **14**(3), 333–335.

Rajesh, S.P., Retnam, B.S.J., Dhas, J.E.R., Lenin, A.H. and Manjunathan, A. (2022a). Specific Fuel Consumption and Exhaust Emission Test on Single Cylinder Four-Stroke Diesel Engine using Polyethylene Extract Biodiesel as Fuel. *International Journal of Vehicle Structures & Systems*, **14**(3), 339–341

Raju, V.D., Reddy, S.R., Venu, H., Subramani, L. and Soudagar, M.E.M. (2021). Effect of nanoparticles in bio-oil on the performance, combustion and emission characteristics of a diesel engine. *Liquid Biofuels: Fundamentals, Characterization, and Applications*, 613–637.

Raju, V.D., Venu, H., Subramani, L., Kishore, P.S., Prasanna, P.L. and Kumar, D.V. (2020). An experimental assessment of prospective oxygenated additives on the diverse characteristics of diesel engine powered with waste tamarind biodiesel. *Energy*, **203**, 117821.

Saheban Alahadi, M.J., Shirneshan, A. and Kolahdoozan, M. (2017). Experimental investigation of the effect of grooves cut over the piston surface on the volumetric efficiency of a radial hydraulic piston pump. *International Journal of Fluid Power*, **18**(3), 181–187.

Sarma, C.J., Sharma, P., Bora, B.J., Bora, D.K., Senthilkumar, N., Balakrishnan, D. and Ayesh, A.I. (2023). Improving the combustion and emission performance of a diesel engine powered with mahua biodiesel and TiO2 nanoparticles additive. *Alexandria Engineering Journal* 72, 387–398.

Senniangiri, N., Bensam Raj, J., Brucely, Y. and Herbert bejaxhin, A.B. (2024). Effect of SnO_2 and Ag nano-additives on the performance, combustion and emission characteristics of diesel engine fueled with mango seed biodiesel. *Petroleum Science and Technology*, **42**(4), 470–490.

Shirneshan, A.R., Almassi, M., Ghobadian, B. and Najafi, G.H. (2014). Investigating the effects of biodiesel from waste cooking oil and engine operating conditions on the diesel engine performance by response surface methodology. *Iranian Journal of Science and Technology. Transactions of Mechanical Engineering*, **38**(M2), 289.

Sivakumar, M., Sundaram, N.S. and Thasthagir, M.H.S. (2018). Effect of aluminium oxide nanoparticles blended pongamia methyl ester on performance, combustion and emission characteristics of diesel engine. *Renewable Energy*, **116**, 518–526.

Srihari S, Thirumalini S. and Prashanth K. (2017). An experimental study on the performance and emission characteristics of PCCI-DI engine fuelled with diethyl ether-biodieseldiesel blends. *Renew Energy*, **107**, 440–447.

Subramani, L. and Venu, H. (2019). Evaluation of methyl ester derived from novel Chlorella emersonii as an alternative feedstock for DI diesel engine & its combustion, performance and tailpipe emissions. *Heat and Mass Transfer*, **55**, 1513–1534.

Subramaniam, M., Solomon, J.M., Nadanakumar, V., Anaimuthu, S. and Sathyamurthy, R. (2020). Experimental investigation on performance, combustion and emission characteristics of DI diesel engine using algae as a biodiesel. *Energy reports*, **6**, 1382–1392.

Sundararaju Perinbakannan, A., Karuppusamy, M. and Ramar, K., (2022). Mechanical and water transport characterization of Indian almond–banana fibers reinforced hybrid composites for structural applications. *Journal of Natural Fibers*, **19**(13), 7049–7059.

Tamilvanan, A., Balamurugan, K. and Vijayakumar, M. (2019). Effects of nano-copper additive on performance, combustion and emission characteristics of Calophyllum inophyllum biodiesel in CI engine. *Journal of Thermal Analysis and Calorimetry*, **136**, 317–330.

Uyumaz, A. (2020). Experimental evaluation of linseed oil biodiesel/diesel fuel blends on combustion, performance and emission characteristics in a DI diesel engine. *Fuel*, **267**, 117150.

Venkatesh, A.P., Kumar, M.R., Venu, H., Maridurai, T. and Kasinathan, D. (2021). Performance and emission analysis of mango seed biodiesel-diesel blends in a single cylinder DI diesel engine. *Materials Today: Proceedings*, **46**, 4219–4223.

Venu, H. and Appavu, P. (2019). Analysis on a thermal barrier coated (TBC) piston in a single cylinder diesel engine powered by Jatropha biodiesel–diesel blends. *SN Applied Sciences*, **1**(12), 1669.

Venu, H. and Appavu, P. (2022). Effect of nano additives in spirulina microalgae biodiesel–diesel blends in a direct injection diesel engine. *International Journal of Ambient Energy*, **43**(1), 6167–6174.

Venu, H., Subramani, L. and Raju, V.D. (2019). Emission reduction in a DI diesel engine using exhaust gas recirculation (EGR) of palm biodiesel blended with TiO2 nano additives. *Renewable energy*, **140**, 245–263.

Yesilyurt, M.K. and Aydin, M. (2020). Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. *Energy Conversion and Management*, **205**, 112355.

Zhang, Y., Yang, Y., Ye, W., Chen, M., Gu, X., Li, X., Jiang, P. and Liu, L. (2024). Assessing and gauging the carbon emission efficiency in China in accordance with the sustainable development goals. *Scientific Reports*, **14**(1), 25993.