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Synergistic impact of hybrid metal-oxide based nanoparticles added waste-derived duck fat biodiesel-diesel blends on CI engine behaviors

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Abstract

Animal-derived waste streams, specifically lipids and osseous tissues, represent a highly viable feedstock for biodiesel production. This approach improves biodiesel yield and provides a sustainable method for managing the animal by-products. In this experimental research, the engine characteristics, including the combustion, performance, and emission analysis, were carried out with biodiesel derived from duck meat derived waste (DMW). The DMW biodiesel has a higher cetane number and higher fatty acid content as compared to the diesel fuel and is derived through a transesterification process. It was blended with conventional diesel fuel at a volumetric ratio of diesel 80% and biodiesel 20% (DMWB20). Furthermore, titanium dioxide (TiO_2) and cerium dioxide (CeO_2) nanoparticles were added to the test fuels to enhance their properties in a separate and hybrid way. In the results, it is seen that particularly DMWB20/hybrid blend provides the smoother combustion profiles with an HRR of 55.9 J CA^{-1}, which indicates the moderated combustion intensity, and superior engine performance parameters, achieving a higher BTE (32.1%). On the other hand, the nanoparticle addition results in a reduction in the exhaust emissions. DMWB20/hybrid blend at full load achieved 36%, and 17% reduction in CO, and NO_X emissions compared to DMWB20, respectively. These enhancements not only improve engine efficiency but also contribute to environmental sustainability. Therefore, DMW biodiesel with hybrid nanoparticle conditions stands out as a promising, eco-friendly alternative fuel option.

Keywords Waste · Energy · Hybrid nanofuels · Fat biodiesel · Emission analysis · Combustion analysis

Abbreviations

BTE	Brake thermal efficiency
CO	Carbon monoxide
DMW	Duck meat derived waste
UHC	Unburned hydrocarbons
BFSC	Brake-specific fuel consumption
Bp	Brake power

List of symbols

V_c	Fuel volume (mL)
HV	Heating value (MJ kg^{-1})
N	Engine speed (rpm)
T	Torque (N-m)
t	Time (s)
ρ	Fuel density (kg m^{-3})
γ	Adiabatic index
P	Pressure
V	Volume
dQ	Heat
$\varnothing$	Crank angle
dP	Change in pressure
dV	Change in volume
$d\varnothing$	Change in crank angle
dQ	Change in heat

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Introduction

Depleting fossil resources and increasing greenhouse gas emissions present significant environmental challenges. To mitigate these issues, a transition from fossil fuels to renewable energy sources is essential. Among the available alternatives, biodiesel has gained attention because it can be derived from vegetable oils or animal fats and offers several advantages. For example, it is renewable, biodegradable, and environmentally friendly, and it reduces emissions through improved combustion efficiency owing to its high oxygen content [1]. Despite these benefits, the commercialization of biodiesel remains limited because of its relatively higher cost compared to that of petroleum-based diesel fuel [2]. One way to overcome this barrier is by identifying low-cost feedstocks such as waste cooking oil, non-edible vegetable oils, and animal by-products [3].

In this context, waste animal fat, which is abundantly available in the leather processing and slaughtering industries, represents a promising feedstock resource for biodiesel production. Its utilization not only provides an energy source for transportation and industrial applications but also addresses waste management challenges, thereby contributing to sustainable energy solutions [4]. Animal slaughter generates significant quantities of lipid-rich by-products, which, if left unmanaged, may cause environmental pollution. Repurposing these lipids into biodiesel production adds value while simultaneously reducing waste disposal concerns [5]. Common rendered fats used for biodiesel include beef tallow, mutton tallow, pork lard, and chicken fat [6, 7]. Typically, wet rendering is employed to separate fats, where water and lipids are heated below 49 °C to separate the fat from protein residues. The resulting fatty acid composition differs across animal species but generally contains C16–C18 fatty acids, with palmitic and stearic acids as major saturated fatty acids, oleic acid as monounsaturated, and linoleic and arachidonic acids as polyunsaturated [8].

The physicochemical properties of animal fats directly influence biodiesel characteristics. For instance, ruminant and pig fats are largely solid due to their higher saturated fatty acid content, while chicken fat remains liquid or semi-solid at room temperature. To use raw animal fats effectively, preheating to about 45 °C is necessary to overcome solidification at ambient temperatures, thus facilitating stable biodiesel production with relatively high cetane values [9]. Transesterification is the standard method for converting these fats into biodiesel, and alkaline catalysts are particularly effective due to their faster reaction rate—nearly 4000 times quicker than acid catalysts—while being cheaper and widely available [10]. Among them, sodium hydroxide and potassium hydroxide are commonly applied, with methoxides offering superior performance though at a higher cost [11]. To further reduce costs, alternative base catalysts such as polyol-derived alkoxides and potassium glyceroxides have been explored, showing comparable performance to conventional potassium methoxide in methanol-based transesterification [12]. By contrast, acid catalysts are mainly used as a pre-treatment step to reduce free fatty acids, since their reaction rates are slower, requiring higher alcohol-to-fat molar ratios and larger, corrosion-prone reactors [13, 14].

While fuel production methods continue to evolve, additional strategies have been explored to improve the performance of biodiesel during combustion. Such a strategy involves incorporating nanoparticles into biodiesel blends. Nanoparticles can significantly influence combustion behavior due to their high surface area, enhanced thermal conductivity, and catalytic activity. This enables faster heat transfer and improved oxidation reactions, ultimately leading to lower emissions and better fuel efficiency [15, 16]. For example, cerium oxide nanoparticles, which exhibit excellent oxygen storage and release capacity, have been effectively used as additives with ethanol and hydrocarbon fuels [17]. Similarly, Kao et al. [18] demonstrated that adding 3–6% aluminum nanoparticles to diesel improved combustion performance and substantially reduced fuel consumption, smoke, and NO emissions. In another study, Selvan et al. [19] reported that cerium oxide nanoparticles reduced exhaust emissions and improved brake thermal efficiency when blended with diesel and biodiesel–ethanol mixtures in a variable compression ratio engine. The challenges of animal fat-based biodiesel and the role of nanoparticle addition are discussed in Table 1.

Collectively, these studies highlight that replacing diesel with biodiesel is an optimal strategy for improving engine performance and reducing emissions, particularly when enhanced with nanoparticle additives. Utilizing animal-derived biodiesel not only addresses waste management and sustainability challenges but also offers a cost-effective feedstock alternative. Furthermore, the addition of nanoparticles into biodiesel fuels enhances combustion, improves engine efficiency, and reduces harmful emissions more effectively than biodiesel alone. However, despite extensive research on various animal fats, studies on biodiesel derived specifically from duck fat remain very limited. Likewise, reports on the addition of nanoparticles with duck fat biodiesel are negligible, creating a research gap. Therefore, the present investigation explores the production of biodiesel from duck fat and evaluates its engine performance under the influence of TiO_2, CeO_2, and hybrid nanoparticles.

Table 1 Challenges of animal fat-based biodiesel and the role of nanoparticle addition

Issue/Challenge	Scientific basis/Shortcomings in previous studies	Key points	Evidence from literature
High Free Fatty Acid (FFA) content	Leads to soap formation during transesterification, requiring a two-step esterification + transesterification process [10, 13, 14]	Nanoparticles do not directly reduce FFA, but can improve stability and prevent secondary oxidation during storage	Studies on animal fats often highlight pre-treatment but do not explore stability enhancers
High Saturated Fatty Acid (SFA) content	Ruminant fats (beef, mutton, pork) have high SFA → poor cold flow, solidification at ambient temperature [8, 9]	Nanoparticles (e.g., CeO_2 and TiO_2) improve combustion reactivity, offsetting ignition delays caused by poor atomization of solidifying fuels	Limited work has been reported on enhancing cold flow with nanoparticles
High Viscosity & Density	Causes poor atomization and incomplete combustion compared to diesel [7, 10]	Nanoparticles improve fuel atomization by increasing thermal conductivity and micro-mixing, lowering viscosity slightly at ultra-low concentrations	Selvan et al. [19] showed CeO_2 improved combustion in biodiesel blends
Lower Calorific Value	Animal fat biodiesels contain oxygen in FAME molecules, lowering energy density and raising BSFC (Brake specific fuel consumption) [7]	Nanoparticles act as oxygen carriers and combustion catalysts, enhancing heat release and effective calorific performance	Kao et al. [18] demonstrated that nanoparticles (Al) improved fuel consumption
Poor Combustion Efficiency	Results in higher CO and UHC emissions due to incomplete oxidation [6, 7]	TiO_2 and CeO_2 nanoparticles supply active oxygen and catalyze oxidation → reducing CO, UHC	Ahmad et al. [20] reported a better combustion with hybrid nanoparticles
High NOx Formation in Biodiesel	Biodiesel's oxygen content increases in-cylinder temperature, producing more NOx [10]	CeO_2 acts as an oxygen buffer, reducing peak flame temperature, moderating NOx formation	Selvan et al. [19] reported lower NOx with CeO_2 addition
Engine Durability Issues	Deposits, injector coking, and fuel filter plugging from high SFA biodiesel remain concerns [10, 13]	Nanoparticles provide cleaner combustion and reduce soot precursors, minimizing deposit formation	Selvan et al. [19] demonstrated lower smoke opacity with nanoparticle fuels
Lack of Research on Duck Fat Oil	Duck fat waste has a high oil yield but remains underexplored; very few published studies are available	The present study fills this gap by producing biodiesel from Duck Meat derived Waste and, for the first time, testing nanoparticles (TiO_2, CeO_2, and their hybrid) for their potential in engine characteristics	No dedicated reports exist on DMW biodiesel + nanoparticles

Animal fat oils have increasingly emerged as promising alternative feedstocks for biodiesel production because of their high lipid content, availability as waste by-products, and favorable thermophysical fuel properties. Diverse fats such as beef tallow, mutton tallow, pork lard, and chicken fat have been widely studied and successfully converted into biodiesel due to their high proportion of long-chain fatty acids, which contribute to higher cetane numbers and offer competitive combustion qualities. Their utilization not only reduces dependence on edible vegetable oils, thereby avoiding the "food vs. fuel" conflict, but also addresses the challenge of managing slaughterhouse and leather industry wastes, which otherwise pose environmental hazards. Fat-derived biodiesels are typically characterized by higher saturation levels (palmitic and stearic acids) that improve oxidative stability, though they may require preheating or blending with diesel to overcome cold flow limitations.

Regarding duck fat oil, very limited research has been reported compared to more common animal fats to the best of the Authors' knowledge. Duck fat waste, however, is rich in lipids and fatty acids, making it a viable candidate for biodiesel production. Some studies have noted the potential of poultry fats, including duck, but dedicated experimental works specifically on duck fat biodiesel are scarce. This underexplored area highlights the novelty and significance of studying duck fat derived biodiesel. The high oil yield and favorable fatty acid profile of duck fat not only support efficient transesterification but also offer competetive combustion qualities. Therefore, using duck fat oil as an alternative fuel is technically and environmentally justified, as it combines waste valorization with clean energy generation. Moreover, adding nanoparticles into duck fat biodiesel, as examined in the present study, represents an innovative step forward since no extensive prior work has investigated this combination for enhanced combustion and emission performance.

From the literature, studies on biodiesel derived from duck fat waste are very limited. Therefore, in this investigation, biodiesel derived from duck fat was tested in engine performance experiments with nanoparticle addition both individually and in hybrid nanoparticle mode. Duck fat waste contains a relatively high lipid fraction suitable for biodiesel production. The DMW was collected and processed by the transesterification process for the oil extraction process. The prepared biodiesel was blended with TiO_2 and CeO_2 nanoparticles at 0.25 g L^{-1} to further enhance fuel properties. Moreover, the hybrid of these two nanoparticles was mixed with biodiesel to analyze the effect of the hybrid nanoparticles' condition on engine combustion. In conclusion, hybrid nanoparticles blended with DMW biodiesel exhibit superior combustion, performance, and emission characteristics compared to single-nanoparticle or non-additive conditions.

The main interest of this study lies in the synergistic use of hybrid metal-oxide nanoparticles (TiO_2 and CeO_2) with duck fat derived waste biodiesel, which not only improves combustion stability but also significantly enhances performance and emission characteristics compared to conventional biodiesel-diesel blends. Accordingly, the present work deals with the engine characteristics of nanoparticles added duck biodiesel-diesel fuels at varying engine loads.

Materials and methods

Biodiesel preparation

A two-stage procedure is utilized for biodiesel production from Duck Meat Wastes (DMW), which have a higher free fatty acid (FFA) content than other meat and fat wastes (such as sheep, chicken, and cattle). Hence, initially, the FFA content is reduced before the transesterification process. The DMW is initially collected from a local commercial supplier in Chennai and then cooked for 60 min at 150 °C. Lipid phase separation occurred post-thermal treatment, and then, it can be easily collected.

The esterification process follows, using methanol and sulfuric acid catalysts with a methanol molar ratio of 6:1. Subsequently, the oil is preheated to remove moisture before transesterifaction. The DMW oil then reacts with potassium hydroxide base catalyst (purity of 99%) and methanol, which is distinctly dissolved in a 6:1 molar ratio, and the mixture is continuously stirred in a flask. Figure 1 depicts the preparation method of biodiesel.

After that, the mixture is allowed to settle under a separation funnel for 15 h. The layer of glycerol is then eliminated, and the raw methyl ester is purified via aqueous washing for other impurities and any other unreacted KOH/catalyst residue. This mixture is subsequently heated to remove any remaining water traces, resulting in clear biodiesel. That is the fat oil extracted from duck meat waste was converted into biodiesel through a two-step chemical process involving esterification and transesterification. Following this, the refined oil underwent transesterification, where it was reacted with methanol in the presence of a potassium hydroxide (KOH) catalyst. In this reaction, the triglycerides present in the fat oil were broken down, and the fatty acid chains were converted into fatty acid methyl esters (FAME), which form biodiesel, while glycerol was produced as a by-product. The separation of glycerol and purification steps, including washing and drying, ensured that the final product was clean and suitable for use as biodiesel fuel.

The selection of TiO_2 and CeO_2 nanoparticles as fuel additives is based on their unique catalytic and oxygen buffering properties, which directly influence combustion

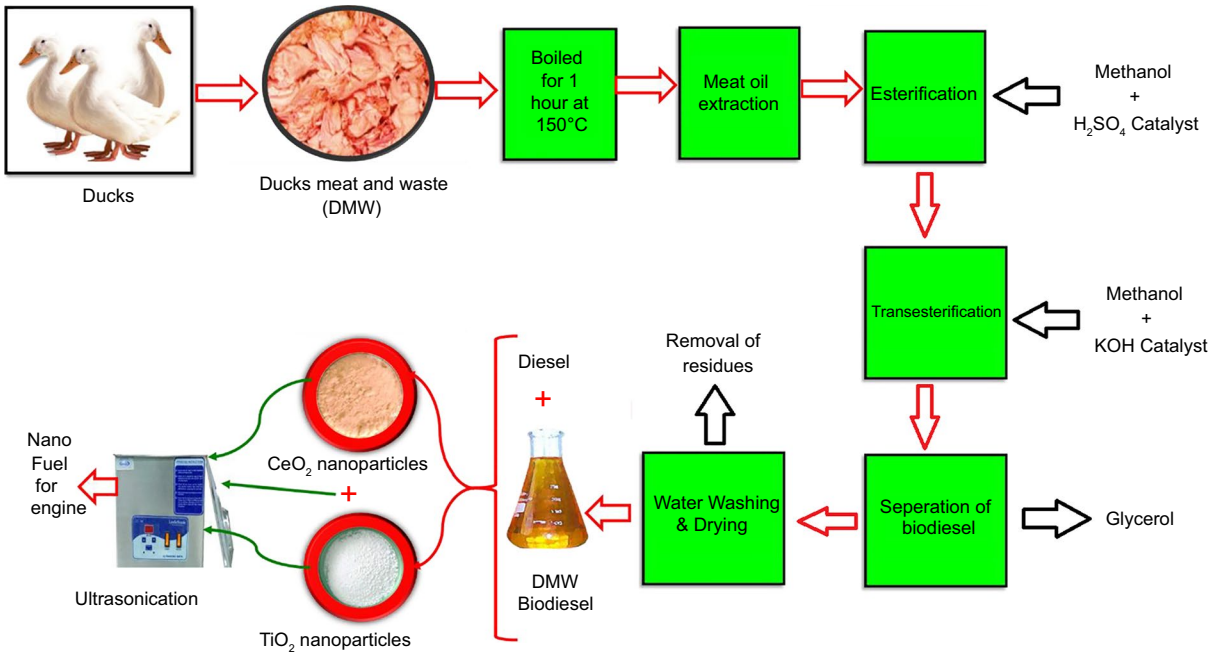


Fig. 1 Preparation method of DMW biodiesel and nanofuel

chemistry and engine performance. TiO_2 nanoparticles possess high thermal conductivity and catalytic surface activity, which improve the atomization and evaporation of fuel droplets, leading to faster ignition and enhanced premixed combustion. CeO_2, on the other hand, is well known for its redox capability (Ce^{3+}/Ce^{4+} cycle) and oxygen storage–release behavior. During combustion, CeO_2 can donate lattice oxygen to oxidize incomplete combustion intermediates such as CO and UHC, while simultaneously reducing peak combustion temperatures, thereby mitigating NOx formation. When used together in hybrid form, TiO_2 provides enhanced fuel–air mixing and radical generation, while CeO_2 ensures sustained oxidation through oxygen buffering, resulting in a synergistic effect on brake thermal efficiency and emissions.

The reaction mechanism primarily involves nanoparticle-assisted catalytic oxidation, where the surface of the nanoparticles promotes the formation of reactive oxygen species (O• and OH•), which accelerate the breakdown of hydrocarbon chains and enable more complete combustion. This results in higher brake thermal efficiency and reduced CO/UHC emissions, while moderating NOx formation through controlled flame temperature profiles.

Nanoparticle stability for the test fuels is a very critic factor to ensure consistent performance. The nanoparticles should be ultrasonicated with biodiesel at a controlled frequency and time to obtain uniform dispersion and avoid the agglomeration.

For this study, the TiO_2 (white color, 96% purity, and purchased from Parry's Corner, Chennai) and CeO_2 (yellowish color, 98% purity, and purchased from Parry's Corner, Chennai) nanoparticles were chosen for the nano-enhanced biodiesel. After the biodiesel/diesel and nanoparticles were chosen, 0.25 g of nanoparticles were added with 1 L of biodiesel/diesel blends. Then, ultrasonication was performed using the UP400S device (Hielscher Ultrasonics GmbH, Teltow, Germany) with a power of 400 W and a frequency of 24 kHz. In this direction, this research discusses whether these nanoparticles could improve the fuel properties, stabilizing blends, provide environmental benefits, process intensification, and lead to efficient combustion, and performance outputs.

Experimental setup

In this investigation, the performance of a single-cylinder, four-stroke water-cooled engine was studied using the prepared DMW biodiesel with TiO_2 and CeO_2 nanoparticles. Figure 2 shows the engine performance analysis experimentation test rig using DMW biodiesel. To measure the cylinder pressure during combustion, a pressure transducer was attached to the engine's top. The test engine incorporates an eddy current dynamometer that operates on water cooling. Initially, a separate storage unit provided the diesel and biodiesel, which were then fed to the engine via a flow sensor that gauges the fuel flow to the engine. In a similar vein, air storage provided the air, while an airflow sensor measured

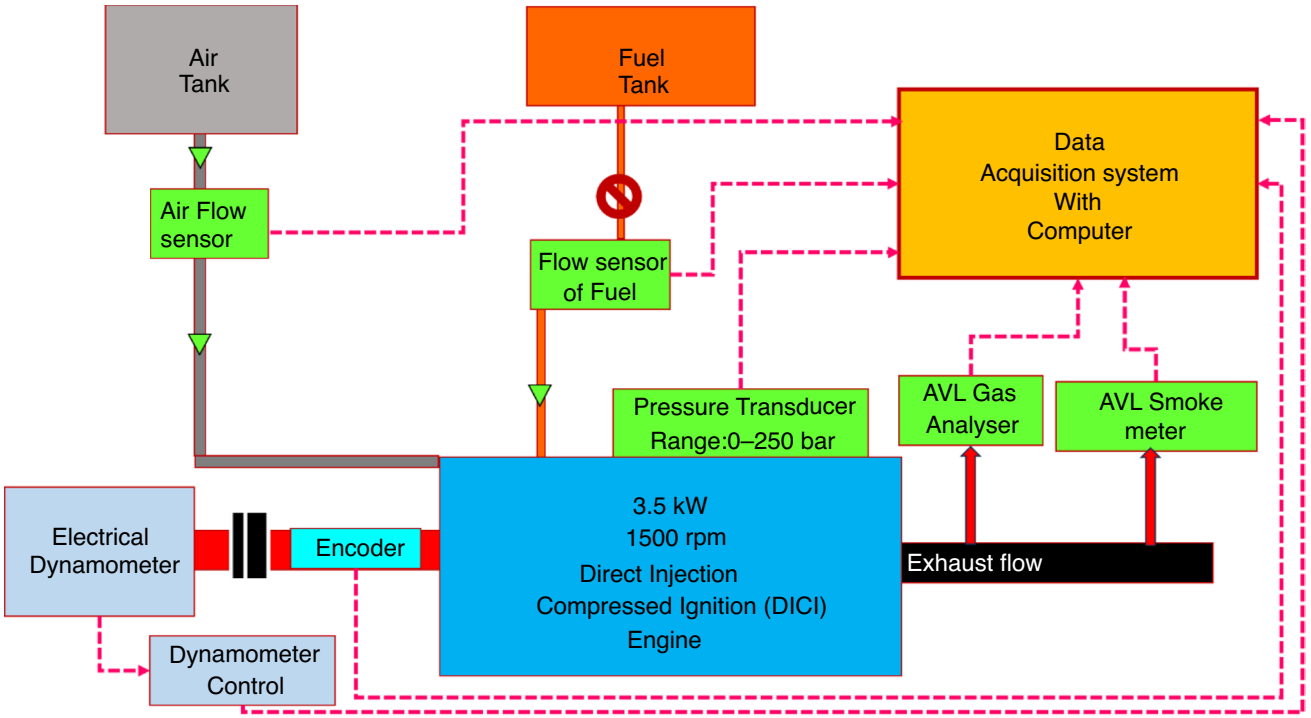


Fig. 2 Experimental test engine setup layout

Table 2 Properties of test fuels

Fuel type/ Properties	Kinematic viscosity cSt at 40 °C	Density/kg m^{-3}	Flashpoint/°C
DMWB0	2.84	823	46.3
DMWB20	3.62	885	59.4
DMWB20/TiO_2	3.58	886	56
DMWB20/CeO_2	3.52	886	58.5
DMWB20/hybrid	3.55	886	55.5

Table 3 Specification of the test engine

Parameters	Specification
Engine make	Kirloskar
Model	240PE
Engine displacement	309 cm^3
Rated power	3.5 kW at 1500 rpm
Loading	Eddy current dynamometer
Bore	87.5 mm
Stroke	110 mm
Crank length	34.5 mm
Cooling type	Water cooling
Fuel	Diesel

the air supply. The fuels' characteristics are displayed in Table 2.

An AVL DiGAS 444N gas analyzer was used to examine the engine's combustion-related emissions in this work. To measure the temperature of the exhaust gas and outlet, K-type chrome thermocouple was used at the exhaust tailpipe. A controller on the eddy current dynamometer was used to vary the engine load. A data gathering system, crank angle encoder, and pressure transducer were used in the combustion measurements. The engine's specifications are given in Table 3**.**

Standard injection timing (23° TDC) and injection pressure (200 bar) were maintained throughout the experiments, but the engine load was varied from 20 to 100% with 20% steps. The experimentation was studied at different fuel conditions: DMWB0, DMWB20 (Diesel 80% and Biodiesel 20%), DMWB20 with TiO_2 (DMWB20/TiO_2), DMWB20 with CeO_2 (DMWB20/CeO_2), and DMWB20 with a hybrid of these nanoparticles (DMWB20/hybrid). The engine combustion parameters, such as heat release rate (HRR), in-cylinder pressure, engine performance metrics including brake thermal efficiency (BTE) as well as engine emissions including hydrocarbons, CO, and NO_X, were analyzed with DMW biodiesel.

Results and discussion

This section explores the results of engine performance, combustion, and emission parameters evaluated using DMW biodiesel combined with TiO_2 and CeO_2 nanoparticles. Accordingly, experiments were conducted under varying load conditions by using a variety of fuel circumstances, including DMWB0 and DMWB20 (diesel 80% and 20%) with TiO_2 and CeO_2. In the results, BTE, HRR, and in-cylinder pressure, HC, CO, and NO_X were also discussed in detail.

Combustion parameters

The combustion parameters, such as cylinder pressure and heat release, were measured. Figure 3 shows the variation of cylinder pressure with different fuel conditions. The peak cylinder pressure for DMWB0 and DMWB20 is about 64.9 bar and 73.9 bar, respectively. Hence, the diesel fuel shows the lowest cylinder pressure among all other fuels. This is because a lower cetane number of DMW biodiesel in comparison to diesel fuel causes longer ignition delay, resulting in abrupt combustion and a sharp rise in cylinder pressure for biodiesel blends. DMW biodiesel with TiO_2 and CeO_2 nanoparticles shows a lowered peak cylinder pressure of about 71.4 bar and 69.5 bar as compared to that of pure diesel fuel. The TiO_2 and CeO_2 nanoparticles may influence the combustion process, potentially altering the rate of fuel oxidation and heat release patterns due to their catalytic properties.

Additionally, the specific properties of DMW biodiesel, such as its fatty acid composition, can interact with the nanoparticles in unique ways, affecting the overall combustion dynamics. Furthermore, the DMWB20/hybrid condition shows the optimized pressure distribution. The hybrid TiO_2 and CeO_2 nanoparticles likely optimize combustion dynamics, promoting efficient fuel oxidation while moderating peak pressure. Their combined effects may facilitate more uniform fuel–air mixing and combustion, leading to a smoother and lower peak cylinder pressure.

Figure 4 depicts the HRR with different fuel conditions. The variation of HRR with different fuel conditions reveals distinct combustion characteristics. In the case of DMWB0 and DMWB20 fuels, the peak HRR value is about 52.6 J CA^{-1} and 68.5 J CA^{-1}, respectively and a pattern addresses the differences in combustion efficiency. A lower cetane number of DMW biodiesel causes longer ignition delay, resulting in abrupt combustion and heat release. This phenomenon underscores the influence of fuel composition on combustion kinetics, with lower cetane fuels exhibiting delayed and prolonged combustion processes. In a similary way, when DMW biodiesel is blended with TiO_2 and CeO_2 nanoparticles, the peak HRR values of approximately 63.4 J CA^{-1} and 58.2 J CA^{-1} bar, respectively.

The nanoparticles likely enhance fuel oxidation and promote more complete combustion, albeit at a moderated rate, leading to smoother HRR profiles compared to

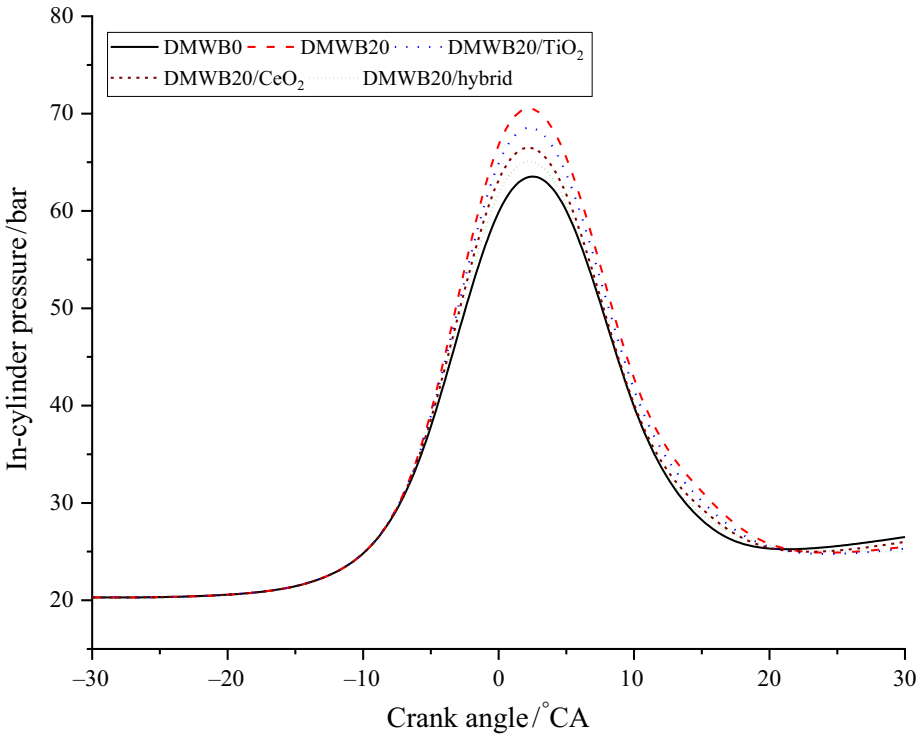


Fig. 3 Effect of fuel and nanoparticles in-cylinder pressure

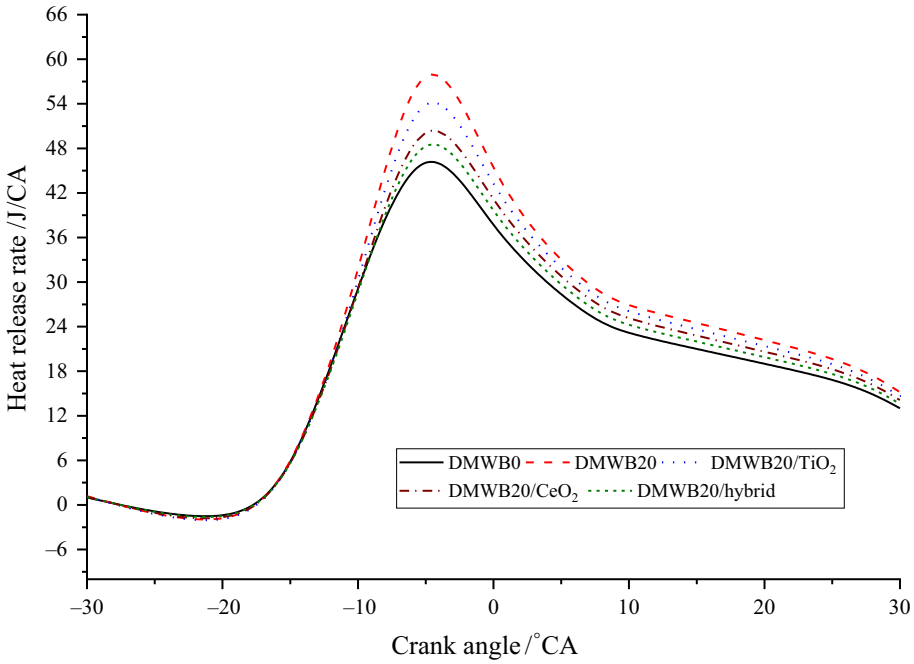


Fig. 4 HRR profile of the engine by using different fuel conditions

DMW20. Moreover, the specific properties of DMW biodiesel interact with the nanoparticles, further influencing combustion behavior. The DMWB20/hybrid condition demonstrates a more controlled, and smoother HRR profile with nearly 55.9 J CA^{-1}. This behaviour indicates the improved combustion stability, and moderated combustion intensity due to the synergistic effects of TiO_2 and CeO_2 nanoparticles. This hybrid blend optimizes combustion dynamics, facilitating efficient fuel oxidation while mitigating peak heat release rates, thus underscoring the intricate interplay between fuel composition and nanoparticle additives in combustion processes. Similar conclusion was reported by Ahmad et al. [20].

The observed variations in cylinder pressure and HRR provide strong scientific evidence of how fuel chemistry, cetane number, and catalytic additives influence in-cylinder combustion dynamics. For DMWB20, the higher cetane number and oxygenated nature of biodiesel promote faster ignition and more premixed combustion compared to diesel, explaining its higher peak cylinder pressure (73.9 bar). However, this rapid heat release can also lead to steeper pressure rise rates. The introduction of TiO_2 and CeO_2 nanoparticles alters this trend by acting as oxygen carriers and surface catalysts, which improve oxidation reactions but distribute them more gradually, lowering peak pressures (71.4 and 69.5 bar). This behavior highlights a catalytic smoothing effect—fuel energy is still effectively released, but the rate is moderated to reduce extreme in-cylinder conditions. The hybrid nanoparticle blend further amplifies this effect, yielding the lowest peak pressure and HRR. This outcome suggests that the synergistic interaction of TiO_2 and CeO_2 balances rapid ignition with controlled diffusion burning, achieving more homogeneous fuel–air mixing and sustained combustion rather than sharp spikes. From a thermodynamic perspective, smoother pressure and HRR traces mean reduced cyclic variability, less mechanical stress on the piston/liner, and more effective conversion of chemical energy into work. These results are consistent with the dual role of nanoparticles in enhancing oxidation while mitigating uncontrolled premixed burn, providing scientific justification that hybrid nanoparticle additives not only improve efficiency but also contribute to engine durability and stable combustion behavior.

Engine performance metric

The BTE values of the test fuels are given in Fig. 5. It is seen that blending of 20% DMW biodiesel to the diesel fuel significantly lowers BTE largely due to biodiesel's lower calorific value and slightly higher viscosity/density, which can worsen atomization and shift heat release later in the cycle, increasing pumping/heat losses. Adding the CeO_2 or TiO_2 nanoparticles to DMWB20 enhances BTE (31.4% and 29.5%, respectively). This is because these metal oxides act as combustion catalysts and oxygen carriers: CeO_2's Ce^{3+}/Ce^{4+} redox pair supplies lattice oxygen and promotes CO/UHC oxidation, while both oxides provide active surfaces that enhance radical formation (OH and O) and shorten afterburning. Nanoparticles also raise the effective thermal conductivity of the fuel, improving droplet heating/evaporation and sharpening premixed burn, which moves heat release closer to top dead center and boosting efficiency without

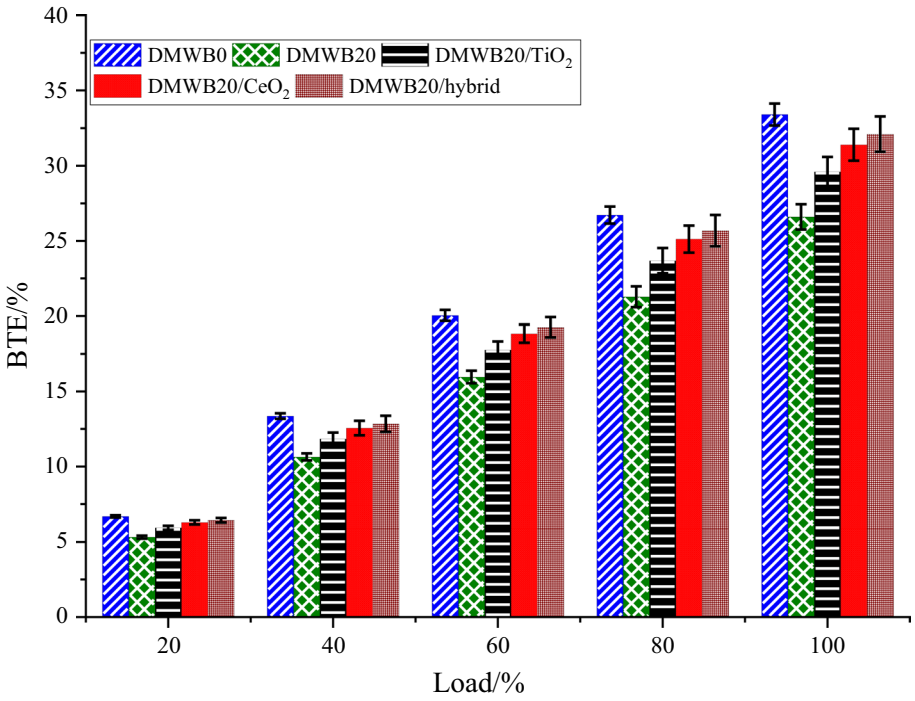


Fig. 5 Variation of BTEwith different fuels

needing a high peak pressure. The hybrid TiO_2+CeO_2 nanoparticles added fuel blend provide the best thermal efficiency (BTE 32.1%) by combining oxygen storage (CeO_2) with robust catalytic/thermophysical support (TiO_2), yielding smoother pressure traces and a more compact heat release profile. Finally, BTE rising with load are expected: Fixed relative losses (friction, wall heat transfer, and pump work) are diluted at higher brake power, so improvements from better oxidation become more visible.

Engine emission parameters

Figure 6 shows the CO emission profile of the engine under diesel and biodiesel conditions at different loads. The CO

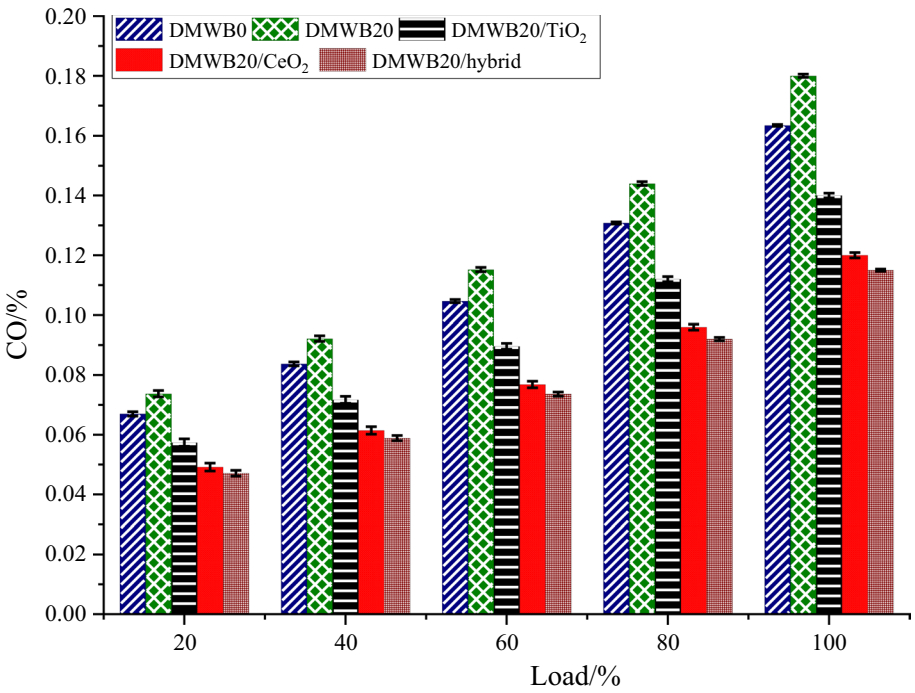


Fig. 6 CO emission of the engine by using different fuel conditions

emission increased as the engine load increased due to more complete combustion at higher loads, where higher temperatures and better fuel–air mixing occur. DMWB0 and DMWB20 showed the lowest CO emissions of about 0.066% and 0.073%, respectively, indicating efficient combustion in both fuel types under high-load conditions.

CO is a primary intermediate combustion product, and its presence in the exhaust is essentially an indicator of incomplete oxidation due to localized oxygen deficiency or insufficient residence time at high temperatures [20]. As it is seen from the figure, CO emissions tend to increase with higher engine loads. This behavior is attributed to the richer fuel-air equivalence ratio required to meet the higher power output, which creates zones within the combustion chamber where oxygen is insufficient to completely oxidize CO into CO_2. The DMWB20 blend exhibited higher CO emissions than diesel fuel, a phenomenon associated with its higher viscosity, which leads to larger fuel droplets and poorer atomization, resulting in the increasing the likelihood of incomplete combustion. However, the addition of TiO_2 and CeO_2 nanoparticles into the DMWB20 noteworthy dropped the CO emissions. In the full engine load, the DMWB20/hybrid blend demonstrated the most profound reduction, achieving a 36% decrease as compared to the base DMWB20. This substantial improvement can be explained by catalytic oxidation and enhanced combustion process as compared to DMWB20.

Figure 7 illustrates the UHC emissions of the test fuels under varying engine loads. The experimental data reveal that UHC emissions escalate as the engine load increases. This upward trend is primarily associated with the increased fuel injection quantity required to provide the higher power demand, which leads to the formation of locally fuel-rich zones and a relative deficiency in oxygen availability within the combustion chamber. Among the test fuels, DMWB20 exhibited the highest UHC levels because of its inferior atomization characteristics resulting from the higher viscosity of the biodiesel added in comparison to the diesel fuel. On the other hand, the addition of nanoparticles significantly suppressed UHC formation. This reduction is attributed to the catalytic effect of the hybrid nanoparticles, which lowers the activation energy for oxidation and promotes a more thorough combustion process even under high-load conditions.

In terms of separate nanoparticle addition, this reduction is still credited to the catalytic properties of TiO_2 and CeO_2 nanoparticles, which enhance the oxidation process throughout combustion. The nanoparticles improve fuel-air mixing and encourage more complete combustion, thus reducing the formation of UHC as compared to biodiesel-diesel fuel. This enhanced combustion efficiency of nanoparticles added test fuels results in fewer incomplete combustion products, such as UHC, thereby lowering overall emissions [21].

Figure 8 depicts NOx emissions by the engine under different load conditions. The NOx emissions increased as the engine load increased for all test fuels. It can be seen from the figure that the biodiesel addition to the diesel fuel (DMWB20) is increasing the NOx amount, but the nanoparticles result in a drop in this increment. The maximum NO_X

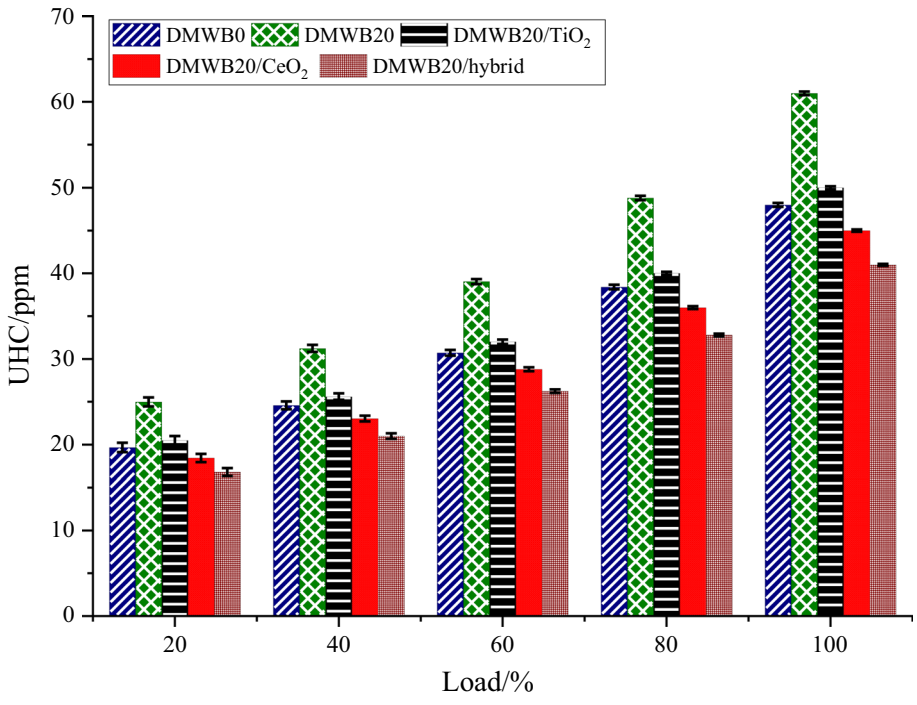


Fig. 7 UHC profile of the engine under different fuels and nanofuels

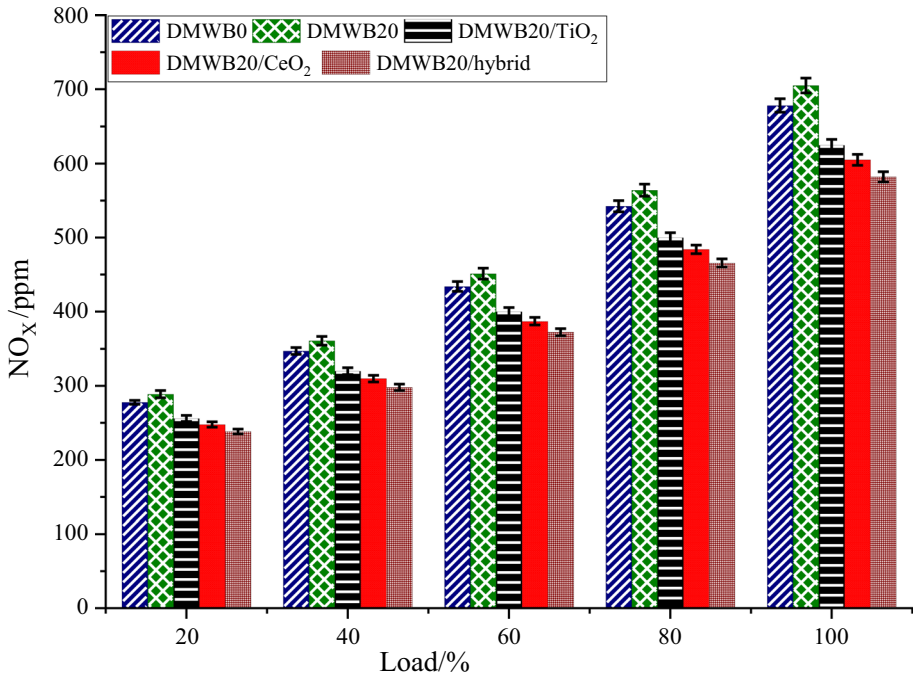


Fig. 8 NO_X emission of the engine by biodiesel and nanoparticle addition

emissions were noticed for DMWB20 at full load condition with the value of 706 ppm due to biodiesel's higher oxygen content, leading to increased combustion temperatures and subsequently higher NO_X formation. However, when TiO_2 nanoparticles are added to DMWB20 fuel, NO_X emissions decrease to 624.3 ppm.

TiO_2 nanoparticles act as combustion catalysts, enhancing fuel-air mixing and combustion efficiency, thereby reducing peak combustion temperatures and NO_X formation. Similarly, the addition of CeO_2 nanoparticles into DMWB20 fuel further reduces NO_X emissions to 605.4 ppm. CeO_2 nanoparticles improve the oxidation process, promoting more complete combustion at lower temperatures, consequently lowering NO_X emissions. The hybrid blend of TiO_2 and CeO_2 nanoparticles achieves the lowest NO_X emissions at each load. The synergistic effect of these nanoparticles optimizes combustion conditions, enhances fuel oxidation, and reduces combustion temperatures, resulting in more efficient combustion with reduced thermal NO_X formation [16, 22].

The emission characteristics observed across CO, UHC, and NOx clearly reflect the interplay between biodiesel chemistry, oxygenated fuel properties, and nanoparticle-assisted combustion catalysis. The progressive reduction in CO and UHC emissions with TiO_2, CeO_2, and particularly their hybrid combination, is consistent with the enhanced surface-catalyzed oxidation of incomplete combustion intermediates. Both nanoparticles act as oxygen storage–release agents, with CeO_2 in particular facilitating cyclic redox reactions (Ce^{3+}/Ce^{4+}), which sustain active oxygen availability even during transient lean/rich zones in the cylinder. TiO_2, meanwhile, enhances radical formation and fuel–air micro-mixing, further lowering the probability of incomplete oxidation products. This dual catalytic action explains why the hybrid blend reaches near-complete elimination of CO and UHC. However, the NOx trends highlight the thermodynamic trade-offs in oxygen-rich biodiesel combustion. DMWB20 produces higher NOx than diesel due to its intrinsic oxygen content and higher in-cylinder temperature peaks, which accelerate thermal NO formation via the Zeldovich mechanism. The introduction of TiO_2 and CeO_2 nanoparticles effectively moderates this, not by suppressing oxidation, but by promoting faster, more uniform combustion at slightly lower peak flame temperatures. CeO_2, with its superior oxygen buffering capability, proves particularly effective in reducing local temperature spikes, while TiO_2 provides catalytic support for uniform flame propagation. The hybrid nanoparticle case achieves the lowest NOx (582.9 ppm), underscoring that their synergistic function allows high oxidation efficiency (reflected in CO/UHC reduction) while simultaneously mitigating the temperature-driven NOx pathway. Scientifically, these results affirm that nanoparticle-assisted biodiesel combustion balances the competing requirements of complete oxidation and thermal NOx suppression, offering a pathway to achieve both cleaner and more efficient engine operation.

Conclusions

In this investigation, the engine performance was analyzed by using biodiesel from Duck meat waste. The DMW biodiesel was derived from the transesterification process

and blended with diesel for analysis, the engine combustion, performance, and emission parameters. Furthermore, the nanoparticles, such as TiO_2 and CeO_2 nanoparticles, were blended with DMWB20 fuel conditions for better combustion and emission reduction purposes. Based on the results, the following conclusions were drawn.

- The DMWB20/TiO_2, DMWB20/CeO_2, and DMWB20/hybrid biodiesel blends show lowered cylinder pressures due to low cetane number and high catalytic than DMWB20.
- The HRR values demonstrate smoother, and more controlled combustion profiles with nanoparticle-enhanced blends, particularly with DMWB20/hybrid nanoparticle fuel.
- The addition of animal-derived biodiesel to the diesel fuel reduced the BTE value, but it started to increase with the presence of nanoparticles in the diesel–biodiesel fuels. In terms of BTE value, the DMWB20/hybrid fuel achieves the highest BTE of 32.1% in this research, while the lowest BTE value is seen for DMWB20 fuel.
- NOx emissions increased with the biodiesel addition to the diesel fuel; however, the availability of the nanoparticles in the biodiesel-diesel fuels ensured a lowered NOx emission. In terms of NOx emissions, the best (the lowest) results were detected when the engine is fueled by DMWB20/hybrid, and it is then followed by DMWB20/CeO_2, and DMWB20/TiO_2 fuels.
- Nanoparticle addition results in reduced emissions across all parameters, with DMWB20/hybrid fuel achieving the lowest emissions, including CO, UHC, and NO_X.

The commercialization of nanoparticle-blended fuels is possible, but it requires careful consideration of both technical and practical aspects. On the positive side, such fuels have shown clear benefits in improving engine performance, fuel efficiency, and emission reduction, making them attractive for sustainable energy applications. However, large-scale adoption depends on factors like the cost of nanoparticle production, ensuring uniform dispersion in fuel during storage and transport, and confirming long-term engine safety without causing wear or deposits. With advancements in nanotechnology, falling material costs, and growing demand for cleaner fuels, there is strong potential for commercial use in the near future, especially if supported by policy incentives and further research into stable, low-cost nanoparticle formulations. On the other hand, this paper reports that the biodiesel from duck fat waste along with the addition of nanoparticles shows improved engine performance, reduced regulated emissions than conventional fuel conditions. Furthermore, nanoparticle addition to biodiesel leads to improved combustion efficiency. Specifically, the TiO_2 and CeO_2 nanoparticles with DMW biodiesel show better engine performance and lower emission values than standalone conditions. Moreover, the different waste feedstocks for biodiesel preparation with different nanoparticles for analyzing the engine combustion and emission parameters are to be studied in the future.

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