

Enhancing Combustion Efficiency and Emission Reduction in Single Cylinder CI Engines: A Study on Waste Dairy Scum Methyl Ester Biodiesel Blends with Aluminium Oxide Nanoparticles

Veeranna Modi^{1,*}, Prasad B. Rampure²

Abstract

In response to the urgent need for sustainable energy solutions and environmental considerations, this study explored the utilization of waste dairy scum methyl ester biodiesel blended with diesel and enhanced with Al₂O₃ nanoparticles as an additive. The biodiesel was prepared by blending waste dairy scum methyl ester with diesel and incorporating 100 ppm Al₂O₃ nanoparticles. Experimental tests were conducted on a single-cylinder diesel engine, comparing neat diesel, B30 biodiesel blends (with and without Al₂O₃ nanoparticles), and B30+ Al₂O₃. At peak load conditions, B30+ Al₂O₃ exhibited the lowest brake-specific fuel consumption (BSFC) compared to neat diesel and B30 biodiesel. Furthermore, the brake thermal efficiency (BTE) with B30+ Al₂O₃ was 2.31% higher than that of diesel and 2.06% higher than B30. Carbon monoxide (CO) emissions were reduced by 16.66% with B30 and B30+Al₂O₃ compared to diesel. Additionally, carbon dioxide (CO₂) emissions decreased with the use of Al₂O₃ nanoparticles, showing a reduction of 4.27% compared to diesel and 2% compared to B30. Hydrocarbon (HC) emissions were also lowered by 7.69% with B30 and 13.46% with B30+ Al₂O₃. Overall, the addition of nanoparticles contributed to improved performance and reduced emissions when compared to B30 biodiesel blend and neat diesel. This research effectively addresses both energy and environmental challenges.

Keywords: Al₂O₃ nano additive, dairy scum methyl ester biodiesel, diesel engine emissions

INTRODUCTION

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Emissions from transportation sector engines significantly impact air quality, the environment, and public health. A global study by Yaoxian Huang and colleagues revealed that diesel engine use in India is associated with increased premature deaths related to respiratory and cardiovascular diseases, surpassing other regions. Additionally, according to an APEDA report, India's dairy exports reached 67,573.03 tonnes in 2022-2023. Research by Raghunath B.V [1]. highlights that dairy farms produce 2.5 liters of wastewater for every liter of milk processed. This rapid decomposition of milk waste leads to reduced water oxygen content, potentially contributing to the spread of diseases like dengue and chikungunya, as well as air pollution. Furthermore, Ashis Ranjan Behera and colleagues demonstrated that dairy wastewater can serve as a successful feedstock for biodiesel

production, particularly when combined with high-fat-accumulating bacteria. Recent literature explores the use of milk waste for milk foam biodiesel and its incorporation into nanoparticles for compression ignition (CI) engines, offering solutions to environmental and health challenges. The visual representation in Figure 1 illustrates the export trend of dairy products.

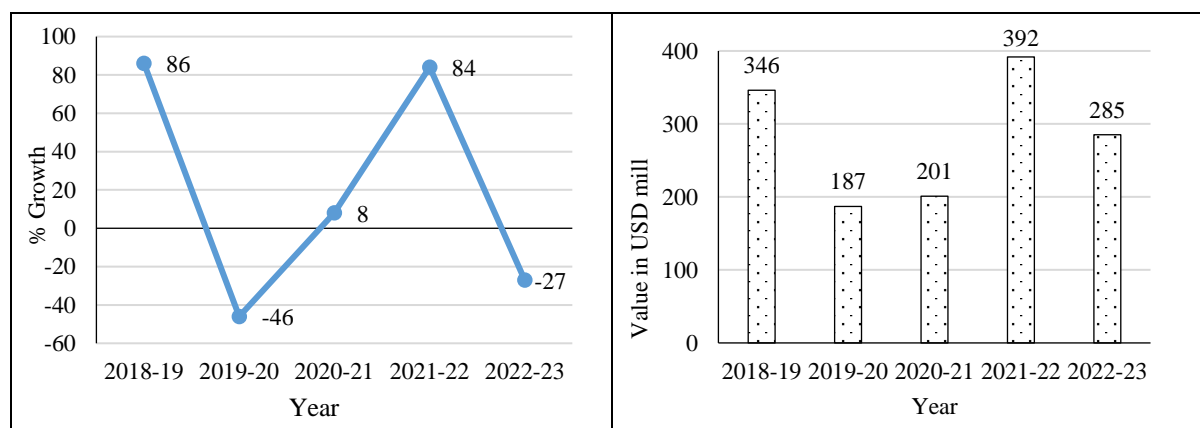


Figure 1. Milk export from India in LASR 5 years [25].

K.A. Sateesh et al [14] ready 1 litre of DSME biodiesel with 20 ppm MWCNT nanoparticles. Its properties meet ASTM standards. Using an ultrasound device for 1 hour at a test frequency of 40 kHz to obtain a homogeneous mixture is a suitable technique and is used. Oleic acid present in DSME biodiesel acts as a surfactant [13,14]. Telgan, Veerbhadrapa et al [19]. Have optimally blended B20 milk scum biodiesel with Al_2O_3 nanoparticles, which could be a suitable replacement for pure diesel fuel from an emissions perspective [15,16]. Manjunath Channappagoudra et al [10]. prepared a DSOME+CuO blend that met ASTM standards [17]. Nanoparticles in DSME increased the viscosity, density, and heating value of the mixture [14]. The production of DSME biodiesel blends containing nanoparticles plays an important role in the study of CI engine performance and emissions [2-11]. Manjunath Channappagoudra [10] and team found that DSMEB20 blended with 75 ppm CuO nanoparticles achieved the highest brake thermal efficiency (BTE) of 31.26%. Remarkably, it maintained brake specific fuel consumption (BSFC) comparable to diesel, thanks to the higher dosage of CuO nanoparticles. [12] K.A. Sateesh et al [14] quantitatively optimized DSME by adding 40 ppm multi-walled carbon nanotube nanoparticles. This resulted in a 4.2% increase in BTE compared to the 60 ppm dosage, especially during operation on producer gas. Veerbhadrapa Telgane's [19] research demonstrated that the DSME B20 blend led to increased BTE and BSFC as the compression ratio of the CI engine increased [14]. The presence of Al_2O_3 nanoparticles in DSME biodiesel significantly improved engine BTE. Studies by Shaik Masthan Shareef [5] revealed that BTE with DSME blends was lower than that with diesel. Manzoore Elahi's work found that adding 40 ppm graphene oxide nanoparticles to DSME B20 increased BTE by 11.56% compared to B20. However, they also observed increased BSFC compared to diesel. Lower concentrations of 20 ppm and 40 ppm MWCNT in DSME + Producer Gas resulted in shorter combustion duration compared to higher concentrations. The addition of Al_2O_3 nanoparticles (with a higher surface-to-volume ratio) stimulated the combustion process [15]. DSME mixture with CuO nanoparticles exhibited higher cylinder pressure compared to DSMEB20 and diesel. DSME + Producer Gas + MWCNT nanoparticles showed reduced heat release rate (HRR) compared to Diesel + Producer Gas. Adding 40 ppm graphene oxide nanoparticles to DSMEB20 increased the heat release rate (HRR) and peak pressure [18,19]. Specifically, they observed a 20.6% decrease in carbon monoxide (CO), a 21.6% decrease in hydrocarbons (HC), a 21.8% decrease in nitrogen oxides (NOx), and a decrease in smoke emissions compared to diesel combined with production gas [14]. Similarly, Manzoore Elahi M et al. [4] investigated the use of 40 ppm graphene oxide nanoparticles in DSMEB20 and found a significant improvement in emissions. A novel nanoparticle mixture demonstrated a significant reduction of 38.62% in CO, 21.68% in HC, and a substantial 24.88% reduction in smoke emissions compared to DSMEB20 [20-22]. In a related study, Manjunath Channappagoudra [6] and colleagues investigated the impact of 50 ppm CuO nanoparticles

in DSMEB20. This blend exhibited lower CO, HC, and smoke emissions than conventional diesel [12]. These findings underscore the potential of nanoparticle additives to significantly reduce toxic emissions, contributing to cleaner and more environmentally friendly combustion in various biodiesel blends. The literature review sets the stage for further exploration and development of aluminium oxide nanoparticle-enhanced DSME biodiesel. This sustainable solution aims to enhance CI engine performance while mitigating harmful emissions in the transportation sector. Our research focuses on studying the performance of a single-cylinder diesel engine by incorporating Al_2O_3 nanoparticles into a biodiesel mixture called Dairy Scum Biodiesel (DSME) at a concentration of 30% (B30). We will evaluate and compare the properties of these biodiesel blends Diesel, DSME, DSME B30 and B30+ Al_2O_3 . Additionally, research is investigating the impact of Al_2O_3 nanoparticles on the performance of compression ignition (CI) engine fuelled with these biodiesel blends. In addition, the study also examined the effect of Al_2O_3 nanoparticles on emissions produced by CI engines running on biodiesel blends.

MATERIALS AND RESEARCH METHODOLOGY

The research methodology employed in this study is visually illustrated through Figure 2

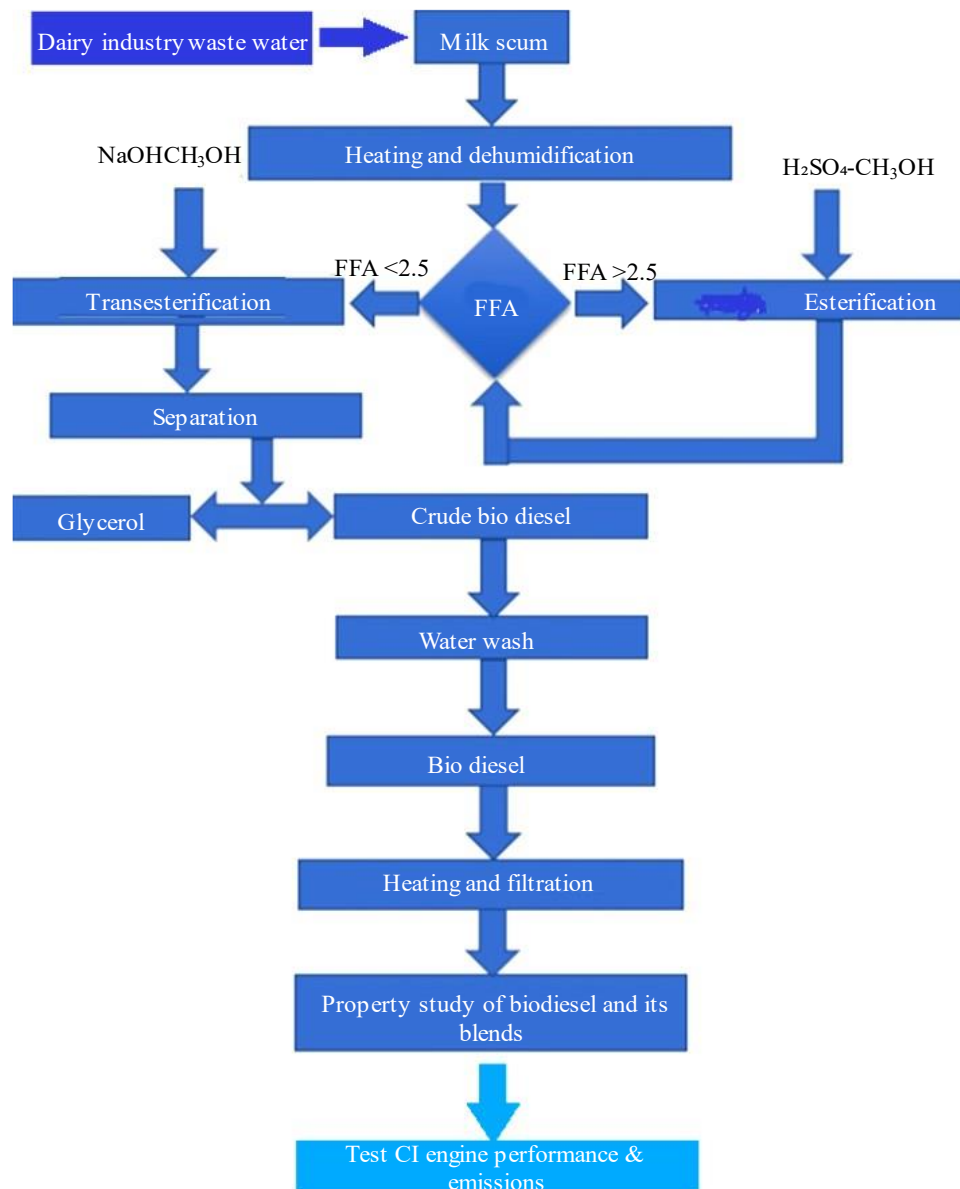


Figure 2. Flow chart of methodology.

Collection of dairy waste

Samarth Dairy and Agro Products Private Limited, situated in Chikodi, Karnataka, India, processes approximately 10,000 kilograms of dairy products daily. Their product range includes milk packets and ghee. During the dairy processing, they generate around 25,000 liters of wastewater per day, which contains scum resulting from equipment cleaning. Remarkably, they can extract 60 to 70 kilograms of fat content from this wastewater daily. This fat content provides the potential to produce approximately 45 to 50 liters of Dairy Scum oil each day, offering an opportunity for sustainable biodiesel production from dairy waste materials. In total, 6 kilograms of dairy scum were collected.

Dairy waste oil

The accumulated dairy residue was heated to a temperature of 130°C, effectively removing all moisture content. Subsequently, the oil extracted from the milk residue underwent filtration to eliminate any coarse or floating impurities. The procedure is shown in Figure 3



Figure 3. Dairy waste boiling.

FFA test

The milk scum oil underwent a series of tests, beginning with an evaluation of free fatty acids (FFA) using FFA test strips in a laboratory setting. Initially, the FFA content was measured at 12.4%, which significantly exceeded the allowed FFA limit of 2.5%. To rectify this issue, an acid-catalyzed esterification process was employed to reduce the FFA content to a more acceptable level of 1.41%. During this process, the milk scum oil was heated to 50°C with continuous stirring. Additionally, 200 ml of methanol and 10 ml of H₂SO₄ were added to the mixture, which was then stirred for 3 hours. Afterward, the reaction solution was allowed to stand for one day, during which excess reactants and impurities (such as methanol and acid) formed another layer on top, facilitating their removal. The resulting mixture of dairy scum oil and dairy scum methyl ester is depicted in Figure 4.

Transesterification Process

In the transesterification process, 1000 ml of scum is heated to 65°C and then transferred to the round-bottom flask of the esterification setup. In the experimental setup, a mixture comprising 300 ml of methanol and 5 grams of NaOH pellets is prepared in a beaker. This mixture is then gradually added to the flask containing the scum. During this process, the combination of milk scum, methanol, and NaOH is continuously stirred until the Free Fatty Acids (FFA) form a distinct upper layer. Subsequently, the

mixture is further stirred until glycerin separates into its own distinct layer. The experimental procedure aims to separate the components effectively, allowing for subsequent analysis or processing. The glycerin has formed this separate layer, the mixture is left to settle for approximately 12 hours. During this period, the FFA and any impurities floating on the top surface are removed from the mixture Figure 5.

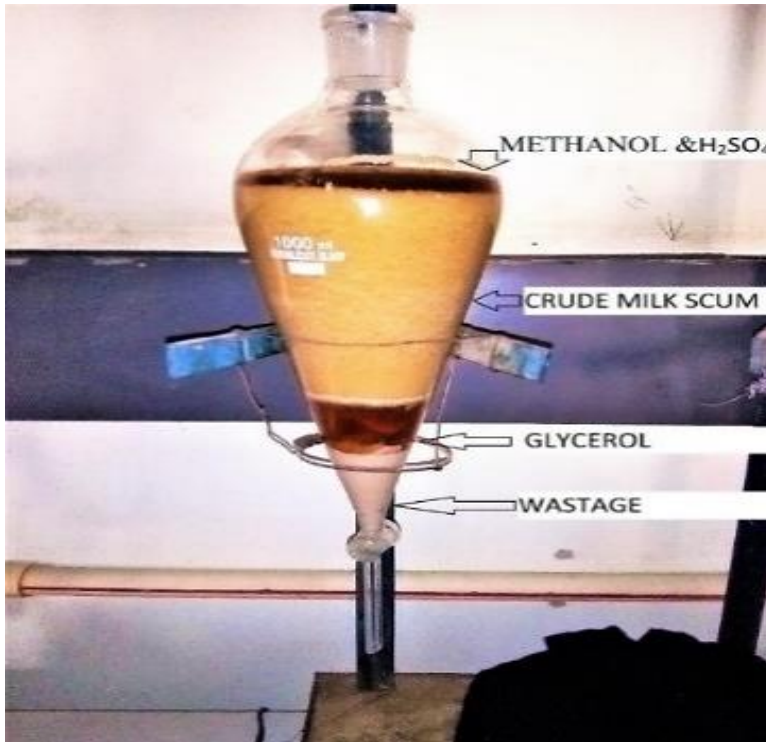


Figure 4. Dairy Scum Oil after Esterification.



Figure 5. Crude biodiesel after transesterification

The obtained biodiesel is washed 12 times with water at 70°C to remove the catalyst. The heating process evaporates the water present in the biodiesel. The complete process is shown in Figure 6.



Figure 6. Biodiesel production process.

Table 1 Properties of diesel and DSME blends

Biodiesel Blend Preparation

The diary scum biodiesel thus produced is named as DSME. The Blend B30 of biodiesel produced with of 30% DSME and 70% diesel was chosen to conduct the experiment. To produce B30 blend 30% DSME and 70% diesel were collected in a flask and continuously stirred with mechanical stirrer. The desirable properties of the diesel, DSME and the B30 blend were tested as per ASTM standards. The B30 blend thus produced is added with the 100ppm (0.10gm) Al_2O_3 nanoparticles. The Ultrasonicator maintained the uniform distribution of the nanoparticles.

Properties of diesel and DSME blends.

Desirable properties of diesel, DSME, and the B30 blend underwent testing according to ASTM standards. The flash point was assessed using the Pensky-Martens apparatus. Viscosity was measured using the Redwood Viscometer. The calorific value was determined using the bomb calorimeter. The resulting properties obtained from these tests are summarized in Table 1.

Effect of Nanoparticles on Properties of Biodiesel

The kinematic viscosity of the DSMEB30+ Al_2O_3 nano additive fuel blend surpasses that of both DSMEB30 and diesel. The inclusion of aluminum oxide (Al_2O_3) nanoparticles elevates fuel viscosity. These nanoparticles possess a high surface area, leading to interactions with fuel molecules and the formation of clusters. These clusters obstruct fuel flow, contributing to increased viscosity. Additionally, the surface chemistry of nanoparticles influences interactions with surrounding molecules, further impacting viscosity. Overall, DSMEB30+ Al_2O_3 exhibits greater kinematic viscosity

than pure diesel due to factors such as biodiesel chemical composition, nanoparticle effects, and the biodiesel-diesel blend effect. The density of DSMEB30+Al₂O₃ increases after the addition of nanoparticles, indicating that the biodiesel blend with Al₂O₃ nanoparticles is denser.

Table 1. Thermo Physical Properties of fuels than pure diesel.

Parameter	Diesel	DSME	B30	B30+Al ₂ O ₃	ASTM Standard
Flash point (°C)	54	90	60	58	ASTM D93
Viscosity (cSt)	2.8	3.2	3.0	3.1	ASTM D445
Density (kg/m ³)	830	836	835	835.01	ASTMD1298
Calorific value (kJ/kg)	42000	30963	39721	39780	ASTM D240

Flash Point

The flash point of DSMEB30+ Al₂O₃ is lower than that of DSMEB30, indicating that the addition of aluminum oxide (Al₂O₃) nanoparticles results in a lower flash point for the biodiesel blend.

Lower Flash Point of DSMEB30+ Al₂O₃ Compared to Diesel.

The flash point of DSMEB30+ Al₂O₃ is lower than that of diesel, suggesting that the biodiesel blend with Al₂O₃ nanoparticles has a lower flash point than pure diesel fuel.

Calorific Value

Calorific Value Enhancement: The calorific value of DSMEB30+Al₂O₃ exceeds that of DSMEB30, implying that the addition of aluminum oxide (Al₂O₃) nanoparticles enhances the energy content of the biodiesel blend. **Improved Combustion Efficiency:** The inclusion of nanoparticles, such as Al₂O₃ enhances the combustion efficiency of biodiesel. These nanoparticles facilitate better fuel-air mixing, promote improved atomization, and increase the available surface area for combustion. Consequently, this leads to more complete combustion and a higher calorific value. **Comparison with Diesel:** DSME and its blends exhibit lower calorific values than diesel, indicating that they have a reduced energy content per unit mass.

There are several reasons for this difference:

- Biodiesel's chemical composition:** Biodiesel, including DSME, is typically made from animal fats. These feedstocks contain oxygen in their molecular structure, reducing the energy content compared to hydrocarbon-based diesel, which contains no oxygen. The presence of oxygen leads to lower energy content in biodiesel.
- Lower energy density:** Biodiesel has a lower energy density compared to petroleum diesel, resulting in a lower calorific value. This is due to the lower hydrogen-to-carbon ratio in biodiesel molecules.

Experimental Setup

A single cylinder, four stroke, water cooled CI engine with, variable compression ratio was used in the present experimentation work. The engine and gas analyzer specifications are represented in the Table 2.

Figure 7 illustrates the computerized experimental setup used for engine testing The Kirloskar make TV! Model, single cylinder engine was used in the experiment. The crankshaft speed was maintained at a constant 1500 rpm. The compression ratio was set to 17.5:1. The load was applied using an Eddy current dynamometer. The engine underwent performance and emission testing initially with regular diesel fuel, followed by B30 fuel and B30 Al₂O₃ fuels. Performance parameters were measured using the Enginesoft software on a computer. The accuracies of these measurements were less than 1.5 in

each measurement parameter. The AVL make five gas analyser was used to measure the emission by engine.



Figure 7. Experimental set up.

RESULTS AND DISCUSSIONS

Performance of Engine

Performance parameters were measured and graphed to analyze the impact of aluminum oxide nanoparticles combined with dairy scum biodiesel on CI engine performance. Gradual load application to the engine resulted in varying brake thermal efficiency, as depicted in Figure 8. The study reveals that as engine load increases, brake thermal performance improves across all three tested fuels. This efficiency enhancement suggests that the engine operates more effectively under heavier workloads. Notably, the highest observed brake thermal efficiency reached 23.07% when the engine ran at full power, signifying its peak capacity. The finding that brake thermal efficiency rises with higher engine loads has significant implications. It implies that heavier workloads enable more efficient engine operation, leading to improved fuel economy and reduced emissions. This discovery may influence engine design and encourage the use of higher loads to optimize efficiency. Additionally, the B30+Al₂O₃ fuel mixture achieved 2.31% greater efficiency compared to the diesel fuel mixture.

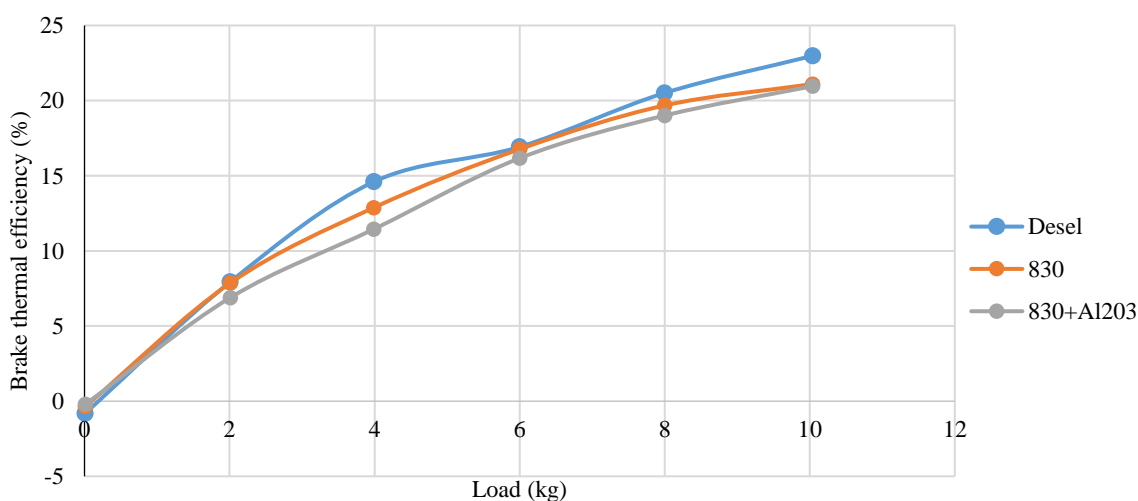


Figure 8. Brake thermal efficiency variation with load.

The comparison between B30+ Al₂O₃ and B30 highlights the importance of combustion quality in engine performance. B30+ Al₂O₃ outperformed B30 by 2.06% in brake thermal efficiency, thanks to its superior combustion characteristics. This finding has implications for fuel formulation and combustion optimization, suggesting opportunities to improve engine performance. The observed 2.31% higher brake thermal efficiency of B30+ Al₂O₃ compared to a diesel engine has significant implications for fuel selection. B30+ Al₂O₃ emerges as a favorable choice, particularly for applications prioritizing performance. This could lead to increased adoption of B30+ Al₂O₃ in engines aiming for enhanced performance and reduced fuel consumption. In summary, the study demonstrates that increasing engine load enhances brake thermal performance across all tested fuel types. Notably, B30+ Al₂O₃ stands out as the most efficient, surpassing diesel by 2.31% and B30 by 2.06% due to its superior combustion characteristics. These findings have broad implications for engine performance, load management, fuel choice, and combustion optimization, potentially influencing future research and engineering decisions in the field of internal combustion engines [23-24].

Effect of Aluminium oxide nanoparticles on Brake Specific Fuel Consumption.

The variation in BSFC with gradual loading on the engine is represented in Figure 9. The results show that as engine load increases, BSFC decreases for diesel fuel and its mixture [25]. Furthermore, at full load, the B30+Al₂O₃ mixture has the lowest fuel consumption, with a specific value of 0.39 kg/kW-h. This mixture helps reduce BSFC by 4.9% compared to pure diesel and significantly more than 9.30% compared to B30 mixture. The B30 blend showed improved fuel efficiency compared to pure diesel, possibly due to its higher biofuel content. Biofuels can have a positive impact on combustion efficiency and emissions. The most significant reduction in BSFC was observed in the B30+Al₂O₃ mixture. The presence of Al₂O₃ nanoparticles in fuel can help to improve combustion efficiency.

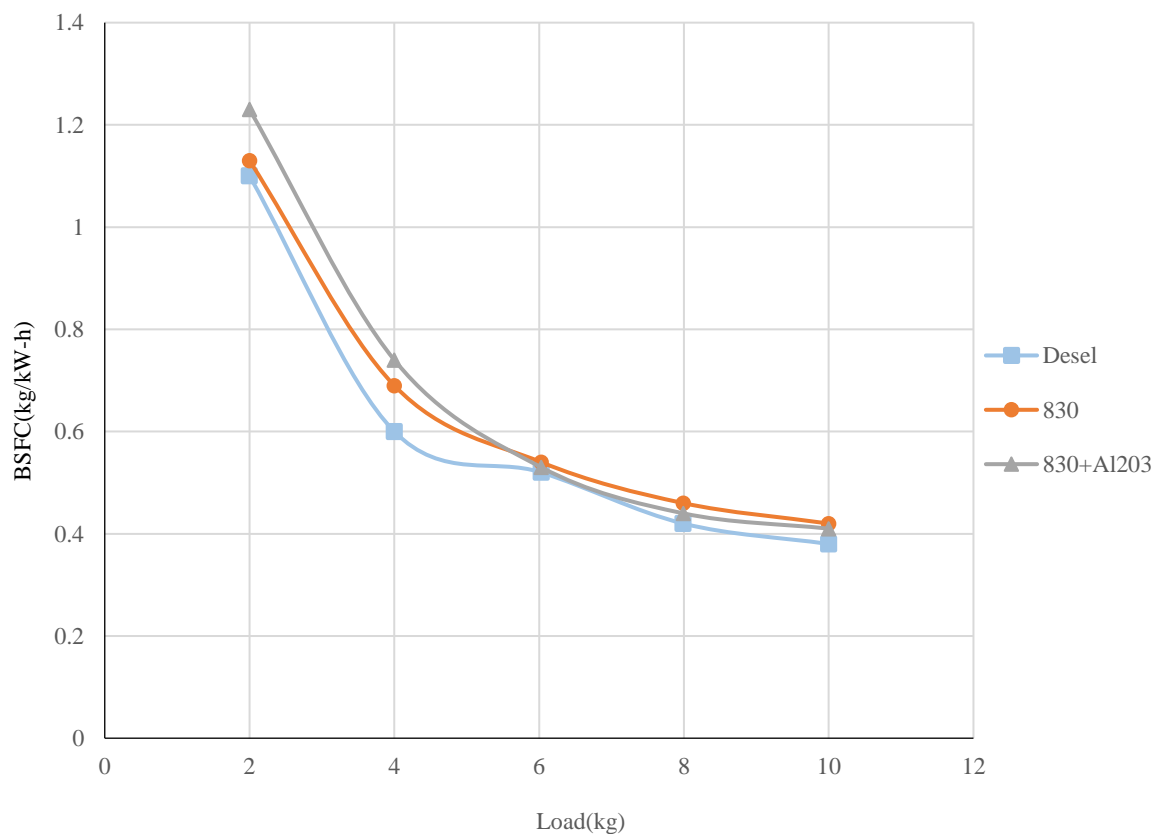


Figure 9. Variation of BSFC with load.

Nanoparticles can improve combustion by promoting better fuel injection and mixing, leading to more complete and efficient combustion. In summary, the study shows that the addition of Al_2O_3 nanoparticles to the B30 diesel fuel mixture can significantly improve fuel efficiency, reduce BSFC, and improve combustion performance. These findings have important implications for the development of cleaner and more efficient combustion technologies.

Emission Characteristics

The measured emissions from the gas analyser are used to plot the graphs. The graphs are analysed to study the effect of aluminium oxide nanoparticles with dairy scum biodiesel on the CI engine emission.

Effect of Aluminium oxide nanoparticles on CO emission.

Figure 10 illustrates the variation in carbon monoxide (CO) levels with gradual loading for three different fuel blends on the engine. A comparative analysis of CO emissions between diesel fuel, B30, and B30+ Al_2O_3 at full load reveals interesting findings. Diesel fuel exhibits the highest CO emissions, measuring 0.18%, while both the B30 blend and the B30+ Al_2O_3 blend show lower CO emissions at 0.15%. Remarkably, this means that the CO emissions of B30 and B30+ Al_2O_3 are 16.66% lower than those of diesel. Opting for B30 or B30+ Al_2O_3 blends instead of pure diesel can serve as a viable strategy to mitigate the environmental impact of carbon monoxide. Notably, the B30 and B30+ Al_2O_3 mixtures boast higher oxygen concentrations than diesel. Oxygen plays a crucial role in combustion, and elevated oxygen levels enhance combustion efficiency. The additional oxygen in the blended fuel contributes to improved combustion kinetics and air-fuel mixing, resulting in cleaner and more thorough combustion. Surprisingly, this leads to reduced CO emissions. In summary, the study highlights that higher oxygen concentrations in B30 and B30+ Al_2O_3 mixtures enhance combustion efficiency while simultaneously reducing CO emissions compared to diesel fuel.

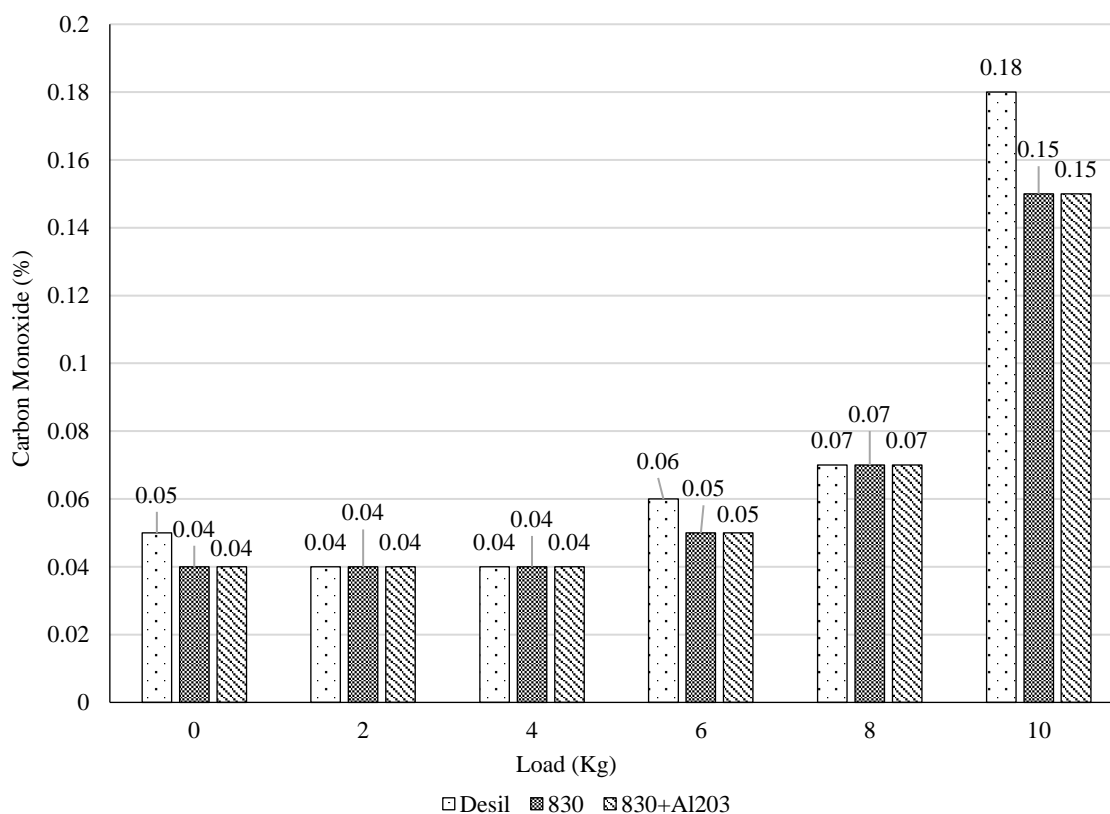


Figure 10. CO Emission with load.

Effect of Aluminium oxide nanoparticles on Hydro Carbon (HC) Emission

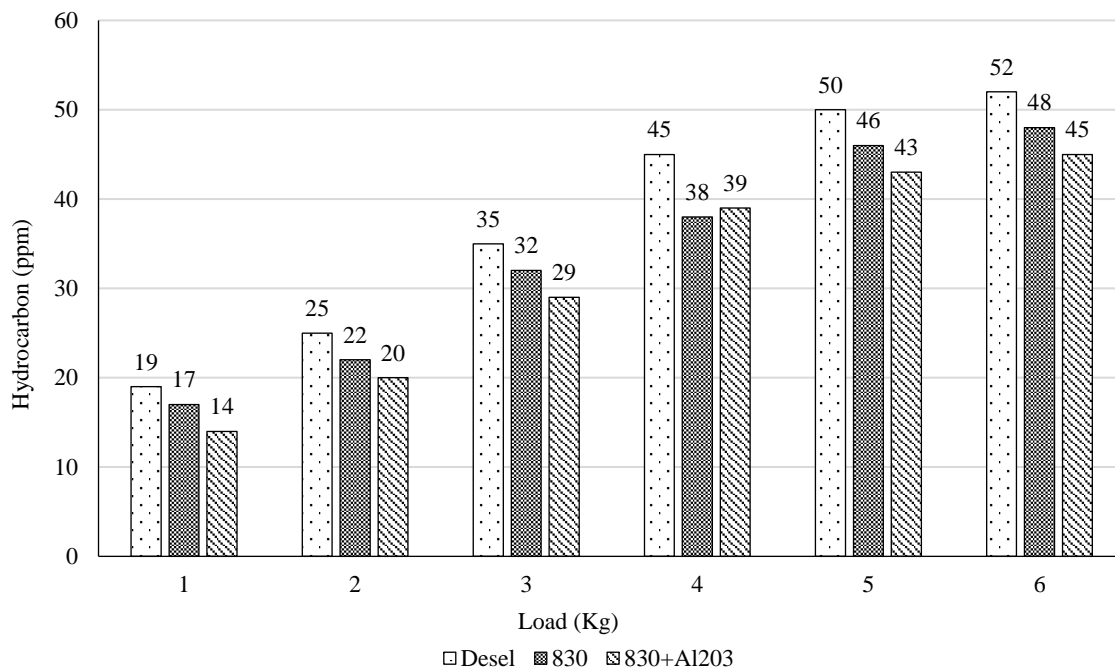


Figure 11. HC emission with load.

The study’s implications extend to all three fuels. Notably, diesel fuel exhibited the highest hydrocarbon (HC) emissions at 52 parts per million (ppm). In contrast, both the B30 blend and the B30+Al₂O₃ blend demonstrated lower HC emissions, reduced by 7.69% and 13.46%, respectively, compared to diesel. This reduction in HC emissions within the B30 and B30+Al₂O₃ blends likely results from improved hydrocarbon oxidation during combustion (fig.11) The additional oxygen present in these blends promotes more thorough combustion, leading to fewer unburned hydrocarbons in the exhaust. Overall, this reduction in HC emissions from B30 and B30+Al₂O₃ compared to diesel has significant implications for air quality Effect of Aluminium oxide nanoparticles on Nitrogen Oxides emission.

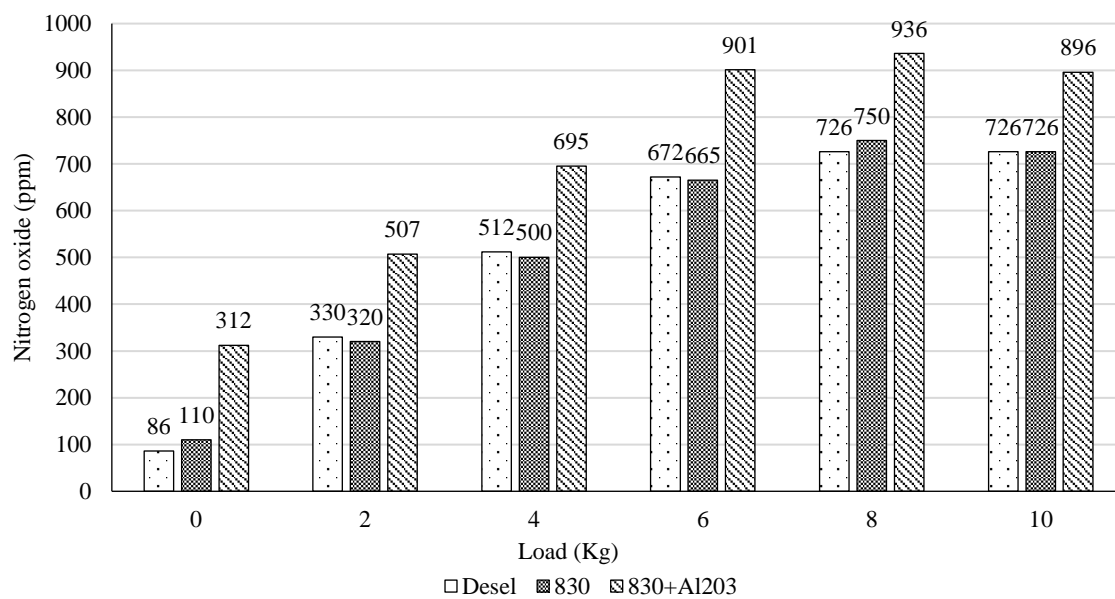


Figure 12. Variation of NO_x with load.3

Figure 12 presents a comparison of nitrogen oxides (NO_x) emissions across different fuels. Notably, the B30 and B30+ Al₂O₃ blends exhibit higher NO_x emissions, measuring 896 parts per million (ppm), in contrast to diesel fuel. Biodiesel blends, including B30 and B30+ Al₂O₃, typically contain elevated oxygen levels compared to pure diesel. This increased oxygen content can lead to more thorough combustion, subsequently raising the combustion temperature and resulting in higher NO_x emissions. Additionally, the inclusion of nanoparticles (Al₂O₃) in the fuel enhances combustion efficiency. Nanoparticles facilitate improved fuel atomization, better mixing, and enhanced combustion kinetics, leading to elevated combustion temperatures and further contributing to NO_x emissions. Consequently, addressing these increased NO_x emissions necessitates the implementation of emission control technologies and strategic measures, especially to comply with emissions regulations and environmental standards.

CONCLUSIONS

- The utilization of DSMEB30, combined with Al₂O₃ nanoparticles, serves as a fuel enhancement strategy to improve engine performance and reduce emissions.
- The addition of Al₂O₃ nanoparticles to the fuel mixture (B30+Al₂O₃) significantly improves the engine's thermal efficiency.
- The improvement in BSFC is attributed to the presence of Al₂O₃ nanoparticles in B30+ Al₂O₃ which played a crucial role in achieving better combustion efficiency.
- B30+ Al₂O₃ demonstrated substantial enhancements in hydrocarbon (HC) emissions and brake thermal efficiency, although it also exhibited elevated nitrogen oxides (NO_x) emissions. The incorporation of Al₂O₃ nanoparticles played a pivotal role in these transformations, acting as a catalyst to improve combustion and mitigate carbon monoxide (CO) and HC emissions.
- This study provides valuable insights for optimizing fuel compositions and combustion processes, ultimately leading to better environmental and efficiency outcomes.
- Utilizing dairy scum for DSME biodiesel production represents a sustainable and environmentally friendly choice.
- The inclusion of nanoparticles has significantly improved performance and emissions compared to both biodiesel blends and neat diesel.

Future scope

Overall, the use of nanoparticles in biodiesel blends is a complex and multifaceted area of research, and their effects on fuel properties have important implications for combustion, emissions, and fuel consumption. Further studies are essential to fully understand and optimize the use of nanoparticles in biodiesel production.

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