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Original Article

Experimental Investigation of Thermal Conductivity Enhancement and Combustion Characteristics of Cashew Nut Shell Biodiesel Blended with Magnesium Oxide Nanoparticles

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Abstract *- The thermophysical constraints inherent in biodiesel, such as low thermal conductivity, increased viscosity, and poor cold-flow characteristics, usually lead to poor burning characteristics relative to traditional diesel. This paper examines the process of improving thermal Conductivity and Combustion Properties of Cashew Nut Shell Biodiesel (CNSBD100) by using Magnesium Oxide (MgO) nanoparticles at ultra-low levels of 50 ppm and 100 ppm. Biodiesel made out of cashew nut shells was done through two-step transesterification with MgO nanoparticles dispersed through ultrasonication. The thermal conductivity obtained showed that at 30°C, 6.6 and 9.6% improvements and at 70°C, 1.3 and 3.9% improvements were made in the 50-ppm and 100-ppm blends, respectively, relative to neat biodiesel. Experiments on a single-cylinder compression ignition engine working at peak load conditions revealed that an increase in the thermal conductivity was directly proportional to an increase in the combustion performance. The highest cylinder pressure rose to 59.50 bar with neat biodiesel and 63.79 bar (50 ppm) and 67.39 bar (100 ppm), and the latter reached 99.8% of the diesel performance (67.54 bar). Equally, maximum heat release rate increased from 67.64 J/°C·A to 72.12 J/°C·A (50 ppm) and 74.31 J/°C·A (100 ppm). The findings create a mechanistic association between the augmented thermal conductivity and combustion enhancement because of nanoparticles and the accelerated fuel evaporation, reduced ignition delay, and enhanced premixed combustion. This paper reveals that the thermophysical drawbacks of biodiesel can be effectively countered by ultra-low concentrations of MgO nanoparticles, which are a viable way to enhance combustion in modern diesel engines, in their current state.*

Keywords *- Biodiesel, Thermal conductivity, Combustion characteristics, Heat Release Rate, Compression Ignition Engine, Nano-Additives.*

1. Introduction

Rapid exhaustion of fossil fuel reserves and the growing strictness of the global emission regulations have led to an increase in the search for sustainable and environmentally benign alternatives to traditional mineral diesel [1]. Biodiesel has become one of the best renewable alternatives since it is biodegradable and is recycled [2]. Its oxygenated molecular structure also improves.

Its combustion as compared to petroleum diesel [3]. Furthermore, an already existing Compression Ignition (CI) engine can be used with biodiesel with few or no alterations to the engine [4]. It has been reported that through experimental studies, there were considerable cuts in the emissions of particulate matter when using biodiesel [5]. Reduction in Carbon Monoxide emissions has also been constantly experienced as a result of the natural oxygen content of biodiesel fuels [6]. On the same note, the unburned hydrocarbon emissions are decreased due to enhanced oxidation reactions during combustion [7]. Although this is the case, biodiesel fuels have various inherent thermophysical constraints limiting their use [8]. The viscosity is high in comparison with that of diesel, which negatively influences the features of spray atomization [9]. Reduced volatility also adds to the bad evaporation behavior within the combustion chamber [10]. The low cold-flow characteristics also pose a challenge in doing operations in low temperatures [11]. These two factors combined are known to cause an increase in ignition delay and slower combustion kinetics [12]. There are instances where biodiesel combustion also causes higher nitrogen oxide emissions because of oxygen-enriched high-temperature areas [13]. Thus, increasing biodiesel thermophysical properties has emerged as one of the key topics of study [14]. The process of feedstock selection is significant to either biodiesel sustainability or economic viability [15]. Food-fuel conflict is an issue that has been driven away by using non-edible and waste-derived feedstocks [16]. One of such underutilized agro-industrial waste products is cashew nut shell oil [17]. It is rich in cashew processing plants and comes at a cost benefit [18]. Cashew nut shells that are processed by biodiesel have favorable cetane properties that can be used in CI engines [19]. Nevertheless, like all the other biodiesels, cashew nut shell biodiesel is plagued by the high viscosity and low thermal transport properties [20]. In order to address such limitations, fuel modification through nanotechnology has attracted much concern over the past years [21]. Nanofuels are made by mixing the metallic or metal oxide nanoparticles with base fuels in trace levels [22]. Three different nanonosized TiO_2 particles, such as 28 nm, 40 nm, and 200 nm, were chosen to disperse in the fuel, and the size effect on performance was investigated. The results showed that the smaller the nanoparticle size, the better the effective cetane number, thermophysical properties, and heating value of the test fuels [23]. The emphasis on nano-fuel performance depends on concentration, sonication, dispersants, and stability, as reviewed in [24].

Nanoparticles such as CuO and Cu/Ag combinations suspended in a B20 blend, with several engine test runs, were carried out for better performance. Thus, a zeta potential value above +30 mV performed well, and this is proven due to its good stability [25]. The strong electrostatic repulsion by Graphene Oxide (GO) revealed a zeta potential value above ± 30 mV, prompting the dispersion of GO nanoparticles in B25 fuel utilized in CI engines, which exhibited good combustion efficiency [26]. Research experimentally showed that the addition of nanoparticles enhances the efficiency of combustion and ignition properties [27]. They also improve the performance of the emission by using catalytic oxidation [28]. Aluminum oxide, cerium oxide, titanium dioxide, and zinc oxide are among the common types of nanoparticles studied in biodiesel [29]. These nano-additives encourage the occurrence of micro-explosions and second atomization [30]. Better oxygen buffering capacity also enhances faster reactions of combustion [31].

Magnesium oxide nanoparticles are some of the nano-additives that are currently rising in popularity because they are highly thermally conductive [32]. They have a high surface area to volume ratio, which increases the catalytic reactivity of combustion [33]. In-droplet heat transfer by MgO nanoparticles is also enhanced, and thus ignition delay time is reduced, and evaporation is accelerated [34]. The efficiency of using MgO nanoparticles for promoting combustion and performance of biodiesel engines has been recently revealed. The combustion efficiency and emissions levels were also improved in jojoba biodiesel CI engines with MgO nanoparticles, which was reported by Savaş (2025) [35]. Jayaraman et al. (2025) observed the same result in a single-cylinder diesel engine using blends of MgO nanoparticle-enriched biodiesel [36]. Similarly, Chaudhari et al. (2025) reported improved combustion efficiency and reduced CO, HC, and smoke emissions in a single-cylinder diesel engine operated with blends of MgO nanoparticle-enriched biodiesel [37]. Sulakhi et al. (2025) compared MgO with other metal oxide nanoparticles and reported significant improvement in combustion efficiency at 100 ppm nanoparticle concentration [38]. There are some previous works on the use of different feedstocks for biodiesel production and different additives, including Al_2O_3, CeO_2, TiO_2, ZnO, and CuO, to enhance the performance and emission properties of the engine. For most studies, the focus has been on the use of conventional feedstocks in the research and higher concentrations of nanoparticles, although some have had positive results in terms of the ability to catalyze and improve atomisation and combustion properties. There are a few investigations that have been undertaken on cashew nut shell biodiesel obtained from waste, especially its combustion properties and poor thermal conductivity. Furthermore, the relationship between the improvement of in-cylinder combustion behaviour and MgO nanoparticle-induced thermal conductivity has not been investigated enough. Thus, the present work aims to explore the effects of ultra-low level concentrations of MgO nanoparticles (50 ppm, 100 ppm) in cashew nut shell biodiesel on its thermophysical properties and to determine the influence of thermophysical properties on the combustion characteristics.

The use of nanoparticles in biodiesel has been extensively researched, but there are still a number of key research gaps. The conventional biodiesel feedstocks and comparatively higher quantity of nanoparticles have been used in most of the previous studies, while waste-derived non-edible feedstocks like cashew nut shell biodiesel have been less explored. Cashew nut shell biodiesel has been proven to have several environmental benefits; however, it has its own thermophysical properties, such as thermal conductivity and higher viscosity, which negatively impact fuel atomisation, fuel evaporation rate, combustion ignition behaviour and overall combustion efficiency. Hence, it is important to enhance these fuel properties without significant engine modifications for the practical application of biodiesel in compression ignition engines. Furthermore, prior researches are primarily focused on engine and emission performance of nanoparticle-biodiesel blends, and the fundamental link between the increase in thermal conductivity and an improvement in-cylinder combustion has not been well established, as illustrated in Table 1. However, the performance of ultra-low concentrations of Magnesium Oxide (MgO) nanoparticles at ppm levels and their influence on modifying the heat transfer behavior, combustion pressure development, and heat release characteristics of cashew nut shell biodiesel are still largely unknown. Therefore, to fill this research gap, the present work explores the effect of the ultra-low concentrations of MgO nanoparticles (50 ppm and 100 ppm) on cashew nut shell biodiesel, thermophysical, and combustion properties. The novelty of this work is that a direct correlation between the improvement in the thermal conductivity of the material and the enhancement in the combustion behaviour of the compression ignition 1-cylinder engine was established.

This study is different from the previous research, which typically assesses performance and emission parameters, as it correlates the direct impact of thermal conductivity increase with the improvement of in-cylinder combustion. This exploration aims to obtain a mechanistic understanding of the way in which the inherent limitations of biodiesel can be overcome by the use of MgO nanoparticles due to their enhanced heat transfer properties, fast evaporation rate, and reduced ignition delay and combustion performance.

Table 1. Comparison of existing studies and advancements of the present work

Research Source	Feedstock / Nanoparticle	Major Findings	Limitation	Advancement in Present Work
Agbulut (2022)	Canola oil methyl ester and diesel fuel binary blends + TiO_2 nanoparticles	Improved cetane number, thermophysical properties, and heating value.	No thermal conductivity–combustion correlation.	Establishes a direct correlation between thermal conductivity and combustion behavior
Borthakur (2025)	Fatty acid methyl Esters +Nanoparticle-TiO_2, Cu-O,CeO_2	Identified concentration, sonication, and stability as key factors.	Review study; no CNS biodiesel validation.	Experimental validation using waste-derived CNS biodiesel with stable MgO dispersion.
Yilmaz (2025)	karanja oil biodiesel-diesel fuel blend + CuO and Cu/Ag nanoparticles	Improved engine performance and combustion.	Thermophysical mechanisms have not been investigated.	Correlation of thermal conductivity enhancement with cylinder pressure and HRR improvements.
Megiso et al.(2025)	Ulva fasciata biodiesel + Graphene oxide	Improved combustion efficiency due to stable dispersion.	Limited thermal transport analysis.	Detailed thermal conductivity measurement and mechanistic combustion analysis.
Anbarsooz (2023)	Nano fuels review	Reported improved combustion characteristics.	No specific thermophysical-combustion correlation.	Demonstrates how MgO-induced thermal conductivity enhancement improves combustion.
Gad et al. (2024)	Waste cooking oil +TiO_2& Al_2O_3	Improved engine performance and emissions.	Higher nanoparticle loading and limited combustion	Achieves near-diesel combustion behaviour using ultra-low MgO concentrations.
Present Work	CNS biodiesel + MgO (50 & 100 ppm)	Thermal conductivity +6.6–9.6%; BTE 30.64%; Peak pressure 67.39 bar; HRR 74.31 J/°CA.	long-term stability, emissions, and techno-economic analyses	First mechanistic relationship between thermal conductivity enhancement and combustion improvement in CNS biodiesel using ultra-low MgO dosage.

2. Materials and Methods

2.1. Cashew Nut Shell Oil Extraction

Cashew nut shells were procured in a local cashew processing unit in Pudukkottai district, as they are a locally available agricultural waste that is available in large quantities. The shells that were obtained were thoroughly washed and left in the sun to dry over a span of 48 hours to eliminate all moisture elements. A Soxhlet apparatus was used in the extraction of the shells in the presence of n-hexane as a solvent (solid-to-solvent ratio 1:5 w/v) at 60°C for a duration of 6 hours to dry the shells and turn them into fine powder. The extraction process was followed by the rotation evaporation at low pressure to recover n-hexane and Cashew Nut Shell Oil (CNSO) filtered as shown (Figure 1).

2.2. Two-Step Transesterification Process

The Free Fatty Acid (FFA) content was evaluated in the CNSO and found to be 4.2% according to ASTM D6751. A two-step transesterification process was used to obtain complete conversion of the product to Fatty Acid Methyl Esters (FAME), by Acid esterification and alkali-catalysed transesterification. The pre-treatment consisted of an acid-catalyzed reaction to reduce the concentration of FFA to less than 1%. A molar ratio of 6:1 (methanol: oil) was used to mix one liter of CNSO with 6 ml of methanol. A 1% (v/v) Sulfuric Acid (H_2SO_4) was added to 10 ml of methanol to act as an acid catalyst. The mixture was poured into a three-necked round-bottomed flask and then heated to 70°C with a reflux condenser, a magnetic stirrer, and a temperature controller. The reaction was conducted at 600 rpm under constant stirring at a temperature of 70°C for 2 hours. The mixture was then allowed to settle for up to 2 hours using a separating funnel. The upper aqueous layer of excess methanol and water was pumped out, and the bottom layer of the esterified oil was decanted to undergo a subsequent base-catalyzed transesterification. In base transesterification, the oil that had undergone the step prior to this was alkaline-trans-esterified. The 0.75% w/w (based on the mass of the oil) Potassium Hydroxide (KOH) was mixed in 200 ml of methanol and converted into potassium methoxide solution [39]. The mixture of this catalyst-methanol was introduced to the esterified oil in the ratio of methanol to oil (6:1). The transesterification process was carried out at 60°C with aggressive stirring at 800 rpm for 1 hour. After the reaction, the mixture was passed into another separating funnel and let stand for 10 hours for phase separation. The lower layer of glycerol-rich biodiesel was collected, and the upper layer of biodiesel was washed with warm distilled water (50-60°C) multiple times to achieve neutral pH. The dried Cashew Nut Shell Biodiesel (CNSBD100) was dried with anhydrous sodium sulphate and then filtered to arrive at a final product as shown (Figure 2).

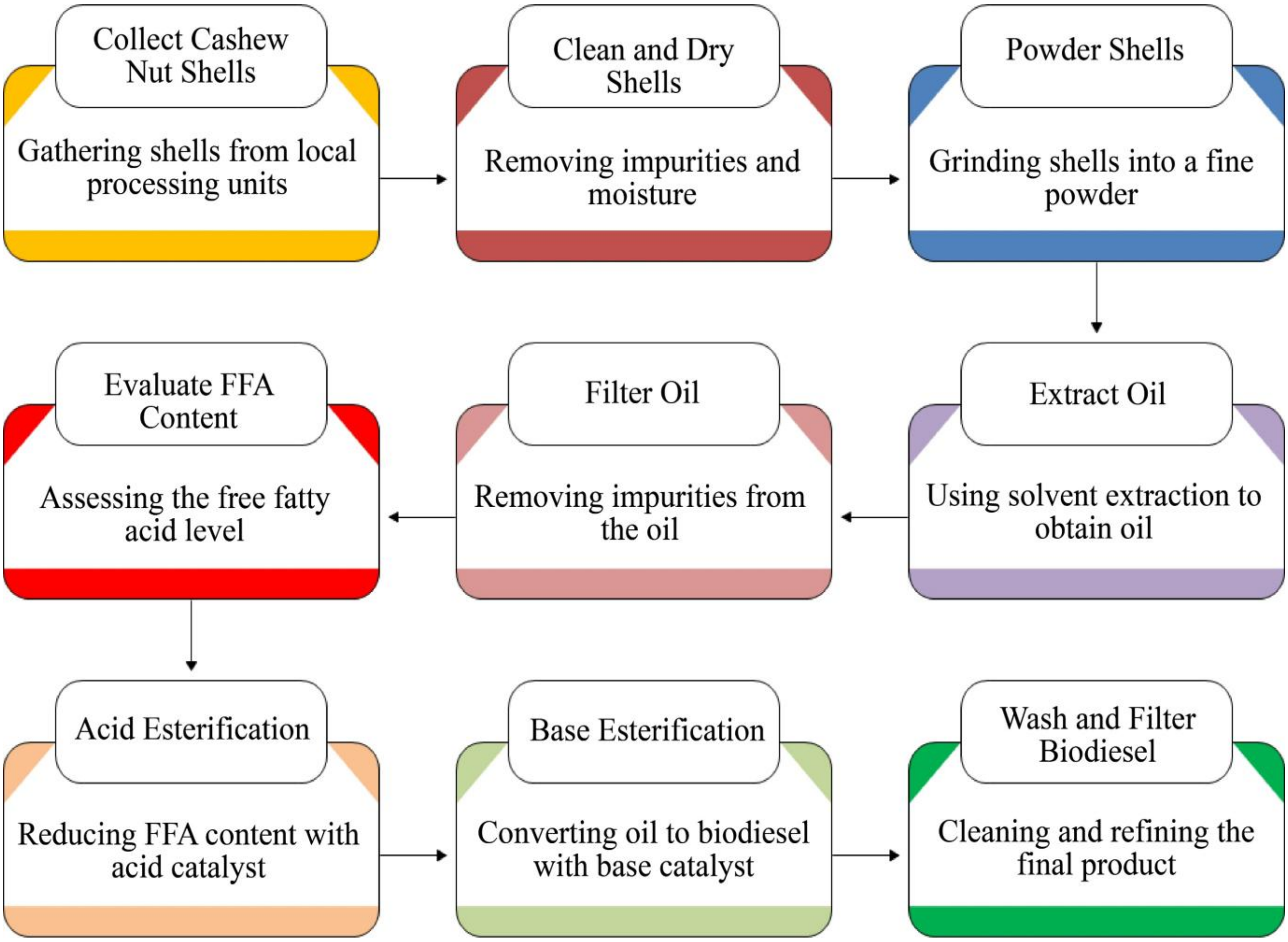

Fig. 1 Process flow diagram for cashew nut shells biodiesel

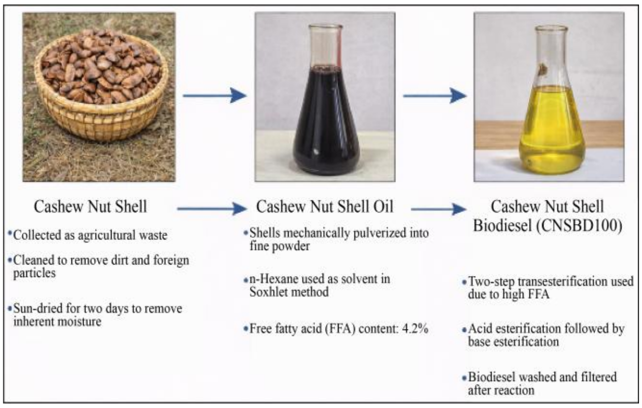

Fig. 2 Conversion pathway from cashew nut shells to biodiesel

2.3. Magnesium Oxide

Magnesium oxide nanoparticles of 40 nm size were purchased from SRL Private Limited, India, and the same were suspended in two concentration levels, namely, 50 ppm and 100 ppm in CNSBD, to improve its thermophysical characteristics and combustion process. The concentrations of 50 ppm and 100 ppm of magnesium oxide nanoparticles were dispersed in CNSBD100. In order to prevent any possible changes to the fuel properties and combustion behaviour, no surfactant was added during the preparation of the blends. The required amount of nanoparticles (MgO (45 mg/l, 90 mg/l)) was first magnetically stirred and then ultrasonicated for 30 minutes to achieve homogeneous dispersion and reduce particle agglomeration. Engine testing was performed after 20 h of stabilisation of the prepared blends. The combustion properties are given in Table 2, the SEM image of the MgO nanoparticles employed in this work (Figure 3). Fine particles with an irregular to nearly spherical shape and a rather uniform distribution are seen in the SEM image. Due to their high surface energy, metal oxide nanoparticles often exhibit some degree of particle aggregation. When distributed throughout biodiesel, the nanoscale structure's high surface-area-to-volume ratio may improve heat transmission and catalytic activity. It is anticipated that these traits will help the MgO-blended fuels exhibit better thermal conductivity and combustion behaviour.

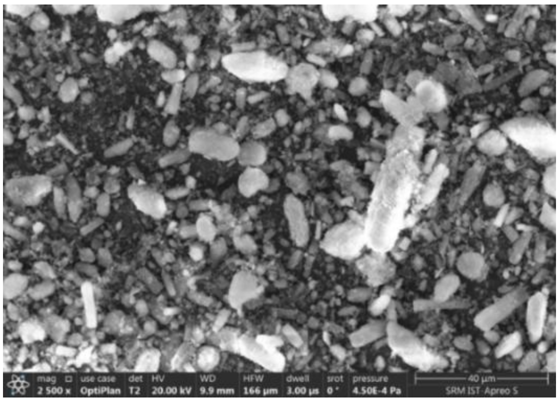

Fig. 3 Microscopic analysis of magnesium oxide

2.4. Stability Analysis

The sonicated MgO-dispersed nanofuel ensures the average particle size through particle size analysis; it is measured by using PSA, Horiba, Japan. The small-sized 40 nm MgO colloidal suspension in fuel reduces the possibility of agglomeration (Figure 4). The image indicates the particle size dispersion shows the peak around 80 nm, endorsing uniform distribution of MgO in the CNSBD100 biodiesel; the figure also illustrates the average particle size of 90 to 100 nm, which is good for proper and better combustion. The stability of the prepared nano-fuels was evaluated using particle size distribution and zeta potential measurements. The stability of the Nano additive loading is an important factor in determining the nanoparticle stability; in turn, it ensures the contribution to the combustion enhancement of the fuel. The Malvern ZetaSizer instrument is utilised to confirm the zeta potential measures and their stability.

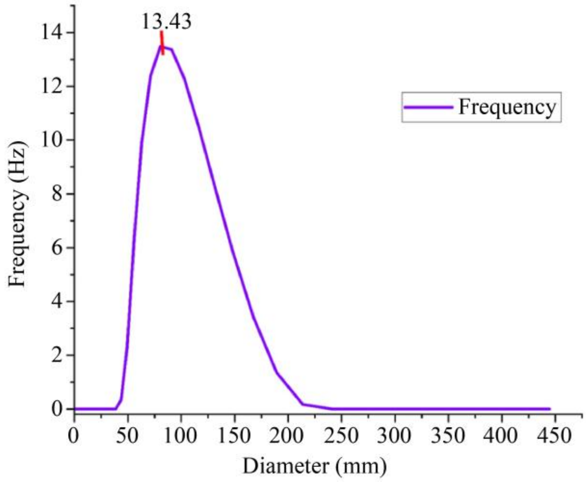

Fig. 4 Particle size distribution of MgO nanoparticles

The zeta potential value, either negative or positive and carrying the value of ± 30 mV and above, suggests good stability; also, ± 25 mV and above proposes moderate stability. This implies the charge value of the particle in the CNSBD. (Figure 5) shows the value for the CNSBD 100+50 ppm MgO and CNSBD 100+100 ppm MgO, respectively, and it exhibited the positive surface charge since the value was also positive. Therefore, the stability of Nano additives will contribute to better combustion ability due to thermal conductivity enhancement.

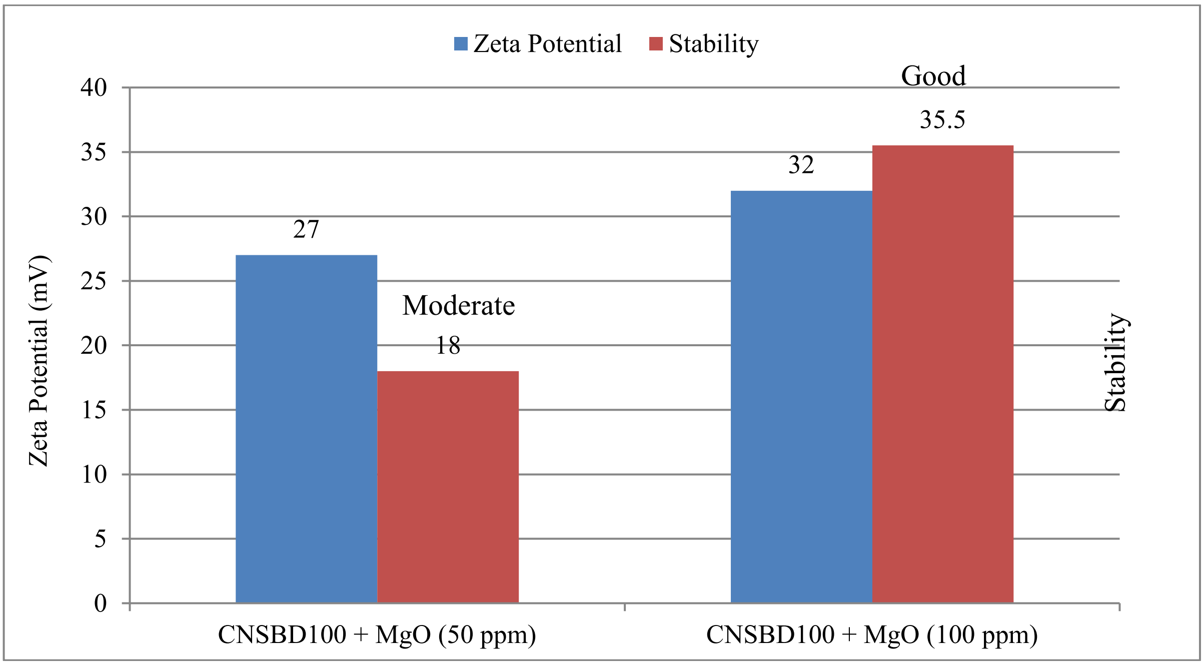

Fig. 5 Zeta potential & stability of blends

Table 2. Thermophysical properties of diesel, CNSBD, and MgO-blend

Properties	ASTM Standard	Diesel (D100)	Cashew Nut Shell Biodiesel (CNSB D100)	CNSBD100 + 50 ppm MgO	CNSB100 + 100 ppm MgO
Kinematic Viscosity @ 40°C (mm^2/s)	ASTM D445	3.2	5.6	5.3	5.1
Calorific Value (MJ/kg)	ASTM D240	43.6	37.5	38.3	38.9
Density (kg/m^3)	ASTM D1298	832	878	882	885
Cetane Index	ASTM D613	51	57	59	61
Flash Point (°C)	ASTM D92	55	150	156	160
Fire Point (°C)	ASTM D92	60	183	190	196

3. Experimental Methods

The Kirloskar-made single-cylinder four-stroke direct injection water-cooled Variable Compression Ratio (VCR) diesel engine was used in the experiments, and its performance was measured with the aid of an eddy current dynamometer applied to the load. The power output of the engine is rated at 3.5 kW. Its compression ratio is adjustable between 12:1 and 18:1, allowing for combustion experiments on varying compression ratios. The standard fuel injection system is provided in the engine; it has a fuel tank connected to a burette with a three-way valve setup to measure the fuel consumption more accurately and also to switch the diesel and test fuel blends easily. Air intake is determined with the help of an air box equipped with an orifice plate and a differential manometer. To ensure the operating temperature remains constant, engine cooling is facilitated by a constant flow of water, as shown in the setup (Figure 6). In order to make the results from the fuel tests reliable and repeatable, each fuel test was repeated three times under the same operating conditions with the same samples, and the average values were used for the analysis. The results of repeated measurements confirmed good repeatability with a maximum deviation of within ±2%. Table 3 summarizes the measurement uncertainties of the parameters used in the present investigation. The engine was run at a perpetual speed of 1500 rpm under steady-state conditions in all experiments and tested for loads of 25%, 50%, 75%, and 100%. It was assumed that the MgO nanoparticles would be uniformly dispersed during the testing period after ultra-sonication and stability tests using particle size and zeta potential analyses. The heat loss during each test run was assumed to be constant, and similar heat loss conditions were assumed to be considered for each of the fuels tested. Before testing, all instruments were calibrated as shown in Table 4, according to relevant ASTM standards.

Table 3. Error analysis and uncertainty

Parameter	Instrument	Range	Accuracy	Uncertainty (%)
Thermal conductivity	Thermal Analyzer	0.02–2.0 W/m·K	±5%	±5
Dynamic viscosity	Rheometer	0.001–1000 Pa·s	±1%	±1
Engine speed	Dynamometer	0–5000 rpm	±1 rpm	±0.5
Load	Dynamometer	0–20 kg	±0.1 kg	±1
Fuel consumption	Stopwatch	0–50 mL	±0.1 mL	±1
Cylinder pressure	pressure transducer	0–250 bar	±1 bar	±1.5
Crank angle	Encoder	0–720°CA	±0.1°CA	±0.1
Temperature	Thermocouple	0–1200°C	±1°C	±0.1
Brake thermal efficiency	Calculated	—	—	±1.5
Heat release rate	Calculated parameter	—	—	±2

Table 4. Calibration of the instrument

Instrument	Calibration Method	Calibration Standard	Accuracy
KD2 Pro Thermal Analyzer	Fluids	ASTM D5334	±5%
Rheometer	viscosity fluids	ASTM D7042	±1%
Pressure Transducer	pressure calibrator	ISO 376	±1 bar
Crank Angle Encoder	synchronization	SAE J2715	±0.1°CA
Dynamometer	weights	ISO 3046-5	±1%
Thermocouple	Ice-point and boiling-point	ASTM E220	±1°C
Burette	Volumetric verification	Laboratory Standard	±0.1 mL

Fig. 6 Experimental setup of the experimental test engine

3.1. Thermal Conductivity

The KD2 Pro thermal properties analyser was employed to measure the thermal conductivity of diesel, cashew nutshell biodiesel, and MgO-suspended nanofuel at two different concentrations of 50 ppm and 100 ppm as per ASTM D5334-14. This is a transient line heat source technique, and the temperature dynamically increased in a test medium to determine thermal conductivity. The measurements have been conducted with the help of a KS-1 needle sensor in closed and sealed insulated vials. The probe was calibrated with deionised water and certified standards of glycerol before testing, and all samples to be tested were thermally equilibrated at 40 ± 0.5 °C in a precision water bath. Proper calibration of the instruments was done by comparing the measured values with the standard reference values for accuracy before taking measurements. Measurements were done when the system was in thermal equilibrium, and each test was repeated three times to ensure repeatability.

3.2. Dynamic Viscosity

The dynamic viscosities of diesel, cashew nutshell biodiesel, and MgO-suspended nanofuel of two proportions of 50 ppm and 100 ppm were measured using an Anton Paar MCR 102 according to ASTM D7042. It had a cone plate geometry, which enabled precise control of the sample over the range of -40°C to 200°C. Before the dynamic viscosity of the various samples was measured, all the samples were thermally equilibrated, and the thermometer's accuracy of measurement is largely related to the unique properties of low torque sensitivity and tool master automatic geometry recognition that allow repeatability in measurements. The rheometer was checked with standard viscosity calibration fluids before the tests. Three measurements were taken, and the mean values were reported.

4. Results and Discussion

4.1. Thermal Conductivity

Thermal conductivity of neat Cashew Nut Shell Biodiesel (CNSBD100) and blends containing MgO nanoparticles and a temperature-dependent nature shown (Figure 7). CNSBD100 has a thermal conductivity of 0.136 W/m K at 30°C, which is 4.2% lower than that of diesel (0.142 W/m K). This decreased thermal conductivity limits internal heat diffusion in the droplets of fuel during the compression stroke, which is another factor in delayed evaporation and prolonged ignition delay periods that are typical of biodiesel fuels. With the MgO nanoparticles, the thermal conductivity is greatly increased. When the temperature is 30°C, thermal conductivity rises to 0.145 W/m·K in CNSBD100+50MgO (6.6% improvement over neat biodiesel) and to 0.149 W/m·K in CNSBD100+100MgO (9.6% improvement). It is more increased at high temperatures, where the thermal conductivity is 0.157 W/mK and 0.161 W/mK in the 50 ppm and 100 ppm blends, respectively, at 70°C, as shown in Table 5. The 100-ppm MgO blend has higher thermal conductivity enhancement than diesel at high temperatures, a 15.4% increase over neat diesel at 70°C. The apparent increase in thermal conductivity can be explained by a number of synergistic effects: (i) MgO nanoparticles have a high thermal conductivity intrinsically that forms an effective path of heat transfer in the base fluid; (ii) Brownian dynamics cause nanoparticles to enhance microconvection and molecular-level thermal transport; (iii) the ordered layers at the nanoparticle-liquid interface enable increased phonon transport; and (iv) ballistic transport of heat through nanoparticle networks reduces interfacial thermal resistance. For the 50 ppm and 100 ppm MgO blends, the thermal conductivity increased from 0.136 W/m·K (for CNSBD100) to 0.145 W/m·K and 0.149 W/m·K, respectively, while the peak cylinder pressure increased from 59.50 bar to 63.79 bar and 67.39 bar, respectively. Similarly, the peak heat release rate increased from 67.64 J/°CA to 72.12 J/°CA and 74.31 J/°CA. These results quantitatively confirm the proposed mechanism of increased thermal conductivity of the droplet, which leads to faster droplet heating to a temperature conducive to ignition, a decrease in ignition delay, and better premixed combustion, in agreement with the results from the literature [21, 27, 32, 34].

Table 5. Thermal conductivity of fuels

Temperature (°C)	Diesel (W/m·K)	CNSBD100 (W/m·K)	CNSBD 100+50ppm MgO (W/m·K)	CNSBD +100ppm MgO (W/m·K)
30	0.142	0.136	0.145	0.149
40	0.145	0.139	0.148	0.152
50	0.148	0.142	0.151	0.155
60	0.151	0.145	0.154	0.158
70	0.154	0.148	0.157	0.161

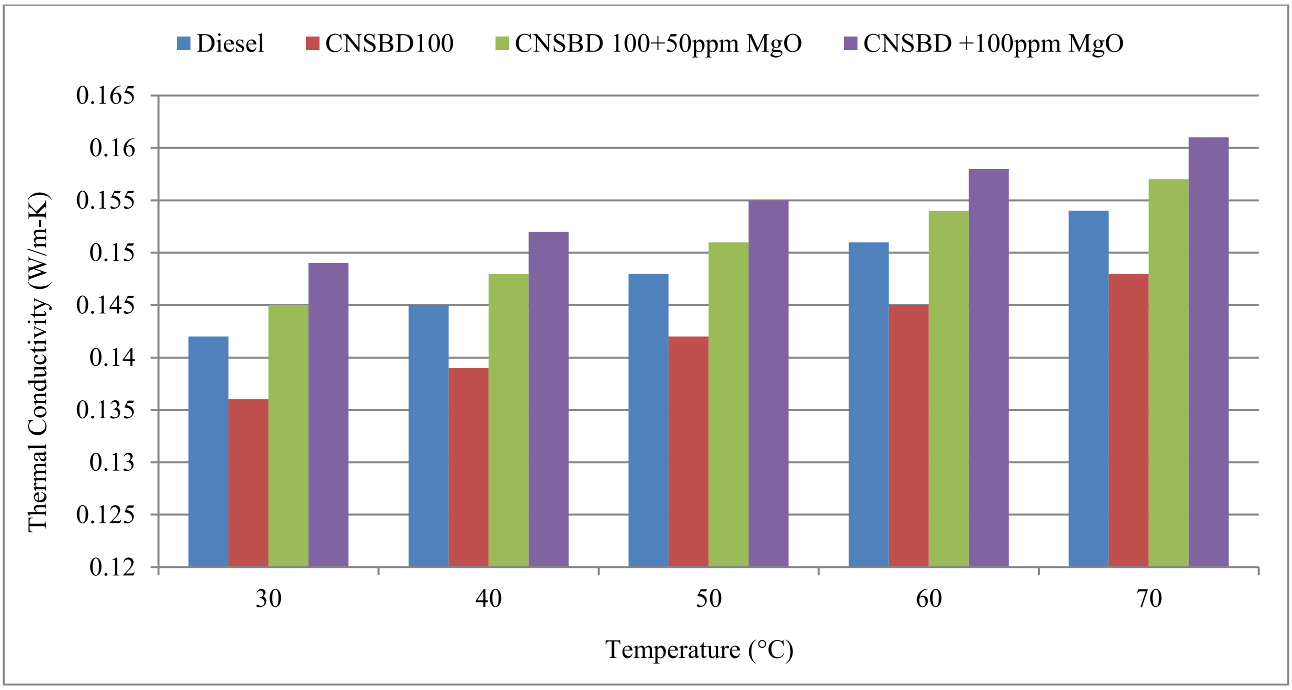

Fig. 7 Variation of thermal conductivity of diesel, CNSBD, and MgO nanoparticle-blended fuels at different temperatures

4.2. Dynamic Viscosity

The dynamic viscosities of 50 and 100 ppm of diesel, cashew nutshell biodiesel, and MgO-suspended nanofuels were compared in the 30 to 70°C temperature range, illustrated in Table 6. The kinematic viscosity of CNSBD100 at 40°C is 3.32 mPa·s, which is 75 times more than diesel (2.72 mPa·s) and results in a poor fuel atomization velocity and a slow air-fuel mixing rate during injection, as shown in Figure 8. MgO nanoparticles added increase the viscosity marginally to 3.36 mPa·s (CNSBD100+50MgO) and 3.43 mPa·s (CNSBD100+100MgO). Although it has higher viscosity, which would negatively affect the spray properties, the improvements in actual combustion inducements imply that nanoscale processes prevail over the bulk viscosity-based reasoning. A number of mechanisms also overturn the viscosity amplification at the microscale: (i) nanoparticles cause localized micro-turbulence on the liquid jet, which further enhances primary atomization; (ii) thermal micro-explosions due to preferential heating of nanoparticles trigger the secondary breakup of droplets; (iii) nanoparticles destabilize intermolecular cohesive forces in the liquid phase, making the liquid jet less stable and promoting the formation of ligaments; and (iv) at high temperatures in the cylinder (>400°C during compression), viscosity of all test fuels decreases substantially, allowing the catalytic and thermal transport benefits of nanoparticles to dominate. The measured increases in the combustion parameters, even with slight changes in viscosity, prove that the major mechanisms controlling the improvement of the combustion in MgO-enhanced nanofuels are the increase in thermal conductivity and the catalyzing activity.

Table 6. Dynamic viscosity of diesel, CNSBD, and MgO-blended cashew nut shell biodiesel

Temperature (°C)	Diesel	CNSBD100	CNSBD100 + 50 ppm MgO	CNSBD100 + 100 ppm MgO
30	3.21	3.57	3.61	3.67
40	2.94	3.32	3.36	3.43
50	2.72	3.06	3.11	3.18
60	2.51	2.87	2.92	2.98
70	2.36	2.71	2.76	2.82

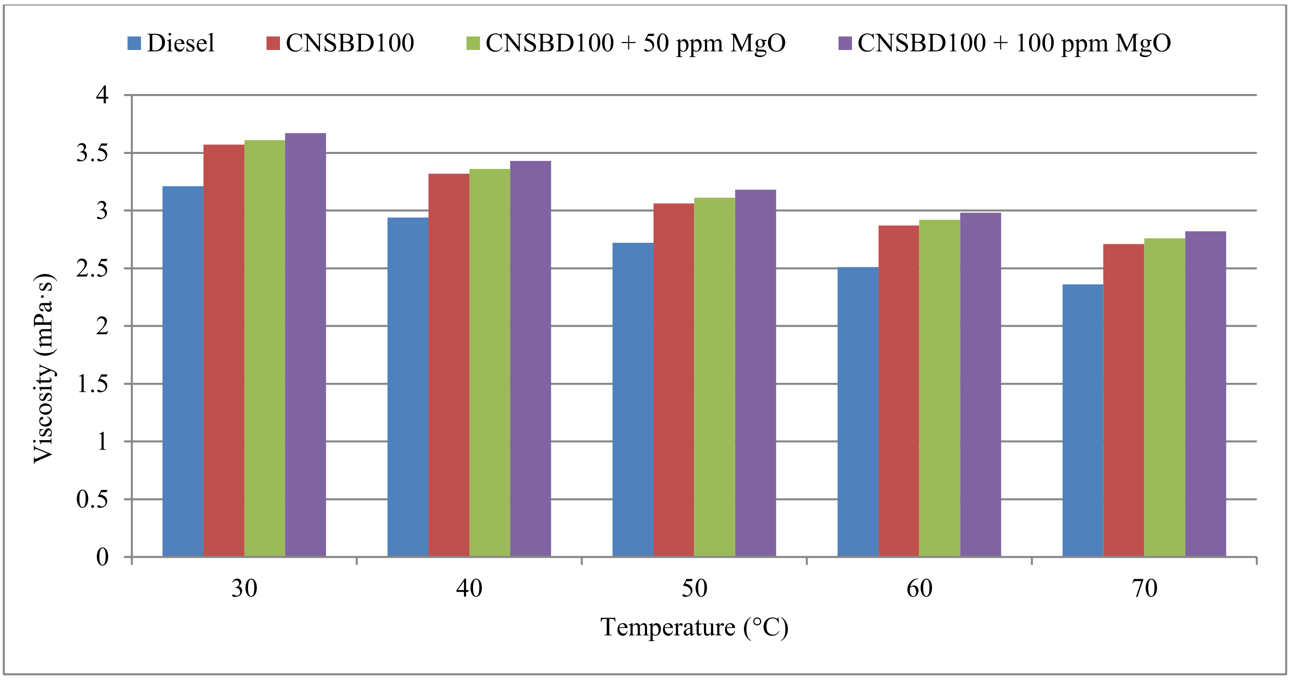

Fig. 8 Variation of dynamic viscosity of diesel, cashew nut shell biodiesel, and MgO nanoparticle-blended fuels at different temperatures

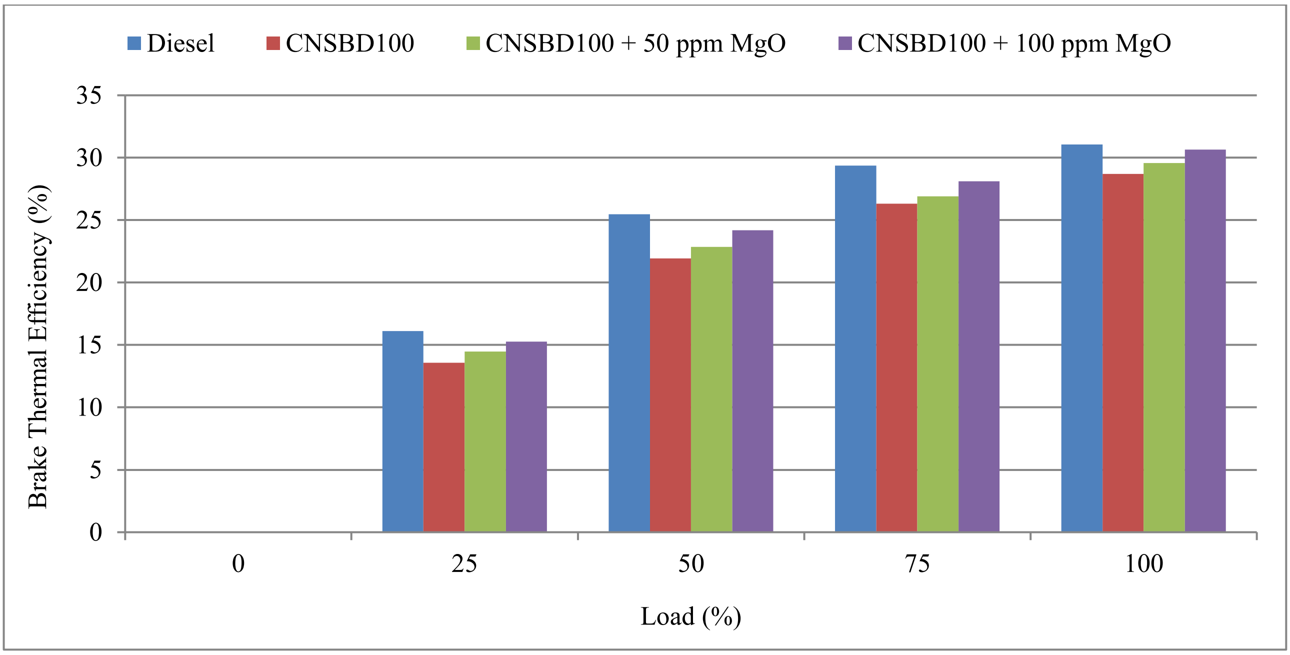

Fig. 9 Variation of brake thermal efficiency of diesel, CNSBD, and MgO nanoparticle-blended fuels at different temperatures

4.3. Brake Thermal Efficiency

The change of Brake Thermal Efficiency (BTE) with the load of the diesel, neat Cashew Nut Shell Biodiesel (CNSBD100), and MgO Nano-additive-blended fuel is shown in Figure 9. All the tested fuels showed an increase in BTE with a rise in engine load. The cause of this is increased in-cylinder temperature, enhanced fuel-air contact, and reduced relative heat loss of high loads. Diesel has a BTE of 16.12% at 25% load as compared to CNSBD100 with a BTE of 13.58%. Neat biodiesel has a low calorific value and higher viscosity, which implies poor atomization and slow combustion, which explains its lower efficiency. Performance increased with the addition of MgO nanoparticles, where CNSBD100 + 50 ppm MgO produced 14.47% and CNSBD100 + 100 ppm MgO produced 15.26%. The enhancement shows enhanced kinetics of combustion as a result of catalysis by nanoparticles. At 50% load, diesel attained 25.48% BTE. CNSBD100 and CNSBD100 + 50 ppm MgO and CNSBD100 + 100 ppm MgO resulted in the production of 21.94% and 22.86% and 24.18%, respectively. The increase in efficiency with the addition of MgO is linked to the increase in the spray properties, the decreased ignition delay, and the increase in the premixed period of combustion. BTE of diesel increased to 29.37 at 75% load. CNSBD100 registered 26.33% as compared to CNSBD100 + 50 ppm MgO with 26.92% and CNSBD100 + 100 ppm MgO at 28.11%. Nanoparticle-facilitated fuels had a better heat release characteristic than pure biodiesel. Diesel had the highest BTE of 31.06 at full load (100%). CNSBD100 produced 28.71%. The inclusion of the MgO nanoparticles greatly enhanced the efficiency, and CNSBD100 + 50 ppm of MgO recorded 29.58%, and CNSBD100 + 100 ppm of MgO recorded 30.64%. The 100 ppm MgO mixture showed a performance that was roughly similar to that of the diesel performance. Diesel had the highest BTE at full load (100 %) of 31.06, and CNSBD100 had 28.71. This shows that diesel had a higher BTE of 8.19 percent compared to neat biodiesel. The efficiency was greatly enhanced by the addition of MgO nanoparticles, with CNSBD100 + 50 ppm MgO reaching 29.58 and CNSBD100 + 100 ppm MgO reaching 30.64; that is, a 3.03 and 6.72 improvement, respectively, over neat biodiesel. Moreover, CNSBD100 + 50 ppm MgO recorded a lower BTE than CNSBD100 + 100 ppm MgO by 4.77%, while CNSBD100 + 100 ppm MgO recorded a deficit of 1.35%, respectively, when compared with the diesel, proving that the increased concentration of nanoparticles made the biodiesel blend approach the performance of diesel under full load conditions.

4.4. Cylinder Pressure

Introduction of metal oxide nanoparticles into biodiesel has proved to be a viable approach to solve the natural conflagration limitations of the combustion of biofuels due to their high viscosity and low thermal conductivity. In this paper, MgO nanoparticles were added to cashew nutshell biodiesel at the concentrations of 50 ppm and 100 ppm to essentially alter the behavior of the fuel physically and chemically before it is injected into the engine in order to regulate the combustion process even at the first stage itself. Contrary to traditional fuel blending, the nano-additives act at a molecular and micro-level, modifying both heat transfer and reaction rates and spray dynamics at the same time. Enhancement of thermal conductivity of the base fuel is one of the major processes by which MgO nanoparticles boost combustion. Neat cashew nutshell biodiesel has a comparatively low thermal conductivity of 0.136 W/mK at 30°C versus 0.142 W/mK for diesel, which limits internal heat diffusion at the level of fuel droplets during compression. When MgO nanoparticles are added, the thermal conductivity rises to 0.145 W/m K at 50 ppm and 0.149 W/m K at 100 ppm, respectively, and at the given temperature. This increase is further intensified at higher temperatures and is observed to be 0.157 W/mK and 0.161 W/mK at 70°C, respectively. The enhanced thermal conductivity allows rapid droplet heating and evaporation, shortening ignition lag and enhancing the fraction of fuel that is involved in the premixed combustion phase. Therefore, nano-blended fuels have an earlier and sharper rise in cylinder pressure as compared to neat cashew nutshell biodiesel. The other important parameter that is highly influenced by the addition of nano-additives is viscosity. The viscosity of CNSBD100 at 30°C is 3.57 mPa.s, and this is very high as compared to diesel (3.21 mPa.s) and results in poor atomisation and slow air-fuel mixing. The viscosity is raised a notch higher by the dispersion of MgO nanoparticles to 3.61 mPa.s in the 50-ppm mix and 3.67 mPa.s in the 100-ppm blend. Though such an increase would traditionally be anticipated to worsen combustion, the nanoscale behaviour of MgO would change the physics of the spray. This results in the nanoparticles creating micro-turbulence in the liquid jet, breaking cohesive intermolecular forces, and, secondly, breaking up fuel droplets. Since viscosity reduces significantly as engine temperature increases, the advantageous nano-effects may dominate over the resistance due to viscosity with all fuels. MgO nanoparticles are heterogeneous combustion catalysts, based on chemocrystallinity. Their high surface area offers rich active sites in the adsorption and decomposition of fuel molecules, giving the reaction an accelerating oxidation speed and increasing the formation of free radicals in the process of combustion. This catalytic effect is very successful in association with the oxygenated structure of cashew nutshell biodiesel, which already carries the oxygen chemically bonded in fatty acid methyl esters. The combination of the natural fuel oxygen and catalysed activity created by MgO causes rapid reaction kinetics, enhanced flame propagation, and complete combustion. (Figure 10) Shows the dependence of the cylinder pressure on the crank angle of diesel, CNSBD100, CNSBD100+50MgO, and CNSBD100+100MgO under 100 percent engine load. At around 5°C after Top Dead Center (ATDC), diesel shows the greatest peak cylinder pressure of 67.54 bar, indicating rapid premixed combustion and optimal energy release close to TDC. Conversely, neat Cashew Nut Shell Biodiesel (CNSBD100) exhibits a significantly lower peak pressure of 59.50 bar, which is 11.9 percent lower than that of diesel. The reduced peak pressure and slower rate of rise in pressure of CNSBD100 suggest slower combustion dynamics, longer ignition delay, and reduced premixed combustion fraction, which are generally the result of increased viscosity and reduced volatility of biodiesel.

The growth of pressure is enhanced progressively with the addition of MgO nanoparticles. CNSBD100+50MgO has the highest peak pressure of 63.79 bar (7.2% better than neat biodiesel), and CNSBD100+100MgO has the highest peak pressure of 67.39 bar, almost the same as diesel (99.8%). The improved peak pressure and pressure rise rate with increasing concentration of MgO give three important indications of the improvements that the combustion has: (i) the delay of ignition by faster heat transfer to the combustion chamber is seen, (ii) the fraction of premixed combustion is higher due to better mixing and evaporation of the fuel-air mixture, and (iii) the strength of combustion reactions is catalysed by MgO nanoparticles that act as active surface sites and oxygen buffers. The pressure trace of CNSBD100+100MgO is closely superimposed with that of diesel during the compression, combustion, and expansion strokes, showing that the addition of nanoparticles to the diesel at 100 ppm is effective in restoring diesel-like behaviour during combustion in biodiesel. Moreover, nano-enhanced fuels have been found to smooth out the pressure decay during expansion, which implies there will be a more stable diffusion combustion and less cycle-to-cycle variation, which leads to better combustion efficiency and less mechanical stress on engine parts.

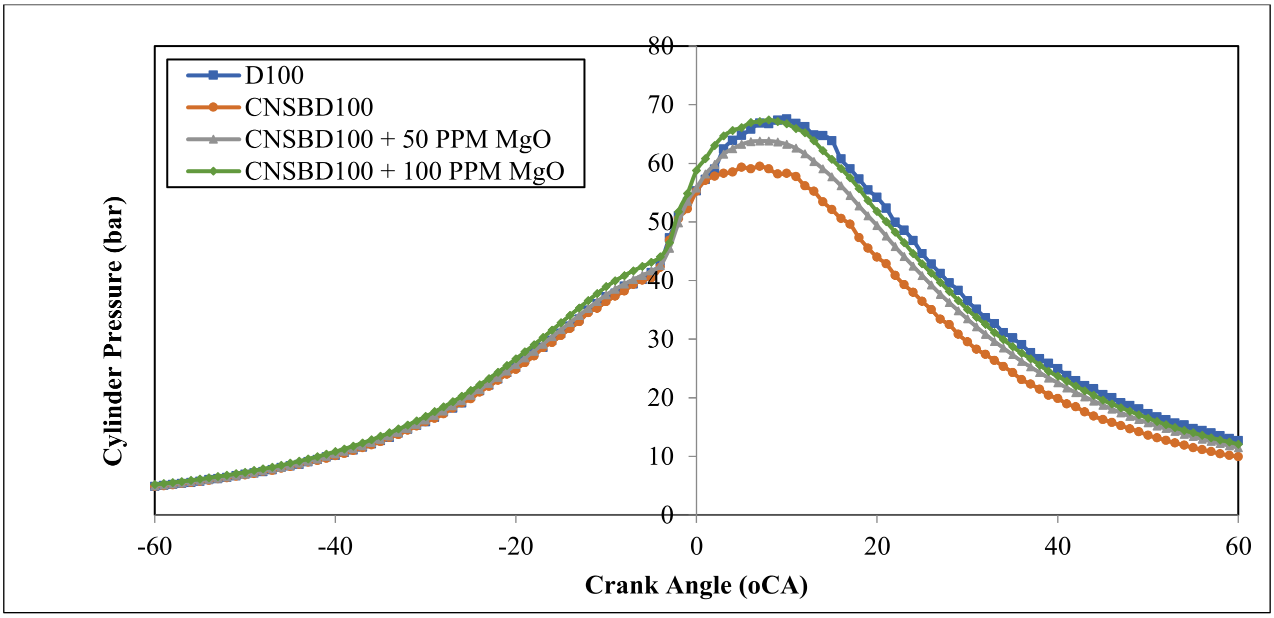

Fig. 10 Variation of cylinder pressure of diesel, cashew nut shell biodiesel, and MgO nanoparticle-blended fuels at different temperatures

4.5. Heat Release Rate

The heat release rate-crank angle curve shows clearly how the type of fuel and MgO nano-additive affect the combustion phasing and intensity. Diesel has a steep and high premixed combustion peak just beneath and at the top dead centre, meaning that the release of energy is rapid as a result of the proper preparation of the fuel and quick ignition. Neat cashew nut shell biodiesel exhibits a significantly lower premixed heat release peak and a more flattened profile during the early stages of combustion, indicating slower combustion initiation and a reduced proportion of fuel undergoing premixed combustion. This action is manifested by the smoother HRR curve and a later peak than that of diesel. When MgO nanoparticles are added, the premixed heat release rate has been significantly increased. With the CNSBD100 + 50 ppm MgO blend, the premixed peak is higher and sharper than the neat biodiesel. The premixed peak of the CNSBD100 + 100 ppm MgO blend has the highest premixed heat release peak as compared to all other biodiesel fuels, and it is almost similar to the behaviour of diesel. The elevated amount of premixed heat release in nano-blended fuels is ascribed to the increased rate of energy release close to TDC, and this implies improved combustion and speedy reactions. This increase aligns with the fact that the thermal conductivity values of the nano-enhanced fuels also increase from 0.136 W/m K of CNSBD100 to 0.145 W/m K and 0.149 W/m K with an increase of 50 ppm and 100 ppm MgO, respectively, and allow faster heat transfer and sooner ignition. (Figure 11) shows the Heat Release Rate (HRR) versus crank angle in all the test fuels at 100 percent load. The HRR profile gives essential information on the phasing, intensity, and the relative role of the premixed and diffusion combustion processes. The highest release of heat per unit of temperature is 75.12 J/°C at about 3° ATDC that diesel experiences, which is significant and rapid energy dissipation during the premixed combustion phase. The formation of this sharp HRR peak is due to the full combustion of the fuel-air mixture, which is well mixed during the ignition delay period. Conversely, CNSBD100 has a much lower peak HRR of 67.64 J/oCA (10 percent lower than diesel). The lower premixed HRR peak of neat biodiesel is indicative of (i) the failure to evaporate all the fuel during the ignition delay period because of reduced thermal conductivity and increased latent heat of vaporisation, (ii) decreased premixed charge preparation, and (iii) slower chemical reactions in the first phase of combustion. Inclusion of MgO nanoparticles results in a progressive increase in premixed heat release. CNSBD100+50MgO has a maximum HRR of 72.12 J/0 CA (6.6 percent higher than neat biodiesel), and CNSBD100+100MgO has 74.31 J/0 CA, about 96.6 percent of the heat release maximum of the diesel mixed into it. The increased and sharpened premixed HRR of nano-enhanced fuels denotes the following: (i) heat transfer during the compression phase of the cycle became faster due to the increase in thermal conductivity (Table 5), which accelerates the process of fuel evaporation and charge preparation; (ii) the reduction of the ignition delay, which is justified by the earlier appearance of the combustion process; and (iii) the catalysed occurrence of oxidation reactions due to the presence of oxygen-rich active sites that MgO nanoparticles provide. Moreover, the diffusion combustion process (10-40° ATDC) exhibits some fuel differences. CNSBD100 has a long diffusion tail and a high HRR past 30° ATDC, indicating that it does not undergo complete combustion and that the oxidation is sluggish at the late cycle. By contrast, CNSBD100+50MgO and CNSBD100+100MgO have a shorter and more regulated time of diffusion, and HRR is approaching baseline much faster. Such behaviour implies more complete combustion in a shorter crank angle period, which enhances thermal efficiency and minimises heat losses in the expansion, the total heat emission (area under HRR curves). CNSBD100+100MgO closely matches diesel and thus confirms practically full energy release and combustion efficiency close to that of conventional diesel.

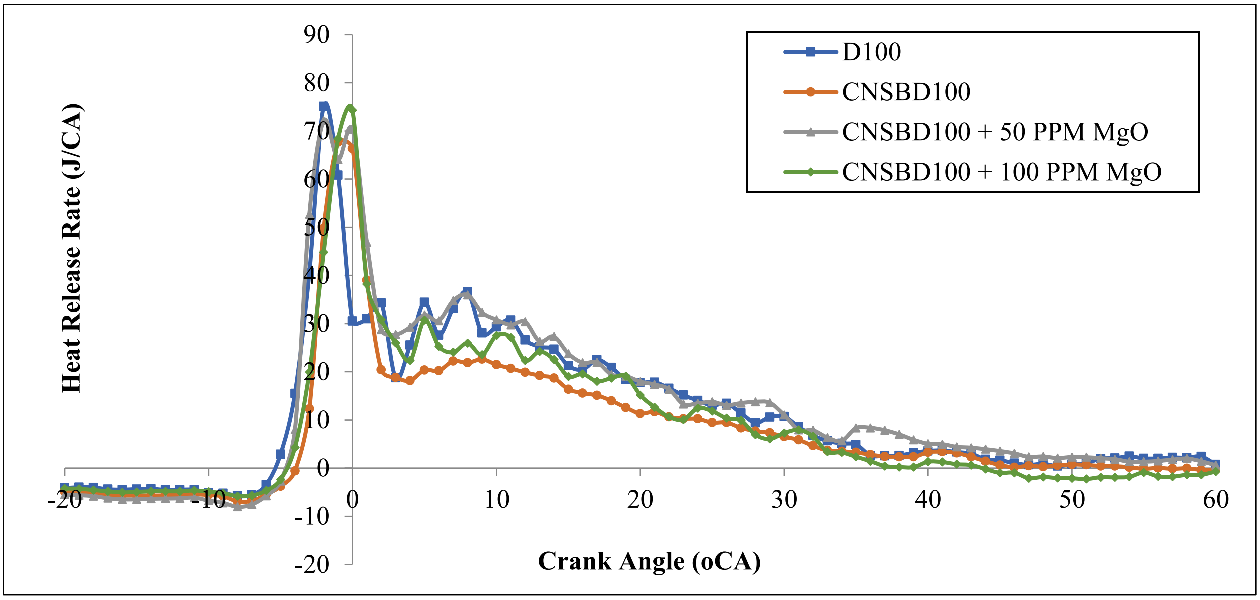

Fig. 11 Variation of heat release rate of diesel, CNSBD, and MgO nanoparticle-blended fuels at different temperatures

5. Conclusion

The present study was a systematic examination into the impacts of Magnesium Oxide (MgO) nanoparticles at 50 ppm and 100 ppm level on the thermal conductivity, viscosity, and the combustion properties of cashew nut shell biodiesel in a compression ignition engine. The experimental results support the following conclusions:

1. Enhancement of Thermal Conductivity: Addition of MgO nanoparticles gave a significant improvement in thermal conductivity of cashew nut shell biodiesel. Thermal conductivity at 30 ^{o} C was found to go up by 6.6 % and 9.6 % in 50-ppm and 100-ppm blends, respectively, relative to pure biodiesel. The improvement was greater at higher temperatures, with a maximum of 15.4% improvement at 70 ^{o} C in the 100 ppm blend, close to the diesel thermal conductivity.
2. Marginal Viscosity Effect: MgO nanoparticles had only a marginal effect on the kinematic viscosity, but the observed improvements in combustion are evidence that nanoscale effects, such as the increase in thermal transport, catalysis, and atomization, dominate over the bulk viscosity effects.
3. Better Combustion Characteristics: The increased thermal conductivity was directly related to better combustion characteristics. Peak cylinder pressure was also found to rise by 59.50 bar in neat biodiesel, and by 67.39 bar in the 100ppm MgO mix, restoring 99.8% diesel performance. The peak heat release rate was also raised by 9.9 %, as the rate rose to 74.31 J/0 CA as compared to 67.64 J/0 CA, and the 100-ppm blend reached 96.6 % of the premixed heat release of diesel.
4. Mechanistic Correlation: Those mechanisms that increased thermal conductivity were found to increase combustion. The enhanced heat transfers in the compression stroke enable: (i) rapid fuel evaporation, (ii) reduced ignition delay, (iii) increased preparation of the premixed charge, and (iv) increased intensity of the premixed combustion, resulting in increased peak forces and previous energy discharge around TDC.
5. Optimal Nanoparticle Concentration: The 100-ppm MgO blend proved to be the best of the tested formulations, with the ability to exhibit combustion properties similar to diesel and still experience improvements in fuel properties. This concentration offers a good trade-off between thermal reinforcement and realism.
6. Engineering relevance and Practical Implications: The findings reveal that ultra-low levels of MgO nanoparticles (50-100 ppm) can be used to effectively overcome the thermophysical drawbacks of biodiesel without having to make any changes to the engine. The use of waste-derived cashew nut shell biodiesel further enhances the sustainability of the proposed fuel. In practical terms, the scaling up of implementation must be considered with regard to storage stability over time, handling of nanoparticles, the distribution network of fuel, and environmental regulations. This technology provides a feasible avenue for enhancing the combustion of biodiesel in the current diesel engines.
7. Future Recommendations: Future studies should aim at: (i) long term stability of nanofuel mixtures over long storage durations, (ii) full characterization of emission (NOx, CO, HC, small particle, etc.), (iii) engine wear and deposition life studies, (iv) techno-economic mapping of large scale nanofuel synthesis, and (v) optimization of size and shape of nanoparticles in promoting maximum combustion. This combined study offers constructive information regarding the intrinsic purpose of nanoparticle-improved thermal conductivity as a technological advancement of biodiesel combustion and suggests a mechanistic model of knowledge about the thermal-combustion association of nano-fuel.

Conflicts of Interest

The author(s) declare that there is no conflict of interest regarding the publication of this paper.

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