Sustainable Energy Technologies and Assessments 58 (2023) 103375

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Optimisation and environmental analysis of waste cashew nut shell oil biodiesel/cerium oxide nanoparticles blends and acetylene fumigation in agricultural diesel engine

G.M. Lionus Leo [a], S. Murugapoopathi [b], Gavaskar Thodda [a], Sagar M Baligidad [c], Ravikumar Jayabal [d,*], Mukilarasan Nedunchezhiyan [e,*], Yuvarajan Devarajan [d,*]

[a] Department of Mechanical Engineering, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India
[b] Department of Mechanical Engineering, PSNA College of Engineering and Technology, Dindigul, Chennai, Tamil Nadu, India
[c] Department of Mechanical Engineering, CMR Institute of Technology, Bengaluru, Karnataka, India
[d] Department of Thermal Engineering, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu, India
[e] Department of Mechanical Engineering, Jeppiaar Institute of Technology, Kancheepuram, Tamil Nadu, India

ARTICLE INFO

Keywords:
Sustainable practices
Waste to energy
Cerium oxide nanoparticle, acetylene
Emission

ABSTRACT

This research aims to comprehensively analyse the performance, combustion, and emissions of cashew nut shell oil (CNSO) biodiesel blends with cerium dioxide (CeO_2) nanoparticles and acetylene injection in agricultural diesel engines. The test fuels are diesel, CNSO biodiesel, B50 (50% CNSO biodiesel + 50% diesel), and CeO_2 blends (diesel + CeO_2 25 ppm, CNSO biodiesel + CeO_2 25 ppm, B50 + CeO_2 25 ppm). Acetylene was injected into the intake manifold at 3 lpm and 6 lpm. The experimental result revealed that the engine brake thermal efficiency (BTE) showed a 1.38% decrease when CNSO biodiesel was used instead of diesel fuel. However, the addition of CeO_2 nanoparticles and acetylene to diesel fuel had a significant improvement in BTE. Furthermore, the injection of acetylene improved combustion, resulting in a 10.42% increase in peak pressure (P_{max}) and a 3.18% increase in BTE. Nitrogen oxide (NOx) emission was lower for diesel with 6 lpm acetylene injection than other test fuels. Additionally, adding CeO_2 nanoparticles to CNSO biodiesel reduced hydrocarbon (HC) and carbon monoxide (CO) emissions by 5.92% and 3.3%, respectively, compared to pure diesel. The investigation utilised Response Surface Methodology (RSM) to analyse the effects of various input parameters on engine performance and emissions. The optimised result indicated that the combination of CeO_2 blended with CNSO fuel yielded the most favourable engine performance. Furthermore, the validation experiments confirmed the reliability of the optimised result, as the predicted values closely matched the experimental values. This work concluded that using CNSO biodiesel with CeO_2 nanoparticles and acetylene injection suits agricultural diesel engines.

Introduction

Internal combustion engines powered by fossil fuels have revolutionised mobility and transformed our travel habits [1]. However, it is crucial to recognise the substantial drawbacks associated with this reliance. Fossil fuels are a significant source of air pollution, releasing various harmful pollutants that affect human health and the environment [2]. One of the primary pollutants emitted by internal combustion engines running on fossil fuels is carbon monoxide (CO), a toxic gas with severe health implications [3]. Additionally, nitrogen oxides (NOx) produced by these engines contribute to smog formation and can cause respiratory issues, particularly for vulnerable groups like children and older people. Adopting alternative fuels is crucial for overcoming foreign oil dependency, mitigating environmental impacts, and paving the way for a cleaner, more sustainable transportation system that benefits both present and future generations [4,5].

Biodiesel has achieved popularity in compression ignition (CI) engines as an alternative to diesel. It is ideal for CI engines due to its better sustainability, environmental friendliness, and reduced hazardous emissions. Reducing emissions is critical for minimising global ecological problems [6]. Bioenergy is a crucial energy source, accounting for 10% of the worldwide energy supply and potentially exceeding 60%.

* Corresponding authors.
E-mail addresses: raviram03@gmail.com (R. Jayabal), mukilarasann@jeppiaarinstitute.org (M. Nedunchezhiyan), yuvarajand.sse@saveetha.com (Y. Devarajan).

https://doi.org/10.1016/j.seta.2023.103375
Received 27 March 2023; Received in revised form 4 July 2023; Accepted 12 July 2023
Available online 19 July 2023
2213-1388/© 2023 Elsevier Ltd. All rights reserved.

Contemporary bioenergy usage is projected to overtake traditional biomass usage by 2060 due to its enormous demand, resulting in a production increase of 145 EJ (present level) by then [6,7]. Much biomass must be captured before bioenergy can be developed [8]. To address this, many bioenergy resources are proposed for large-scale cultivation. Plants and biologically produced household, industrial, agricultural, and commercial waste can make biofuels. Furthermore, vegetable oil waste, food waste, municipal rubbish, manure, and plant materials are the starting materials for biofuel production [9,10]. Pocha *et al.* used lignocellulosic biomass waste to produce bioenergy [11].

In comparing four different biodiesel blends with conventional fuel, Srivastava *et al.* found that Spirulina B20 has the most significant reduction in emissions [12]. A study by Sujeet Kesharvani *et al.* found that the CPB20 blend of microalgae was most promising as a biodiesel feedstock [13]. To reduce carbon emissions, James Frost *et al.* blended furanic molecules with diesel fuel [14]. A study by Asgar Asadi *et al.* found that premixing biodiesel decreased soot emissions while increasing NOx emissions [15]. Dhinesh *et al.* studied a new biofuel feedstock, Cymbopogon flexuosus. They found that a 20% diesel blend with diesel had properties close to those of diesel but slightly higher NOx and CO_2 emissions [16].

The study examined the biological mechanisms that produce biofuels from agricultural waste, emphasising improving technical procedures to increase fuel production. Cashew nuts are commonly farmed in tropical locations, with roughly 5.7 million hectares used for cashew farms worldwide [17]. The cashew nut shells can be used to extract oil, named CNSO. Due to its renewable nature and local availability, CNSO is an excellent resource. CNSO is less expensive than conventional diesel fuel, making it an attractive option for transportation and industry [18]. Because of its antioxidant properties, CNSO can help improve the performance of other biodiesels [19]. It also helps to stabilise the biodiesel over time. Fossil fuels contain high concentrations of carbon; when burned, they release CO_2 into the atmosphere. In comparison, CNSO has a lower carbon content. The shells of cashew nuts consist of a mixture of lignin, cellulose, and other organic compounds, which results in lower carbon emissions when combusted. Fossil fuels often contain sulfur compounds, contributing to sulfur dioxide (SO_2) formation when burned [20-22]. Several studies have been reported on the performance of CNSO biodiesel [23]. Kumar *et al.* evaluated CNSO biodiesel combustion and emission in a CI engine [24]. The study concluded that 40% CNSO substitution is conceivable without affecting engine performance. Olugasa *et al.* studied the emission and performance of a 70:30 (B70) orange peel biodiesel blend with CNSO [25,26].

A dual-fuel engine does not require any modifications to its construction, which is one of its advantages. Acetylene is a fuel alternative for internal combustion engines with high flame speed, flammability, and range. The study by Loganathan *et al.* investigated the effects of adding diethyl ether (DEE) to hydrogen-enriched CSNO in a DI diesel engine [27]. Enes Fil et al. tested acetylene as a secondary fuel in a diesel engine, which led to decreased soot emissions but increased CO, HC, and NOx [28]. A multi-fuel engine experiment by Kapil Dev Choudhary *et al.* was found to increase peak cylinder pressure, thermal brake efficiency, and exhaust gas temperature with higher compression ratios, suggesting acetylene may be a viable alternative fuel for dual-fuel engines [29,30].

Research on the potential benefits and drawbacks of nano additive blended combustion is ongoing. There are potential benefits, such as improved fuel efficiency, reduced emissions, and improved engine performance. However, there may also be drawbacks, such as increased production costs and environmental impacts associated with the production and disposal of the nanoparticles. Hayder et al. showed that adding nano-Al_2O_3 and nano-TiO_2 to diesel fuel increased ignition and BTE while reducing pollutant emissions [31]. Vigneswaran *et al.* found that using emulsion fuel with TiO_2 nanoparticles improved efficiency and reduced specific emissions but increased nitrogen oxide emissions [32]. Bioethanol-diesel blends containing aluminium oxide and titanium oxide nanoparticles perform better and emit less pollution [33].

Using renewable energy sources is paramount in addressing today's global energy and environmental challenges. Among the promising alternatives, biodiesel derived from CNSO has gained considerable attention due to its potential as a sustainable and environmentally friendly fuel. However, to fully exploit the advantages of CNSO biodiesel, it is crucial to investigate its performance characteristics and determine its optimal utilisation in IC engines. A comprehensive analysis of CNSO biodiesel blend performance in IC engines is the goal of this study, which aims to fill the existing research gap. The study evaluates engine performance, combustion, and emissions of CNSO biodiesel with CeO_2 nanoparticles and acetylene. This work utilised acetylene injection rates of 3 lpm and 6 lpm, and 25 ppm of CeO_2 nanoparticle additive was mixed with diesel, B50, and CNSO biodiesel. By examining the impact of various blend ratios and considering the blending of CNSO biodiesel with conventional diesel, the research aims to determine the optimal fuel composition for achieving the best engine performance.

Materials and methods

Nanoparticle preparation

The nano additive was prepared using the Sol-Gel combustion method. Hexahydrate and glycine were dissolved in deionised water, with glycine as a reducing agent and cerium nitrate as an oxidising catalyst [34]. The solution was continuously stirred for two hours at 60 °C before being transferred to an electric furnace and heated to 100 °C. Excess water was evaporated to form a translucent viscous gel. As a result of the self-propagating combustion reaction, a yellow permeable foam of nanoparticles was produced. As a result of the combustion process, non-toxic gases such as N_2, CO_2, and H_2O were released in the form of brown vapour. Before being evaluated, the nanoparticles were fine-ground and heat-treated at 600 °C for three hours. The scanning electron microscope (SEM) and transmission electron microscopy (TEM) images of the CeO_2 nano additive are shown in Fig. 1 (a) and (b).

Experimental setup

Fig. 2 (a) and (b) show a schematic and actual representation of an experimental test rig. The experimental single-cylinder, four-stroke CI engine produced 3.5 kW. Table T1 shows engine specifications in the appendix. The engine block and fuel system were fitted with piezoelectric sensors for measuring cylinder and fuel system pressure. A solenoid gas injector was installed below the throttle pipe to enable acetylene gas to be used in the engine chamber. Manometers measured pressure loss across the air surge chamber's radial entrance to determine airflow. An observation of fuel consumption over a fixed period was used to measure fuel consumption. Chromel-Aluminium K-type thermocouples measured exhaust gas temperature. Experiments at different loading conditions are conducted using hydraulic dynamometers. An AVL gas analyser measured CO, HC, NOx, CO_2, and O_2. Table T2 shows the properties of the fuel blends in the appendix.

Experimental procedure

After starting the engine with diesel fuel, acetylene fuel was introduced into the cylinder through the electronic gas injector in the intake port. The Electronic Control Unit processed the voltage signal from the proximity sensor to open and close the injector. With a pressure of 220 bar, diesel was injected 23° before the top dead centre (bTDC). An acetylene gas regulator regulated the gas from the high-pressure cylinder to a pressure of 2 bar. A ball valve controlled the gas flow, and a gas flow meter measured it. Flame traps and flame arrestors were used in the flow line to prevent backfire from the engine. A National Instruments data acquisition device was used to record and store the experimental data for offline analysis. On the flywheel was a sensor that detected

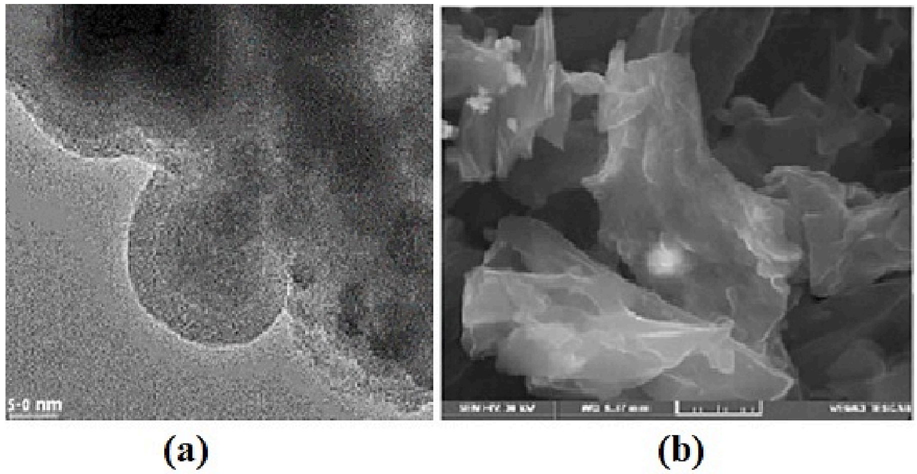

Fig. 1. (a) SEM morphological and (b) image TEM morphological image of CeO_2 nanoparticles.

crank angle utilising an encoder.

Error analysis and uncertainty analysis

Errors and uncertainties can arise from different factors when conducting experiments and calculating performance parameters [35]. These sources of error and uncertainty can be attributed to environmental conditions, observations, calibration, equipment, and the order in which tests are performed [36]. The accuracy of measuring instruments was determined through uncertainty analysis. Instrument details and percentage of uncertainties are provided in Appendix Table T3.

The percentage of uncertainty (% δ) occurring in the current experiments was calculated using equation (1).

$$\%\delta = squarerouteof\left(\left(\delta_{PressureTransducer}\right)^2\right) + \left(\delta_{CrankAngleEncoder}\right)^2 + \left(\delta_{NOx}\right)^2 + \left(\delta_{HC}\right)^2 + \left(\delta_{CO}\right)^2 + \left(\delta_{CO_2}\right)^2 + \left(\delta_{Smoke}\right)^2 + \left(\delta_{K-2thermocouple}\right)^2 + \left(\delta_{stopwatch}\right)^2 + \left(\delta_{manometer}\right)^2 + \left(\delta_{burette}\right)^2 \quad (1)$$

$$\text{e of uncertainty} = \sqrt{\left(0.01^2 + 0.2^2 + 0.25^2 + 0.2^2 + 0.35^2 + 0.2^2 + 0.35^2 + 1^2 + 0.2^2 + 0.2^2 + 1.5^2 + 1.5^2\right)}$$

$$Percentage\ of\ uncertainty = \pm 2.451\%$$

Results and discussion

Combustion characteristics

In-cylinder pressure and heat release rate

An illustration of the variations in in-cylinder pressure for the injection of acetylene, CSNO biodiesel, and CeO_2 nano additive is provided in Fig. 3 (a). CNSO showed a 2.17% drop in P_{max} values compared to conventional diesel. The decrease in P_{max} when using CNSO is caused by the different physical and chemical properties of CNSO when compared to diesel. Since CNSO has a lower heating value and a higher oxygen content than diesel, it affects the combustion process and generates less pressure [37,38]. Blending with a CeO_2 nano additive resulted in a significant improvement in P_{max} values. The CeO_2 nano additive combined with diesel resulted in a 4.5% increase in P_{max} compared to neat diesel. As a result of adding CeO_2 nano additive to diesel fuel, the combustion efficiency of the fuel was improved, which in turn led to an increase in P_{max}. CeO_2 nanoparticles are beneficial for atomising and mixing fuel with air during combustion due to their high surface area and unique surface properties [39,40].

Acetylene injection significantly improved P_{max} values by 10.42% compared to neat diesel operation. Compared to traditional diesel fuel, acetylene has a faster flame speed and a superior heating value. This allows acetylene to burn more quickly and release more energy, resulting in higher pressure and temperature inside the cylinders during combustion [41]. The ignition of acetylene requires less energy than diesel because its activation energy is lower. In turn, this results in more efficient use of fuel and a higher P_{max} [42].

Fig. 3 (b) shows the variations of HRR. Experimental results revealed that for CNSO-fuelled combustion, the HRR was less than for traditional diesel-fuelled combustion. It was found that the HRR for CNSO was less than for diesel by 19.62%. Because CNSO fuel has a lower cetane number than diesel fuel, a more extended delay occurs before ignition, resulting in a slower HRR. CNSO also has a lower heating value than diesel fuel, releasing less heat energy per unit of fuel burned. CNSO HRR is less than diesel's [41,43]. The addition of the CeO_2 nano additive enhanced HRR values. Compared with neat diesel, CeO_2 nano additive blended diesel showed a 4.92 % increase in HRR. CeO_2 nanoparticles provide additional oxygen to the combustion process of diesel fuel, resulting in faster and more complete combustion. As a result, HRR values increase [44,45]. Acetylene injection significantly improved combustion and resulted in an enhanced HRR. A 3.7% improvement was observed when acetylene fuelled combustion compared to traditional combustion. Compared to diesel, acetylene is a hydrocarbon fuel with a higher flame speed and energy content. Due to its higher flame speed and increased reaction rates, acetylene results in complete combustion and a higher HRR]29].

Performance analysis

Brake thermal efficiency and brake specific fuel consumption

Fig. 4 (a) shows the influence of CNSO and CeO_2 on BTE. Biodiesel use in CI engines has been shown to reduce BTE slightly. According to these experiments, CNSO fuel can reduce engine performance by up to

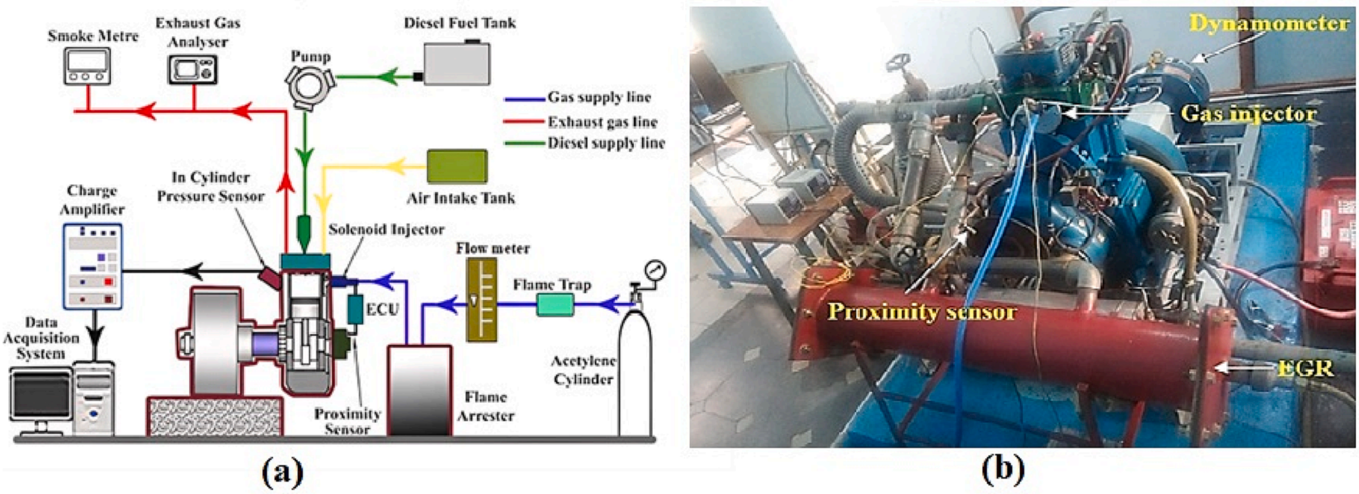

Fig. 2. (a) Experimental layout and (b) Experimental test rig setup.

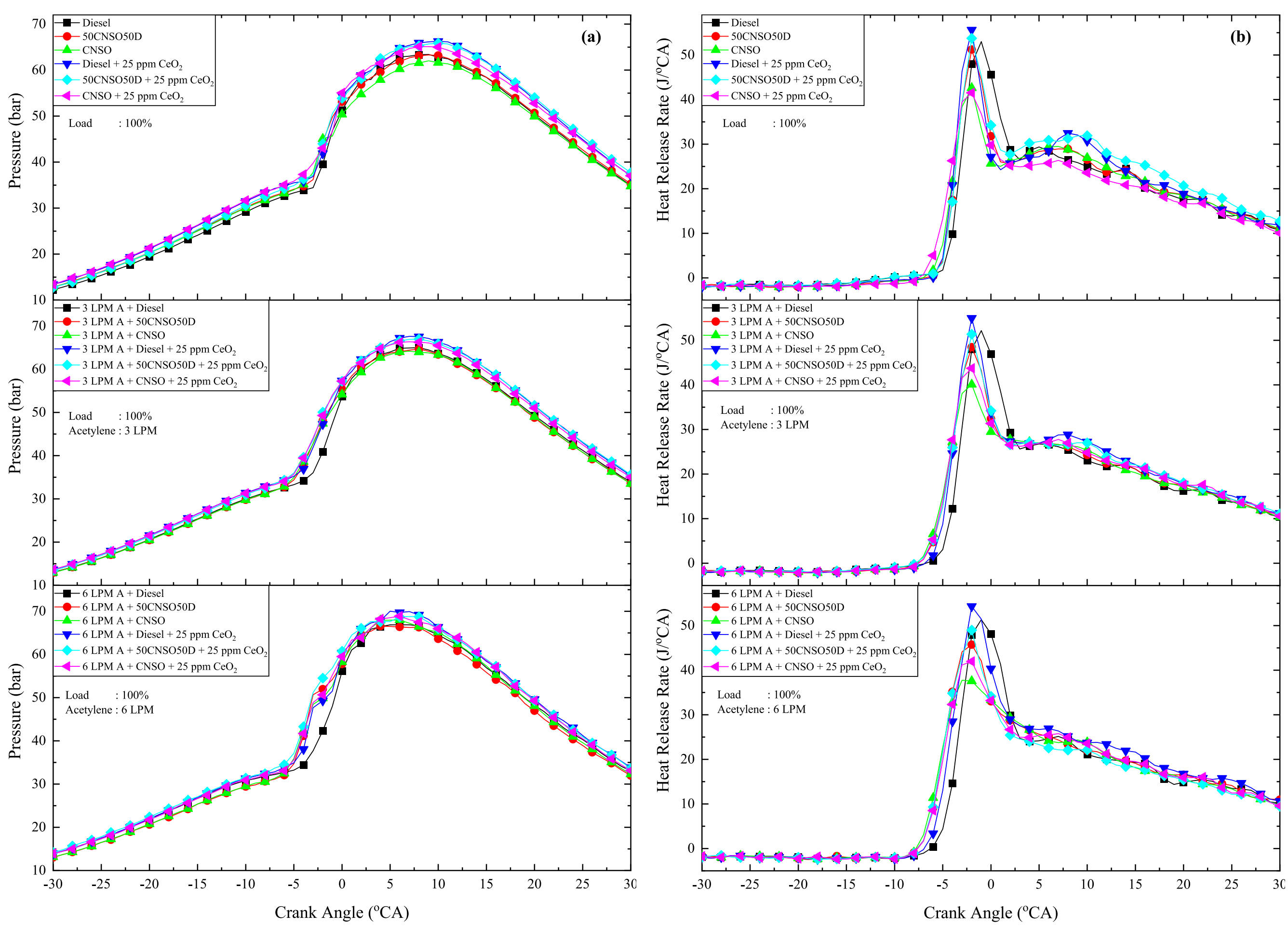

Fig. 3. (a) In-cylinder pressure (b) HRR of CeO_2, CNSO and acetylene injection at maximum load.

1.38% compared to diesel fuel. CNSO has less energy content than diesel, which means that more fuel may be required to produce the same power output. This results in reduced efficiency. Low cetane numbers in biodiesel result in delayed ignition, incomplete combustion, and reduced efficiency. Furthermore, CNSO biodiesel is more viscous than diesel fuel, which reduces fuel atomisation and results in incomplete combustion [46,47]. Adding CeO_2 nano additive to diesel fuel improved engine performance significantly. In experiments, CeO_2 additive blended diesel performed 1.96% better than neat diesel in BTE. CeO_2 nano additive blended CNSO biodiesel combustion showed a 2.54% increase in brake thermal efficiency over neat CNSO biodiesel. By promoting a more uniform mixture of fuel and air and by reducing the fuel's viscosity, CeO_2 nanoparticles can improve CNSO fuelled combustion efficiency [48]. Acetylene fuelled combustion at 3 lpm significantly

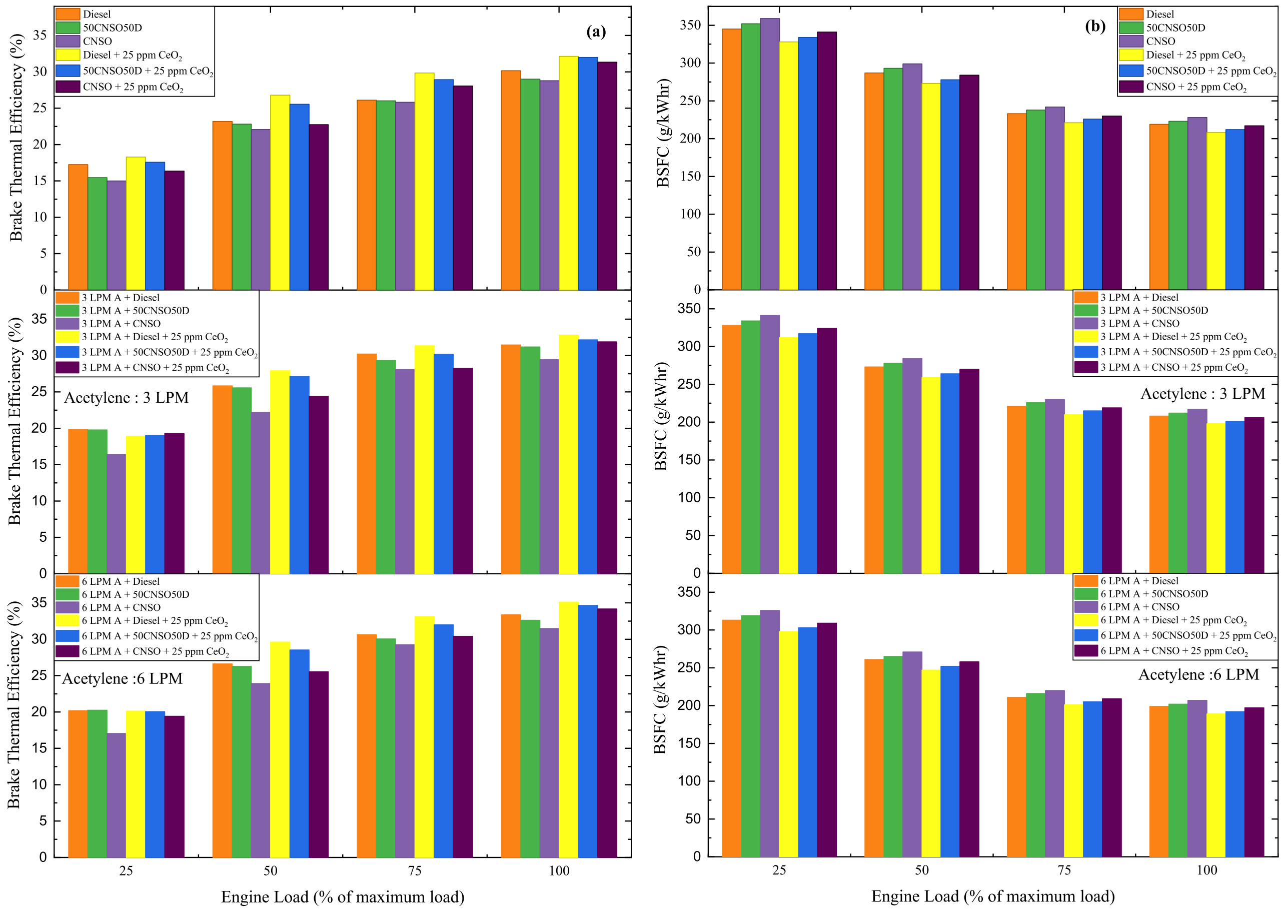

Fig. 4. (a) BTE (b) BSFC of CeO_2, CNSO and acetylene injection.

improves performance characteristics compared with traditional combustion for diesel fuel and biodiesel DI by up to 1.29% and 0.65%, respectively. Compared to conventional combustion, acetylene-fuelled combustion showed improvements in BTE of up to 3.18% for 6 lpm. The energy content of acetylene per unit of volume is higher than that of diesel and biodiesel. Therefore, more energy can be released per unit of fuel injected into the engine, resulting in better performance [29].

According to the experimental findings depicted in Fig. 4 (b), the BSFC decreased as the engine load increased. Moreover, it was observed that an increase in the proportion of CNSO in the fuel blend led to a rise in the BSFC value. One of the primary factors contributing to this higher consumption is the lower energy content of CNSO compared to conventional fossil fuels. Due to the lower energy content, engines operating on CNSO may require a more significant fuel volume to generate the same amount of power as conventional fuels. This increased fuel consumption can be observed through the higher BSFC values, which indicate the fuel consumed per unit of energy produced [49].

Incorporating CeO_2 nano additive into diesel fuel has demonstrated a significant improvement in fuel efficiency, as evidenced by a 5.02% reduction in BSFC compared to neat diesel fuel. This reduction in BSFC signifies a more efficient fuel utilisation, enhancing overall performance and economic benefits. CeO_2 nano additives possess unique properties that contribute to their effectiveness in improving fuel efficiency. These nanoparticles exhibit a high surface area and catalytic activity, facilitating better fuel combustion and reducing energy losses during combustion.

Acetylene-fuelled combustion has demonstrated promising results in reducing fuel consumption compared to conventional diesel combustion. Experimental studies have revealed a significant reduction in BSFC by up to 9.13% when utilising 6 lpm of acetylene injection. Acetylene has a higher energy content per volume unit than diesel fuel. This means that a smaller amount of acetylene can generate the same amount of energy, reducing fuel consumption [50]. Acetylene has excellent combustion properties, including a high flame propagation rate and low ignition delay. These characteristics allow for more efficient and complete combustion, resulting in better fuel utilisation and reduced wastage [41].

Emission analysis

Nox and CO emissions

A comparison of the effects of CNSO, CeO_2 nano additive and acetylene on NOx is shown in Fig. 5 (a). The experimental results showed an increase in NOx when the proportion of biodiesel was increased. Compared to diesel, there was a 9.83% increase in NOx from combustion using CNSO fuel. As CNSO contains more oxygen than diesel, it produces higher combustion temperatures and more NOx. Furthermore, the spray characteristics and fuel mixing with air in the combustion chamber are also affected by CNSO chemical properties, including higher viscosity and lower volatility. The use of CeO_2 nano additive significantly reduced NOx emissions during combustion. Compared with neat diesel, CeO_2 blended diesel reduced NOx formation by 10.5%. CeO_2 blended CNSO reduced NOx formation by 5.92%. As a result of its catalytic properties, the CeO_2 nano additive used in fuel reduces NOx emissions. By oxidising soot particles, CeO_2 facilitates the complete combustion of fuel [51].

The presence of acetylene in the combustion process also affects the temperature, affecting NOx formation [29]. Because acetylene's combustion temperature is too high, it leads to thermal NOx formation, which occurs when nitrogen and oxygen in the air interact at high temperatures. Acetylene also undergoes pyrolysis, which is the

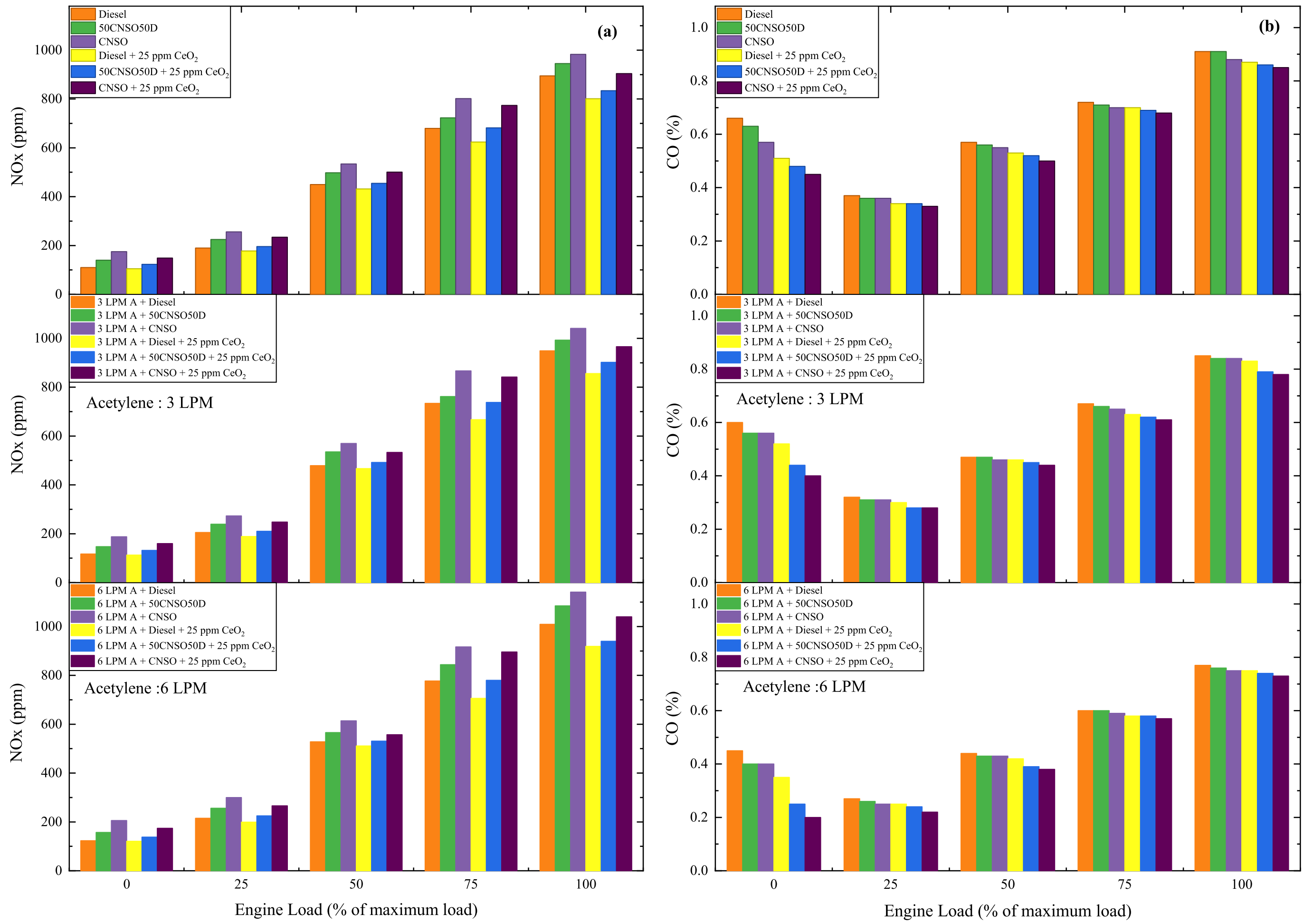

Fig. 5. (a) NOx (b) CO emissions of CeO_2, CNSO and acetylene injection.

breakdown of a compound by heat, resulting in other compounds that affect NOx emissions. As acetylene is pyrolysed, soot is produced, a carbon source that reacts with NO to form additional NOx. There was an increase of 12.74% in NOx in the experimental results. Although, CeO_2 was influential in the combustion process and significantly reduced NOx emissions.

Fig. 5 (b) shows the effect of CSNO, CeO_2 nano additive, and acetylene on CO. In the experiment, CO levels increased as the engine load increased. Unbalanced air–fuel ratios result in incomplete combustion, which produces more CO. CNSO biodiesel reduces CO emissions by up to 3.3% at maximum engine load owing to biodiesel containing more oxygen atoms, which promotes complete combustion [52]. The higher cetane number of CNSO fuel allows engines to ignite faster and cleaner than traditional diesel fuel. The result is a more efficient combustion process, which results in fewer carbon monoxide emissions. Due to its lower sulfur content, CNSO produces fewer harmful emissions, including CO. Traditional diesel fuel contains aromatic hydrocarbons [53]. Among these compounds are compounds that contribute to the formation of harmful emissions, including carbon monoxide. CNSO produces less CO in combustion due to its lower aromatic content [54].

CeO_2 reduces CO emissions from diesel engines. This is because cerium oxide is a catalyst capable of oxidising CO into CO_2, a less harmful greenhouse gas. Creating oxygen vacancies on the surface of cerium oxide reduces CO emissions. Vacancies in oxygen can attract oxygen molecules, which then react with CO to form CO_2. In addition, cerium oxide has been shown to improve diesel fuel combustion efficiency, reducing CO emissions. Compared to neat diesel, 25 ppm CeO_2 blended diesel and CNSO showed significant reductions in CO formation of up to 4.4% and 6.59%, respectively. CO emissions are reduced because acetylene burns at a higher temperature than diesel fuel. A complete combustion process of acetylene also results in lower CO emissions since its carbon-to-hydrogen ratio is lower than diesel fuel [55,56].

HC and smoke emissions

Fig. 6 (a) shows the variations in HC emissions. As a result of its higher oxygen content and lower sulfur content, CNSO results in lower HC than conventional diesel due to the carbon-to-hydrogen ratio of CNSO biodiesel being lower than that of diesel fuel, which is another benefit. For CNSO biodiesel-fuelled combustion, HC decreased by up to 21.44% compared to diesel-fuelled combustion. Further, CeO_2 blending with fuel also supports the reduction in HC. Compared to neat diesel, CeO_2 additive mixed diesel and CSNO reduced HC by 25.84% and 44.45%, respectively. Due to its high oxygen storage capacity, CeO_2 can store and release oxygen during combustion. Hydrocarbon molecules can be broken down during combustion by CeO_2 catalytic properties. HC emissions increase when acetylene is used as a fuel. Since acetylene is a highly unsaturated hydrocarbon, it can readily form other HC compounds, such as ethylene and propylene, during combustion. By reacting with other pollutants in the exhaust gas, these compounds can create more complex organic molecules, including harmful secondary pollutants such as formaldehyde and acetaldehyde.

Fig. 6 (b) illustrates the impact of CeO_2 nano additive and acetylene on the smoke emitted from a CNSO fuelled engine. The graph demonstrates that an increased proportion of CNSO leads to a reduction in smoke emissions. CNSO has a higher oxygen content, which promotes

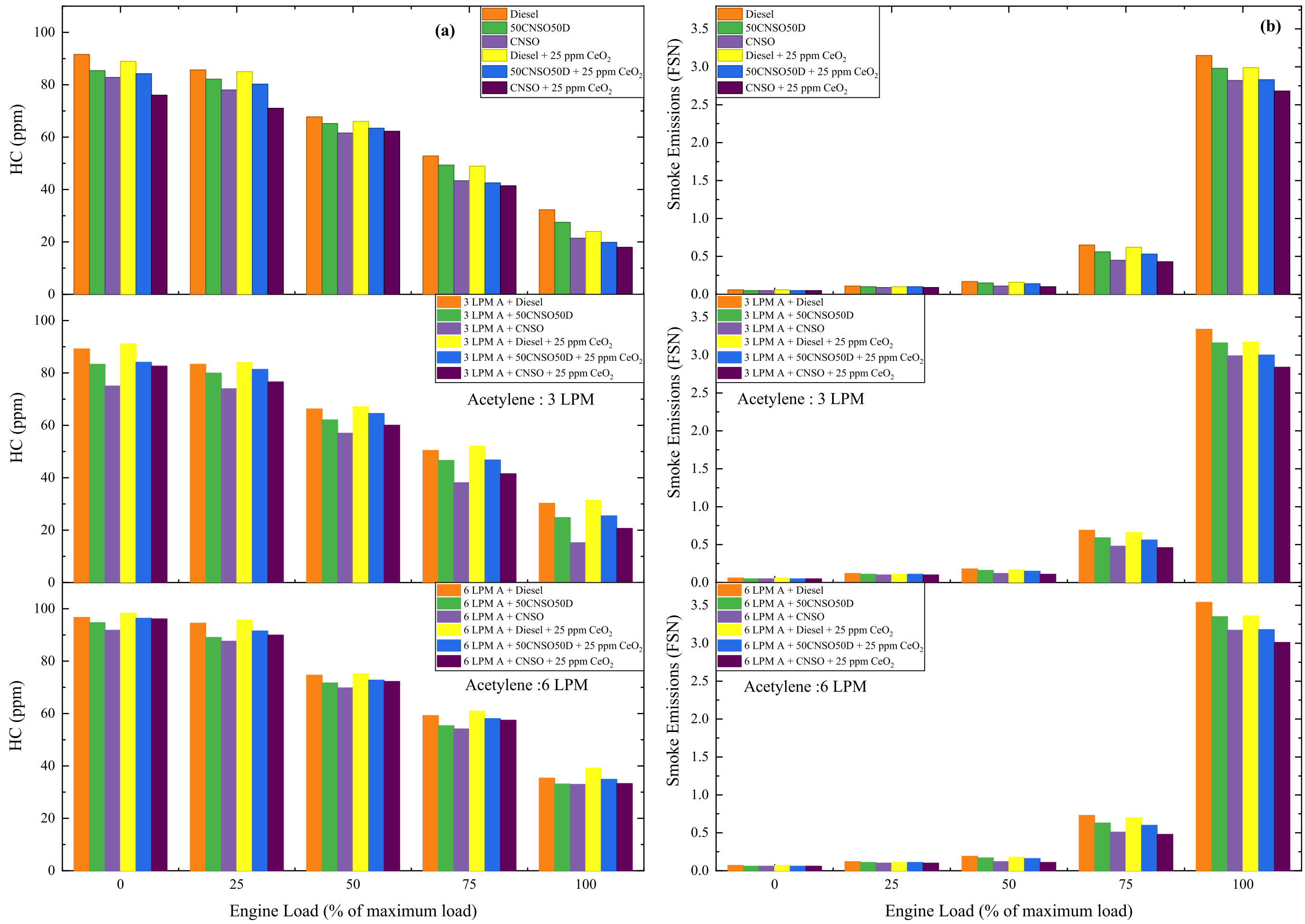

Fig. 6. (a) HC (b) smoke emissions of CeO_2, CNSO and acetylene injection.

complete combustion. It burns more cleanly and efficiently, resulting in reduced smoke emissions. As the proportion of CeO_2 nano additive increases, the smoke emitted from the engine decreases significantly. This reduction can be attributed to the catalytic properties of CeO_2, which promote complete combustion of the fuel and reduces the formation of smoke particles [45]. Furthermore, introducing acetylene into the CNSO fuel mixture contributes to a further decrease in smoke emissions. Acetylene, a high-energy hydrocarbon, aids combustion by providing additional reactive species [20]. This leads to improved fuel burnout and a consequent reduction in smoke production.

Optimisation

The RSM approach allows performing optimisation studies to identify the optimal combination of engine parameters that maximise performance and minimise emissions. By employing statistical analysis techniques like the design of experiments (DOE) and regression analysis, RSM helps to quantify the effects of different parameters, determine their interactions, and develop predictive models [33].

In this study, the investigations were done to analyse the effects of four input parameters on engine performance and emission. The input parameters included three numeric factors: CNSO proportion, acetylene injection rates, and load, and one categoric factor: CeO_2 dosage. The experiments were designed a set of experiments using the DOE approach. The study employed a complete factorial design, where all possible combinations of the levels of each factor were tested. In this case, the levels chosen were as follows: CNSO proportion: 0%, 50%, and 100%. Acetylene injection rates: 0 lpm, 3 lpm, and 6 lpm. Load: 0%, 50%, and 100%. In addition to the complete factorial design, the study employed a central composite design (CCD). The CCD is a standard design used in RSM, including a set of factorial, axial and centre points. This design allows for exploring the response surface in both the centre and at the extremes of the experimental space [50].

Analysis and evaluation of the model

The experiments were conducted using the DOE approach, and engine performance and emission data were collected. Analysis of Variance (ANOVA) and regression analysis were used to analyse the data and evaluate the model. From the experimental data, an RSM model was developed for predicting and optimising engine performance and emission. In assessing the model, it is essential to determine the significance of the factors and their interactions and the mathematical relationship between the input parameters and the response variables. The model could optimise the input parameters for desired engine performance and emission levels.

In the appendix, Table T4 presents the model analysis and evaluation results for various response variables related to engine performance and emission. The standard deviation measures the dispersion or variability of the response variable values around the mean. The studies showed that the SD values varied between 0.0224 and 5.91. The minor standard deviation indicates less variability in the data. C.V. % presents the coefficient of variation as a percentage. The C.V. % ranged between 0.2741 and 5.16. A lower coefficient of variation indicates lower relative variability. Statistically, R^2 measures a model's goodness of fit. Whenever the model is closer to 1, it better fits the data.

The adjusted R^2 is a modified version of R^2 that adjusts for the number of predictors in the model. A more conservative goodness-of-fit estimate is provided by penalising unnecessary predictors. The predicted R^2 measures the accuracy of the model in predicting new data. It evaluates the model's predictive capability by using a portion of the data to estimate the model and the remaining data to assess the prediction accuracy. The values closure to one for R^2, adjusted R^2, and predicted R^2 values indicate that the model provides an excellent fit to the data and has strong predictive capabilities. Adequacy precision measures the signal-to-noise ratio in the model. It determines if the model is suitable for making predictions within the design space. Higher values indicate a more precise model. The Adeq Precision values suggest the model is suitable for making predictions within the experimental design space.

The study aimed to maximise the BTE while minimising the BSFC and exhaust emissions. Sixty solutions were found, representing different combinations of factors and their corresponding outcomes. The high desirability value of 0.853 suggests that the CeO_2 blended, CNSO-fuelled combustion solution is the most favourable choice among the combinations tested in the study. This solution can optimise engine performance by maximising BTE, minimising fuel consumption, and reducing harmful exhaust emissions. Figure F7 shows the response surface plots for all the responses in the appendix.

Validation of optimised result

Experiments were conducted in the test engine under optimal operating conditions to validate the optimised result. The experiments were repeated three times to ensure reliability and accuracy. The results of these experiments are presented in Appendix Table T5, which includes the average experimental values and the predicted values obtained from the model.

Analyse the validation outcomes; it was observed that the model proposed in the study was highly accurate. The predicted values closely matched the experimental values, indicating a low error in the prediction. This suggests that the model successfully captured the relationships between the factors and outcomes, and its predictions aligned well with the actual experimental results.

Conclusion

CNSO biodiesel, with and without CeO_2 nano additive and acetylene injection, was used as the DI fuel in a diesel engine to test its performance, emissions, and combustion properties. Experimental results led to the following conclusions:

- BTE was slightly reduced when using CNSO biodiesel. Adding CeO_2 nano additive significantly improved engine performance, as evidenced by higher BTE values. Acetylene-fuelled combustion demonstrated superior performance characteristics to traditional diesel combustion, with increased BTE values.
- Using CNSO biodiesel led to increased BSFC values compared to traditional diesel. Incorporating CeO_2 nano additive and acetylene-fuelled combustion in diesel fuel reduced BSFC, indicating improved fuel efficiency.
- CNSO biodiesel led to increased NOx emissions compared to diesel fuel. Adding CeO_2 nano additive in diesel and CNSO fuel significantly reduced NOx emissions during combustion.
- By comparing CNSO biodiesel-fuelled combustion with diesel-fuelled combustion, CNSO biodiesel-fuelled combustion results in a 21.44% reduction in HC emissions. It has also been found that the CeO_2 nano additive can reduce HC emissions, with a decrease of 25.84% for CeO_2 additive blended diesel and a decrease of 44.45% for CNSO biodiesel.
- The investigation utilised RSM to analyse the effects of various input parameters on engine performance and emissions. The optimised result indicated that the combination of CeO_2 blended with CNSO fuel yielded the most favourable engine performance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103375.

References

[1] Soudagar MEM, et al. Effect of Sr@ZnO nanoparticles and Ricinus communis biodiesel-diesel fuel blends on modified CRDI diesel engine characteristics. Energy 2021;215:119094. https://doi.org/10.1016/J.ENERGY.2020.119094.

[2] Ramachander J, Gugulothu SK, Sastry GRK. Performance and Emission Reduction Characteristics of Metal-Based Sio2 Nanoparticle Additives Blended with Ternary Fuel (Diesel-MME-Pentanol) on CRDI Diesel Engine. SILICON Apr. 2022;14(5): 2249–63. https://doi.org/10.1007/S12633-021-01024-4/METRICS.

[3] Ağbulut Ü, Gürel AE, Sarıdemir S. Experimental investigation and prediction of performance and emission responses of a CI engine fuelled with different metal-oxide based nanoparticles–diesel blends using different machine learning algorithms. Energy 2021;215:119076. https://doi.org/10.1016/J.ENERGY.2020.119076.

[4] Duraisamy P, Subramani S. Performance and Emissions Characteristics of a Common Rail Direct Injection Diesel Engine Powered by Ignition Enhancer-Biodiesel Blends. International Journal of Environmental Science and Technology 2023;26. https://doi.org/10.1007/s13762-023-04891-z.

[5] Li Y, Chen Y, Wu G, Liu J. Experimental evaluation of water-containing isopropanol-n-butanol-ethanol and gasoline blend as a fuel candidate in spark-ignition engine. Appl Energy 2018;219:42–52. https://doi.org/10.1016/j.apenergy.2018.03.051.

[6] Næss JS, Cavalett O, Cherubini F. The land–energy–water nexus of global bioenergy potentials from abandoned cropland. Nat Sustain Jan. 2021;4(6): 525–36. https://doi.org/10.1038/s41893-020-00680-5.

[7] Duarah P, Haldar D, Patel AK, Dong C-D, Singhania RR, Purkait MK. A review on global perspectives of sustainable development in bioenergy generation. Bioresour Technol Mar. 2022;348:126791. https://doi.org/10.1016/j.biortech.2022.126791.

[8] Rather RA, et al. Bioenergy: a foundation to environmental sustainability in a changing global climate scenario. J King Saud Univ Sci Jan. 2022;34(1):101734. https://doi.org/10.1016/j.jksus.2021.101734.

[9] Simsek S, Uslu S. Experimental study of the performance and emissions characteristics of fusel oil/gasoline blends in spark ignited engine using response surface methodology. Fuel Oct. 2020;277:118182. https://doi.org/10.1016/j.fuel.2020.118182.

[10] Sarkar B, Mridha B, Pareek S, Sarkar M, Thangavelu L. A flexible biofuel and bioenergy production system with transportation disruption under a sustainable supply chain network. J Clean Prod Oct. 2021;317:128079. https://doi.org/10.1016/j.jclepro.2021.128079.

[11] Pocha CKR, Chia SR, Chia WY, Koyande AK, Nomanbhay S, Chew KW. Utilisation of agricultural lignocellulosic wastes for biofuels and green diesel production. Chemosphere Mar. 2022;290:133246. https://doi.org/10.1016/j.chemosphere.2021.133246.

[12] Babu, Rajesh Kumar, Ravikumar Jayabal, and Yuvarajan Devarajan. "Mitigating Carcinogenic Smoke Opacity in a Light-Duty Diesel Engine by Utilizing Cyclohexanol, Polyethylene Glycol, and 2-Methoxyethanol." Environmental Science and Pollution Research, February 24, 2023. https://doi.org/10.1007/s11356-023-26020-6.

[13] Kesharvani S, Verma TN, Dwivedi G. Computational analysis of chlorella protothecoides biofuels on engine combustion, performance and emission. Sustainable Energy Technol Assess Feb. 2023;55:102972. https://doi.org/10.1016/j.seta.2022.102972.

[14] Frost J, Hellier P, Ladommatos N. A systematic study into the effect of lignocellulose-derived biofuels on the combustion and emissions of fossil diesel blends in a compression ignition engine. Fuel Apr. 2022;313:122663. https://doi.org/10.1016/j.fuel.2021.122663.

[15] Asadi A, Zhang Y, Mohammadi H, Khorand H, Rui Z, Doranehgard MH, et al. Combustion and emission characteristics of biomass-derived biofuel, premixed in a diesel engine: A CFD study. Renew Energy 2019;138:79–89.
[16] Dhinesh B, Isaac JoshuaRamesh Lalvani J, Parthasarathy M, Annamalai K. An assessment on performance, emission and combustion characteristics of single cylinder diesel engine powered by Cymbopogon flexuosus biofuel. Energ Conver Manage 2016;117:466–74.
[17] Paula RSF, Vieira RS, Luna FMT, Cavalcante CL, Figueredo IM, Candido JR, et al. A potential bio-antioxidant for mineral oil from cashew nutshell liquid: an experimental and theoretical approach. Braz J Chem Eng 2020;37(2):369–81.
[18] Zombe K, Nyirenda J, Lumai A, Phiri H. Impact of Solvent Type on Total Phenol and Flavonoid Content and Sun Protection Factor of Crude Cashew Nutshell Liquid. Sustainable Chemistry Jul. 2022;3(3):334–44. https://doi.org/10.3390/suschem3030021.
[19] F. Bastos and M. Tubino, "The Use of the Liquid from Cashew Nut Shells as an Antioxidant in Biodiesel," *J Braz Chem Soc*, 2016, 10.21577/0103-5053.20160223.
[20] S. Karthikeyan, S. Amudhavalli Paramasivam, D. Dillikannan, and R. Jayabal. "Effect of Pilot Fuel Injection Strategies and EGR on a CRDI Diesel Engine Powered by Simmondsia Chinensis Seed Biodiesel-Methyl Acetate Blend." *Sustainable Energy Technologies and Assessments* 58 2023: 103345. https://doi.org/10.1016/j.seta.2023.103345.
[21] Zhao X, Jiang J, Zuo H, Jia G. Soot combustion characteristics of oxygen concentration and regeneration temperature effect on continuous pulsation regeneration in diesel particulate filter for heavy-duty truck. Energy Feb. 2023; 264:126265. https://doi.org/10.1016/J.ENERGY.2022.126265.
[22] Zhao X, Zuo H, Jia G. Effect analysis on pressure sensitivity performance of diesel particulate filter for heavy-duty truck diesel engine by the nonlinear soot regeneration combustion pressure model. Energy Oct. 2022;257:124766. https://doi.org/10.1016/J.ENERGY.2022.124766.
[23] Maia FJN, Ribeiro FWP, Rangel JHG, Lomonaco D, Luna FMT, Lima-Neto Pd, et al. Evaluation of antioxidant action by electrochemical and accelerated oxidation experiments of phenolic compounds derived from cashew nut shell liquid. Ind Crops Prod 2015;67:281–6.
[24] S. Kumar, D. P, and M. A. Rosen, "Cashew Nut Shell Liquid as a Fuel for Compression Ignition Engines: A Comprehensive Review," *Energy & Fuels*, vol. 32, no. 7, pp. 7237–7244, Jul. 2018, 10.1021/acs.energyfuels.8b00579.
[25] T. T. Olugasa, M. L. Adekanbi, and S. K. Fasogbon, "Performance and Emission Characteristics of Compression Ignition Engine Running on a Blend of Cashew Nut Shell Liquid and Biodiesel Produced from Orange Peel," *European Journal of Sustainable Development Research*, vol. 6, no. 4, p. em0197, Jul. 2022, 10.21601/ejosdr/12233.
[26] Karthick M, Logesh K, Baskar S, Sharma A. "Performance and Emission Characteristics of Single-Cylinder Diesel Engine Fueled with Biodiesel Derived from. Cashew Nut Shell" 2022:521–9. https://doi.org/10.1007/978-981-16-8341-1_44.
[27] M. Loganathan, V. M. Madhavan, K. Arun Balasubramanian, V. Thangaivelan, M. Vikneswaran, and A. Anbarasu, "Investigation on the effect of diethyl ether with hydrogen-enriched cashew nut shell (CNS) biodiesel in direct injection (DI) diesel engine," *Fuel*, vol. 277, p. 118165, Oct. 2020, 10.1016/j.fuel.2020.118165.
[28] H. Enes Fil, S. Orhan Akansu, and M. Ilhan Ilhak, "Experimental assessment on performance, emission and combustion characteristics of the use of diesel-acetylene mixtures at different loads in a ci engine," *Fuel*, vol. 324, p. 124469, Sep. 2022, 10.1016/j.fuel.2022.124469.
[29] Singh G, et al. Optimisation of performance, combustion and emission characteristics of acetylene aspirated diesel engine with oxygenated fuels: An Experimental approach. Energy Rep Nov. 2021;7:1857–74. https://doi.org/10.1016/j.egyr.2021.03.022.
[30] Choudhary KD, Nayyar A, Dasgupta MS. Effect of compression ratio on combustion and emission characteristics of C.I. Engine operated with acetylene in conjunction with diesel fuel. Fuel Feb. 2018;214:489–96. https://doi.org/10.1016/j.fuel.2017.11.051.
[31] Dhahad HA, Ali SA, Chaichan MT. Combustion analysis and performance characteristics of compression ignition engines with diesel fuel supplemented with nano-TiO2 and nano-Al2O3. Case Studies in Thermal Engineering Aug. 2020;20: 100651. https://doi.org/10.1016/j.csite.2020.100651.
[32] Vigneswaran R, Balasubramanian D, Sastha BDS. Performance, emission and combustion characteristics of unmodified diesel engine with titanium dioxide (TiO2) nanoparticle along with water-in-diesel emulsion fuel. Fuel Feb. 2021;285: 119115. https://doi.org/10.1016/j.fuel.2020.119115.
[33] Ağbulut Ü, Polat F, Sarıdemir S. A comprehensive study on the influences of different types of nano-sized particles usage in diesel-bioethanol blends on combustion, performance, and environmental aspects. Energy Aug. 2021;229: 120548. https://doi.org/10.1016/j.energy.2021.120548.
[34] Hoang AT. Combustion behaviour, performance and emission characteristics of diesel engine fuelled with biodiesel containing cerium oxide nanoparticles: A review. Fuel Process Technol Jul. 2021;218:106840. https://doi.org/10.1016/J.FUPROC.2021.106840.
[35] Sahu TK, Sarkar S, Shukla PC. Combustion investigation of waste cooking oil (WCO) with varying compression ratio in a single cylinder CI engine. Fuel Jan. 2021;283:119262. https://doi.org/10.1016/J.FUEL.2020.119262.
[36] Jaikumar S, Srinivas V, Rajasekhar M. Influence of dispersant added nanoparticle additives with diesel-biodiesel blend on direct injection compression ignition engine: Combustion, engine performance, and exhaust emissions approach. Energy Jun. 2021;224:120197. https://doi.org/10.1016/J.ENERGY.2021.120197.
[37] Nanthagopal K, Ashok B, Saravanan B, Korah SM, Chandra S. Effect of next-generation higher alcohols and Calophyllum inophyllum methyl ester blends in diesel engine. J Clean Prod Apr. 2018;180:50–63. https://doi.org/10.1016/j.jclepro.2018.01.167.
[38] Leo GML, Sekar S, Arivazhagan S. Experimental investigation and ANN modelling of the effects of diesel/gasoline premixing in a waste cooking oil-fuelled HCCI-DI engine. J Therm Anal Calorim Sep. 2020;141(6):2311–24. https://doi.org/10.1007/s10973-020-09418-z.
[39] Devarajan Y, Munuswamy DB, Mahalingam A. Investigation on behaviour of diesel engine performance, emission, and combustion characteristics using nano-additive in neat biodiesel. Heat Mass Transf Jun. 2019;55(6):1641–50. https://doi.org/10.1007/s00231-018-02537-2.
[40] G. M. Lionus Leo, G. Thodda, and S. Murugapoopathi, "Experimental investigation on effects of gasoline premixed - Al_2O_3 additive blended fish oil biodiesel fuelled HCCI-DI engine," *J Phys Conf Ser*, vol. 2054, no. 1, p. 012040, Oct. 2021, 10.1088/1742-6596/2054/1/012040.
[41] B. Aisosa Oni, S. Eshorame Sanni, M. Daramola, and A. Victoria Olawepo, "Effects of oxy-acetylation on performance, combustion and emission characteristics of Botryococcus braunii microalgae biodiesel-fuelled CI engines," *Fuel*, vol. 296, p. 120675, Jul. 2021, 10.1016/j.fuel.2021.120675.
[42] Armin M, Gholinia M, Pourfallah M, Ranjbar AA. Investigation of the fuel injection angle/time on combustion, energy, and emissions of a heavy-duty dual-fuel diesel engine with reactivity control compression ignition mode. Energy Rep Nov. 2021; 7:5239–47. https://doi.org/10.1016/J.EGYR.2021.08.115.
[43] G. M. Lionus Leo, S. Sekar, and S. Arivazhagan, "Experimental investigation, optimisation and ANN model prediction of a gasoline premixed waste cooking oil fueled HCCI–DI engine," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 40, no. 2, p. 49, Feb. 2018, 10.1007/s40430-018-0967-1.
[44] Devarajan Y, Nagappan B, Subbiah G. A comprehensive study on emission and performance characteristics of a diesel engine fueled with nanoparticle-blended biodiesel. Environ Sci Pollut Res Apr. 2019;26(11):10662–72. https://doi.org/10.1007/s11356-019-04446-1.
[45] Lionus LGM, Subramani S, Sundaraganesan A. Experimental Investigation, ANN Modelling and TOPSIS Optimization of a Gasoline Premixed HCCI-DI Engine with Direct Injection of FeCl3 Nanodditive Blended WCO. TFAMENA 2019;43(3): 83–100.
[46] Agarwal D, Sinha S, Agarwal AK. Experimental investigation of control of NOx emissions in biodiesel-fueled compression ignition engine. Renew Energy Nov. 2006;31(14):2356–69. https://doi.org/10.1016/j.renene.2005.12.003.
[47] Emiroğlu AO, Şen M. Combustion, performance and exhaust emission characterisations of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel). Appl Therm Eng Mar. 2018;133:371–80. https://doi.org/10.1016/j.applthermaleng.2018.01.069.
[48] F. C. P. Leach, M. Davy, and B. Terry, "Combustion and emissions from cerium oxide nanoparticle dosed diesel fuel in a high-speed diesel research engine under low-temperature combustion (LTC) conditions," *Fuel*, vol. 288, p. 119636, Mar. 2021, 10.1016/J.FUEL.2020.119636.
[49] Thodda G, Kathapillai A, Madhavan VR, Saravanamuthu M. Experimental analysis on the influence of compression ratio, flow rate, injection pressure, and injection timing on the acetylene — diesel aspirated dual fuel engine. Environ Sci Pollut Res May 2022. https://doi.org/10.1007/S11356-022-21483-5.
[50] Thodda G, Madhavan VR, Thangavelu L. "Predictive Modelling and Optimisation of Performance and Emissions of Acetylene Fuelled CI Engine Using ANN and RSM," *Energy Sources, Part A: Recovery*. Utilization and Environmental Effects 2020. https://doi.org/10.1080/15567036.2020.1829191.
[51] Madhu S, Lionus Leo GM, Prathap P, Devarajan Y, Jayabal R. Effective utilisation of waste pork fat as a potential alternate fuel in CRDI research diesel engine – Waste reduction and consumption technique. Process Safety and Environmental Protection 2023;172:815–24. https://doi.org/10.1016/j.psep.2023.02.057.
[52] Geo VE, Sonthalia A, Nagarajan G, Nagalingam B. Studies on performance, combustion and emission of a single cylinder diesel engine fuelled with rubber seed oil and its biodiesel along with ethanol as injected fuel. Fuel Dec. 2017;209: 733–41. https://doi.org/10.1016/j.fuel.2017.08.036.
[53] S. Murugapoopathi, T. Ramachandran, and C. Rajaganapathy, "Theoretical performance on energy and exergy analysis of methyl esters of rubber seed oil fuelled on supercharged VCR engine," *Environ Dev Sustain*, pp. 1–20, Aug. 2022, 10.1007/S10668-022-02642-7/METRICS.
[54] Murugapoopathi S, Vasudevan D. Performance, combustion and emission characteristics on VCR multi-fuel engine running on methyl esters of rubber seed oil. J Therm Anal Calorim Oct. 2019;138(2):1329–43. https://doi.org/10.1007/S10973-019-08281-X/FIGURES/16.
[55] Murugapoopathi S, Vasudevan D. Experimental and numerical findings on VCR engine performance analysis on high FFA RSO biodiesel as fuel using RSM approach. Heat and Mass Transfer/Waerme- und Stoffuebertragung Mar. 2021;57 (3):495–513. https://doi.org/10.1007/S00231-020-02961-3/FIGURES/20.
[56] Murugapoopathi S, Vasudevan D. Energy and exergy analysis on variable compression ratio multi-fuel engine. J Therm Anal Calorim Apr. 2019;136(1): 255–66. https://doi.org/10.1007/S10973-018-7761-2/FIGURES/4.