Evaluating the Performance of a Direct Injection Diesel Engine Using Corn Oil Biodiesel Blended with Graphene Oxide Nanoparticles and Hydrogen

Dhana Sekhar Yepuri[1], P. Tamilarasan[1], T. Dharma Raju[2], A. Velmurugan[1]
[1]*Department of Mechanical Engineering, Annamalai University, Annamalainagar, Chidambaram, Tamil Nadu 608002, India*

[2] *Department of Mechanical Engineering, Kakinada Institute of Engineering and Technology, Coringa, Andhra Pradesh 533461, India*

Abstract:- Global environment and emission policies are mandating vehicle manufacturers to control diesel engine emissions. In this work, the performance of Corn oil biodiesel doped with Graphene oxide (GO) nanoparticles and enriched with hydrogen is studied with a focus on combustion efficiency and emissions. Experiments were conducted on diesel and biofuel blends with varying biofuel vol/vol content ranging from 0% to 25%. Initial results indicate that the B20 blend optimizes combustion, with a notable Brake Thermal Efficiency increase. Later B20 is doped with GO nanoparticles at 100 ppm and experiments were conducted with incremental hydrogen flow rates ranging from 2 to 10 lpm. Further, the integration of GO nanoparticles and hydrogen into B20 significantly reduced emissions, with B2H10 achieving the most significant reduction in both hydrocarbon (93.9%) and carbon monoxide (73%) emissions. Smoke opacity also significantly decreased, particularly with B2H10, which demonstrated a 34.4% reduction at full load. Finally, a Deep Long Short-Term Memory (DLSTM) regression model is developed to predict the emissions characteristics of the fuel blends that showed an averaged RMSE and MAE of 0.498 and 0.413, respectively.

Keywords: *biofuel, hydrogen, nanoparticle, dual fuel engine, prediction, deep learning*

1. Introduction

In the present energy sector, the dominance of fossil fuels is evident, propelled by the rapid expansion of global economies and population growth. This has led to an increased reliance on these energy sources to satisfy the expanding demand [1], [2]. Among these, petroleum is particularly prominent, emerging as the most cost-effective and reliable energy source. Its widespread use spans various industries, notably in the transportation sector [3], [4]. The widespread adoption of internal combustion engines, particularly in transportation vehicles and construction machinery, has contributed to economic growth and process efficiency. However, this reliance on petroleum and other fossil fuels has its drawbacks, notably the high energy consumption and environmental impact, including the release of gases detrimental to the ozone layer, contributing to global warming and climate change [5], [6]. The environmental challenges posed by fossil fuel consumption necessitate a shift towards more sustainable energy alternatives [7]–[9]. Biofuels have emerged as a viable solution in this context, attracting considerable scientific interest due to their environmental friendliness and performance capabilities. These fuels are characterized by lower emissions of harmful gases, making them a cleaner energy source. The global distribution of biofuel resources ensures a consistent supply. Sugar, starch, and oil are the primary sources for biofuel production. Crops like sugar-beet, sweet sorghum, and sugarcane, known for their high sugar content, are commonly used for ethanol production, a process widely adopted due to its efficiency and high yield [10], [11].

Starch-based biofuels are derived from crops like corn and cassava, while oil-based biofuels are produced from palm, coconut, rapeseed, sunflower, and soybean oils [12], [13]. To further enhance the performance of biofuels, research has been directed towards the addition of catalysts at varying concentrations, which has been shown to improve their properties significantly [14]–[16]. This research is crucial in mitigating the environmental impact associated with traditional fossil fuels and advancing towards a sustainable energy future.

Recent research has indicated significant advancements in diesel engine performance and emission reduction through the utilization of nanoparticles. Studies have demonstrated that the integration of nanoparticles into diesel fuel, particularly biodiesel blends, enhances combustion efficiency while simultaneously decreasing harmful emissions [17], [18]. This improvement can be attributed to the inherent high surface area and reactivity of nanoparticles like copper oxides, zinc oxide, and cerium oxide (CeO2), and magnesium oxide (MgO), which have been the focus of recent investigations [19]–[21]. The effectiveness of nanoparticles in diesel engines is largely due to their high surface-area-to-volume ratio. This characteristic facilitates better interaction between fuel and oxidizer, resulting in enhanced fuel combustion. Additionally, this ratio contributes to a reduction in ignition delay and the evaporation rate of the fuel, leading to more efficient combustion processes [22], [23]. Furthermore, when these nanoparticles are added to liquid fuels, they elevate the energy density of the fuel, culminating in improved combustion characteristics [24]. El-Adawy [25] demonstrated that adding zinc oxide nanoparticles to diesel-biodiesel blends improves engine torque and reduces fuel consumption, with specific enhancements in torque and brake specific fuel consumption across various blends. Yusuf et al. [26] found that CeO2 nanoparticle-doped biodiesel blends enhance combustion parameters and significantly reduce toxic pollutants, including a notable decrease in polycyclic aromatic hydrocarbon emissions. Ranjan et al. [27] reported improved cold flow properties and combustion characteristics of waste cooking oil biodiesel with MgO nanoparticles, leading to higher brake thermal efficiency and lower emissions. Venkatesan et al. [28] showed that diesel-aqueous zinc oxide nanofluid blends improve brake thermal efficiency and reduce emissions, including NOx, smoke, HC, and CO, highlighting the potential of nanoparticle additives in diesel engine fuel optimization.

Nanoparticles, when mixed with biodiesel, enhance combustion while simultaneously reducing emissions. However, this blend's low viscosity does not significantly reduce NOx emissions [22], [29], [30]. Introducing hydrogen into diesel engines can optimize air-fuel mixing, leading to better combustion with reduced soot production [31]–[33]. Hydrogen, used extensively in petroleum refining, manufacturing, and transportation, can be produced from diverse sources including biomass, nuclear energy, natural gas, and renewable energies like solar and wind. As an energy carrier, hydrogen boosts the performance of base fuels. It's also beneficial for augmenting the efficacy of alternative fuels, thanks to its clean energy profile [34]. Studies have indicated that nanofuels enriched with hydrogen tend to exhibit elevated NOx emissions [30]. Additionally, it has been noted that controlling the hydrogen flow rate is crucial, as excessive rates can increase NOx emissions. In this research, Corn oil biodiesel fuel blended with hydrogen and graphene oxide nanoparticles were assessed for emission and performance study.

2. Biodiesel production and characterization

2.1. Materials

Corn oil extracted from corn (Bisco X 5129 hybrid), scientifically called Zea mays (Bisco X 5129 hybrid), is procured form the local vendors of Kakinada, Andhra Pradesh, India. This corn oil is used to produce biodiesel using transesterification. Analytical grade reagents and the chemicals to conduct the experiments were procured from Pon Pure Chemicals Group, Chennai, India. The nanoparticles of Graphene oxide (GO) are procured from Intelligent Materials Private Limited, Punjab, India. All the chemicals, reagents, and nanoparticles are commercial grade and does not require any secondary processing and characterization. Convectional diesel is procured from a local Hindustan Petroleum Corporation Limited oil pump, Kakinada, Andhra Pradesh, India.

2.2. Biodiesel production

Vegetable oils, known for their higher viscosity compared to diesel, face challenges in efficient fuel atomization within the combustion chambers of compression ignition (CI) engines. This issue is particularly evident at the end of the compression stroke when the fuel is injected under high pressure. The higher viscosity of vegetable oils leads to less effective atomization, potentially causing incomplete combustion and increased emissions when used directly in CI engines. To mitigate these issues and improve the adaptability of vegetable oils for use in CI engines, reducing their viscosity is essential. This reduction can be accomplished through methods like pyrolysis, but transesterification is more commonly employed due to its effectiveness in bringing the viscosity of vegetable oils closer to that of standard diesel fuel. This process also facilitates the production of biodiesel with yields varying between 50% and 90%. Transesterification, a key process in this context, involves a chemical reaction where vegetable oil triglycerides react with an alcohol, typically methanol or ethanol, in the presence of a catalyst like sodium hydroxide (NaOH) or potassium hydroxide (KOH). This reaction results in the formation of alkyl esters, commonly known as biodiesel, and glycerol as a by-product. In this work, 1000 ml of corn oil and 220 ml of dehydrated methanol is used for transesterification procedure. In this process, 7.5 g of NaOH was utilized as a catalyst. The methanol and NaOH were mixed and stirred until the NaOH completely dissolved. Concurrently, the corn oil was preheated to 65ºC while stirring to eliminate moisture and reduce its viscosity. Following this, the methanol-NaOH mixture was blended with the corn oil and stirred continuously for 3 hours. After blending, biodiesel and glycerine were separated using a separating funnel, allowing a separation time of 22 hours. The setup for biodiesel production is shown in Figure 1.

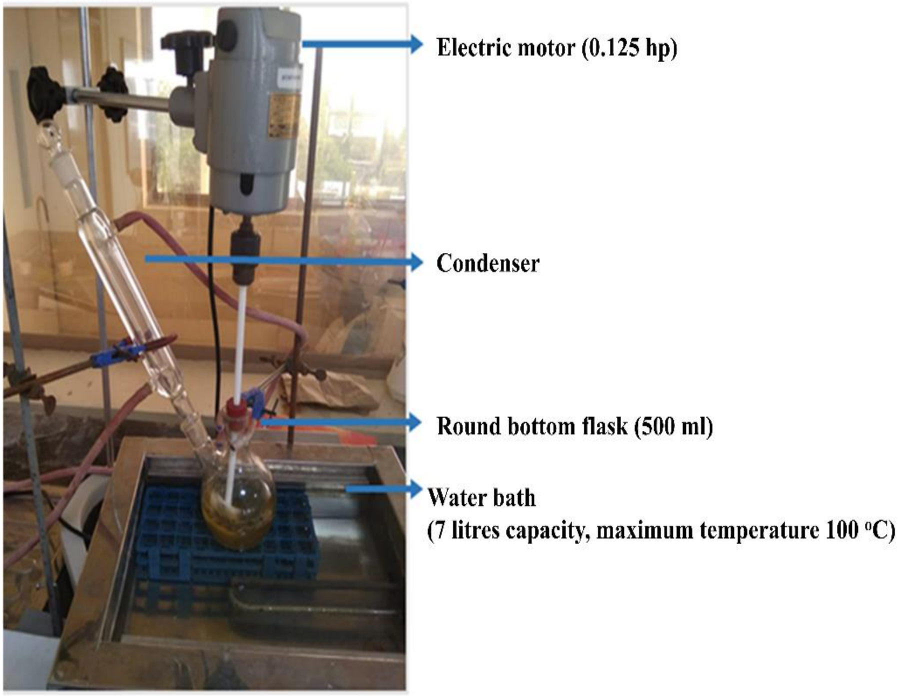


Figure 1. Biodiesel production setup

2.3. Biodiesel blends

Six different blends of biodiesel and conventional diesel were prepared in this study. The prepared blends have biodiesel content varying from 0% to 100% on volume basis (%v/v) and the properties of these mixtures were evaluated using ASTM D6751 fuel properties testing procedures. Analysing the properties of pure biodiesel is critical for determining its effectiveness as an unadulterated renewable energy source. This work delves into the impact of different biodiesel concentrations on engine performance and emission of pollutants and provides an understanding on the role of biodiesel in meeting sustainability and environmental regulations. The flash point of various fuels was determined using a Cleveland Open Cup Flash Point Tester, model PC-102. To determine the density of these fuels, a lab density analyser from Phase Technologies, model DFA-70Xi, was employed. Zeltex (model ZX440) infrared fuel analyzer was used to measure the Cetane number of the blends. Additionally, the

Saybolt Universal Viscometer is used to measure viscosity levels of the fuels under test. The results of these measurements are detailed in Table 1.

Table 1. Properties of fuel blends

Blend notation	Biodiesel content, %v/v	Kinematic viscosity @40 °C, cSt	Flash point, °C	Fire point, °C	Calorific value, MJ/kg	Density, kg/m^3	Cetane number
B0	0	2.91	60	68	46.446	828.8	46.7
B5	5	3.21	75	81	42.788	845.6	47.2
B10	10	3.25	81	87	42.153	857.2	47.9
B15	15	3.28	87	93	41.865	859.7	48.5
B20	20	3.32	89	97	41.218	861.1	49.1
B25	25	3.8	91	101	38.649	875.8	50.3
B100	100	4.28	103	113	36.905	911	54.5

Diesel fuel in its pure form (B0) is characterized by a comparatively lower density, which is a contributing factor to its higher energy content, thus providing it with a greater calorific value compared to various alternatives. On the other hand, Corn oil-based biodiesel (B100) demonstrates a substantially higher cetane number. This higher cetane number is indicative of superior ignition qualities, which may lead to smoother engine performance and reduced operational noise. Additionally, the safety features of B100 are enhanced, as evidenced by its significantly elevated flash and fire points. These higher points suggest a decreased likelihood of accidental ignition at lower temperatures, enhancing safety during storage and handling. The blends of diesel with biodiesel shows intermediate cetane number and calorific value reflecting a balance between energy content and combustion quality. This blend offers improved ignition quality over pure diesel while partially retaining the high-energy content, presenting a viable option for reducing emissions and improving renewable content in fuels without drastically compromising engine performance. The characteristics of biodiesel blends tend to align closely with those of traditional diesel and fall within the parameters set by the EN14214 standards for biodiesels, ensuring their suitability and compliance.

1. Experimental procedure

In this work, a water-cooled and single-cylinder Kirloskar TV-1 direct injection engine is utilized to test the performance of the fuel blends. It functions primarily using diesel fuel, with hydrogen serving as an auxiliary fuel. This four-stroke engine has a bore diameter and stroke of 87.5 mm and 110 mm, respectively, and operates at a compression ratio of 17.5:1. Its peak output is rated at 5.20 kW, equivalent to 7 Hp, achieved at a rotational speed of 1500 rpm. The engine has a total volume of 0.661 cubic litres. A detailed schematic of the engine and its experimental setup is depicted in Figure 2. The initial experiments are conducted using different blends of biodiesels only. Upon performance evaluation of these blends, it is found that the B20 has superior performance compared to the other blends, discussed in section 4. Later, the B20 biofuel is doped with graphene oxide (GO) nanoparticles and the doped biofuel's performance is evaluated along with hydrogen additive at different flow rates of hydrogen.

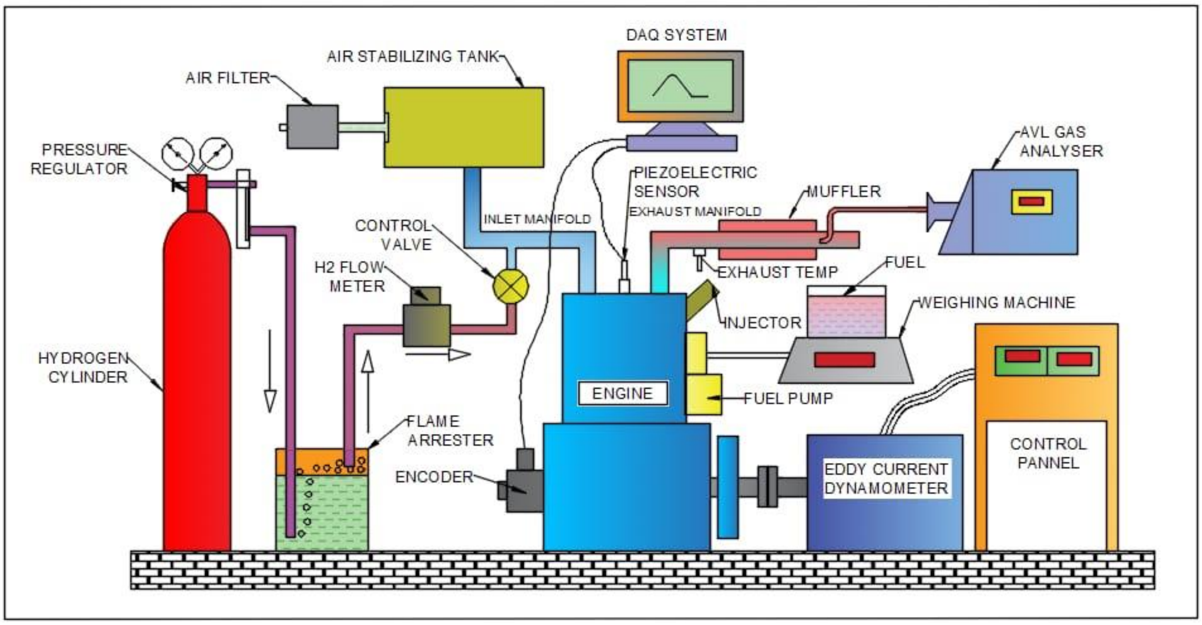


Figure 2. Experimental test rig schematic

In this study, a systematic approach was adopted to explore the effects of hydrogen addition on engine air intake, utilizing hydrogen as a supplementary fuel. The hydrogen was introduced at varying flow rates - 2, 4, 6, 8, and 10 litres per minute (lpm) - while maintaining a constant 20% volume percentage relative to the air in all test mixtures. This approach ensured a stable consumption of biodiesel irrespective of the changes in hydrogen flow rates. The experimental setup included a high-pressure hydrogen cylinder calibrated at 180 bar, with the hydrogen exiting at a pressure of 4 bar. Critical components like a pressure regulator, flame arrestor, flame trapper, and a flowmeter were integrated for accurate control and safety measures. Both hydrogen and air flow rates were meticulously measured to achieve a precise air-to-hydrogen mixture ratio. The experimental protocol involved infusing hydrogen into the air stream, maintaining a 15% hydrogen-to-air volume ratio in each mixture, which included a B20-GO nanoparticle blend. For ensuring a homogenous mixture, GO nanoparticles were sonicated into diesel at 100 parts per million concentration. The fuel blends evaluated in this experiment were B0 (100% diesel) and five additional blends (B2H2, B2H4, B2H6, B2H8, B2H10) each comprising 80% diesel, 100 ppm GO nanoparticles, and varying hydrogen flow rates of 2, 4, 6, 8, and 10 lpm, respectively. The impact of these blends on engine performance and emissions was assessed under various engine loads, ranging from no-load to full-load conditions, reaching a maximum output of 5.2 kW. Emissions including CO, CO_2, HC, and NOx along with smoke opacity were monitored using an AVL gas analyser and smoke meter to evaluate the environmental impact of each fuel blend. Table 2 gives the nomenclature of the blends with hydrogen additives.

Table 2. Nomenclature for fuel blends with hydrogen

Symbol	Description
B2H2	80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 2 lpm Hydrogen
B2H4	80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 4 lpm Hydrogen
B2H6	80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 6 lpm Hydrogen
B2H8	80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 8 lpm Hydrogen
B2H10	80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 10 lpm Hydrogen

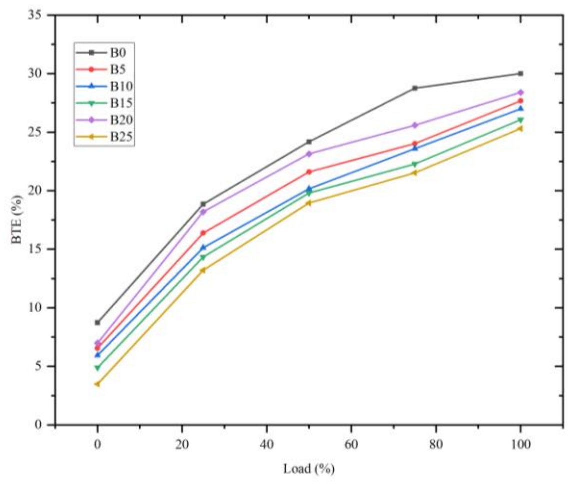
2. Results and discussion

This work investigates the impact of various fuel combinations on engine functionality, focusing on combustion efficiency and emission levels. The study involved testing a range of blends: B0 (100% diesel), B5 (5% biofuel, 95% diesel), B10 (10% biofuel, 90% diesel), B15 (15% biofuel, 85% diesel), B20 (20% biofuel, 80% diesel), and B25 (25% biofuel, 75% diesel). Additionally, the study explored the effects of integrating graphene oxide (GO) nanoparticles and varying hydrogen flow rates into a 20% diesel blend. The specific blends were B2H2 (80 % Diesel + 20% Corn oil biodiesel + 100 ppm GO + 2 lpm Hydrogen), B2H4, B2H6, B2H8, and B2H10, with the last number indicating the liters per minute (lpm) of hydrogen flow, increasing in increments of 2 lpm from 4 to 10. The performance evaluations involve examining the engine performance under various operational loads ranging from 0% to 100 % load in five intervals (no load, 1.3 kW, 2.6 kW, 3.9 kW, and 5.2 kW) to determine the effect of incorporating hydrogen and GO nanoparticles into diesel fuel. This comprehensive analysis aims to understand how the addition of nanoparticle additives and hydrogen influenced the operational characteristics of diesel engines. The results were represented graphically, enabling a comparative analysis and interpretation of the effect of the addition of nanoparticles and hydrogen on the operational characteristics of diesel engines.

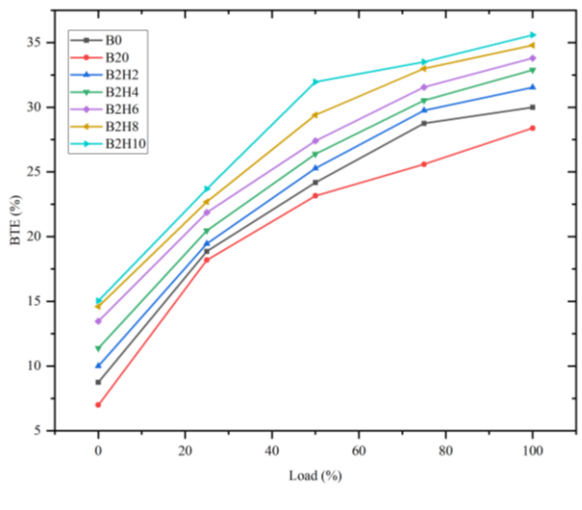
4.1. Performance characteristics

4.1.1. Brake thermal efficiency (BTE)

The effect of various biofuel blends and the integration of GO nanoparticles and hydrogen flow rates on Brake Thermal Efficiency (BTE) is presented in Figure 3. The B0 blend, pure diesel, displayed a gradual increase in BTE with the load, starting at 8.74% at no load and peaking at 30% at full load. This increase is estimated as diesel engines typically run more efficiently under higher loads due to better combustion and reduced relative heat losses. Introducing biofuel into the mix with B5 through B25, a slight decrement in BTE was noted at lower loads, which may be attributed to the higher viscosity and lower calorific value of biofuels compared to diesel. However, the BTE was found to increase with the biofuel content at higher operational loads, potentially due to improved combustion properties such as enhanced cetane number and oxygen content inherent in biofuels. Specifically, B20 blend showed a substantial increase in efficiency under full load conditions, achieving a BTE of 28.39%, which suggests that the combustion of biofuel blends becomes more efficient as the engine load increases. Influence of incorporating GO nanoparticles with a 20% biofuel blend (B20) at variable hydrogen flow rates on BTE is presented in Figure 3. The presence of GO nanoparticles can create more surface area that enhance fuel-air mixing, resulting in more complete combustion and higher thermal efficiency. This is reflected in the B2H2 to B2H10 data, where BTE improved with the addition of hydrogen flow, reaching up to 35.59% for B2H10 at full load. This indicates that hydrogen, with its high energy content and fast flame speed, can significantly enhance the combustion process, especially in combination with GO nanoparticles. The increasing trend of BTE with higher hydrogen flow rates is due to hydrogen's property of shortening the quenching distance and its high diffusivity, promoting a more homogenous air-fuel mixture and a faster combustion rate.



(a)

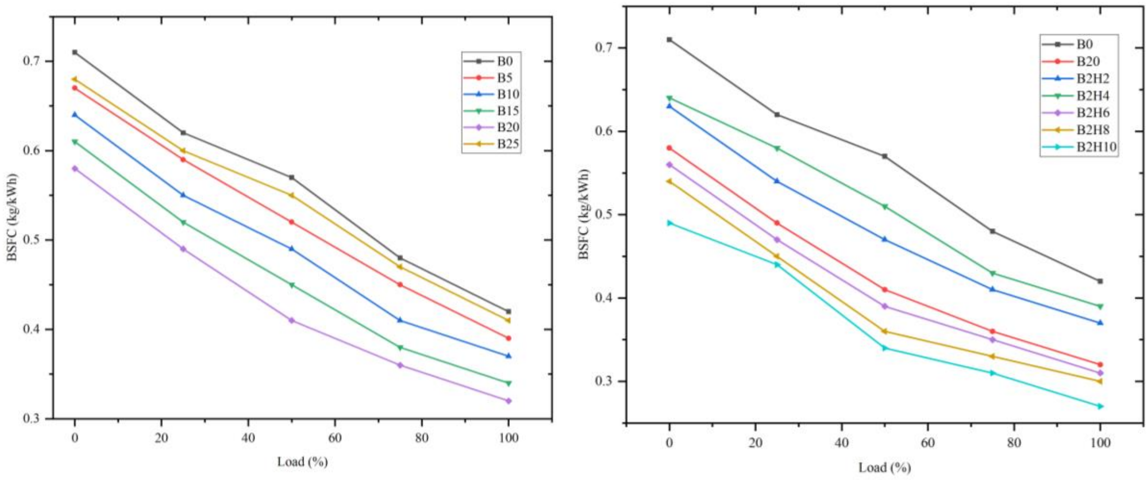


(b)

Figure 3. BTE variation for: (a) different test blends, (b) B20 doped with GO + hydrogen

4.1.2. Brake specific fuel consumption (BSFC)

The variation in Brake Specific Fuel Consumption (BSFC) with the use of different biofuel blends under various engine load conditions reveals the combustion efficiency of these fuels. Figure 4(a) shows variation of BSFC with biodiesel content. The BSFC is lowest for the B20 blend across all load conditions, highlighting the effect of the 20% biofuel-diesel mixture in optimizing fuel consumption. The data exhibits a clear trend of decreasing BSFC with increasing engine load for all blends, with the B20 blend achieving 0.32 kg/kWh at 100% load, highlighting the efficiency of biofuels under higher operational demands. This trend reflects the inherent properties of biofuels, such as higher oxygen content and cetane numbers, which enhance the combustion process, thereby reducing the quantity of fuel required per unit of power produced. However, while the blends up to B20 demonstrate improved BSFC with increasing engine load, the B25 blend deviates from this pattern, suggesting a threshold beyond which the reduction of diesel with biofuel no longer yields efficiency gains. This due to the lower energy density of biofuels compared to conventional diesel. This threshold effect is considered for fuel formulations while doping with GO nanoparticles and hydrogen additives at different flow rates.



(a) (b)

Figure 4. BSFC variation for: (a) different test blends, (b) B20 doped with GO + hydrogen

The change in BSFC for diesel-biofuel blends augmented with GO nanoparticles and varying hydrogen flow rates is shown in Figure 4(b). It can be observed that the incorporation of hydrogen, starting from 2 liters per minute in B2H2 up to 10 liters per minute in B2H10, into the GO doped B20 blend consistently and significantly reduces the BSFC across varying engine loads. At full engine load with B2H10 showed the least BSFC of 0.27 kg/kWh as opposed to the 0.42 kg/kWh noted for the pure diesel Pure, indicating a substantial enhancement in fuel efficiency and this reduction can be attributed to hydrogen's characteristics – primarily its high diffusivity and low ignition energy, which significantly improve the combustion process. The presence of GO nanoparticles catalyzed the combustion process, thus promoting the high-energy release from hydrogen, which is known for its tendency to expedite flame speed and reduce ignition delay, leading to a more complete and efficient fuel burning. Notably, at idle conditions (0% load), the data highlights the positive influence of hydrogen, with a decrease in BSFC compared to conventional diesel. As hydrogen flow rate increases, BSFC lowers, indicating better combustion due to nanoparticles and hydrogen mixing enabling complete combustion and higher heating value.

4.2. Emission characteristics

4.2.1. Hydrocarbon emission

Hydrocarbon (HC) emissions, indicative of unburnt fuel, are a key parameter in assessing the combustion efficiency of engine fuels. Figure 5 shows the HC emissions for fuel blends. At idle, the HC emissions from the Pure diesel (B0) are measured at 98 ppm, which is significantly reduced to 29 ppm with B20, illustrating a significant decrease of approximately 70.4%. This suggests that the oxygen content in biofuels facilitates a more complete combustion process, resulting in lower emissions of unburnt hydrocarbons. However, B25 showing a smaller reduction to 49 ppm at full load, which is still a notable decrease of 47.9% compared to B0. This could indicate that beyond a certain biofuel content, the benefits in reducing HC emissions may not continue to improve and can be offset by other factors such as changes in fuel viscosity affecting atomization and combustion. The addition of graphene oxide (GO) nanoparticles and hydrogen in varying flow rates into a B20 blend further influences HC emissions. At idle, the B2H2 variant emits 49 ppm of HC but as the hydrogen flow rate increases, a sharp reduction is seen with B2H10 achieving the lowest emissions at 6 ppm, a substantial 93.9% reduction compared to B0. This trend of decreasing HCs emissions with increasing hydrogen flow rates is consistent at higher loads, with B2H10 maintaining lower emissions at 41 ppm at full load, showing a decrease of 56.4% from B0 suggesting that the catalytic action of nanoparticles and the superior combustion properties of hydrogen significantly enhance the fuel's combustion efficiency.

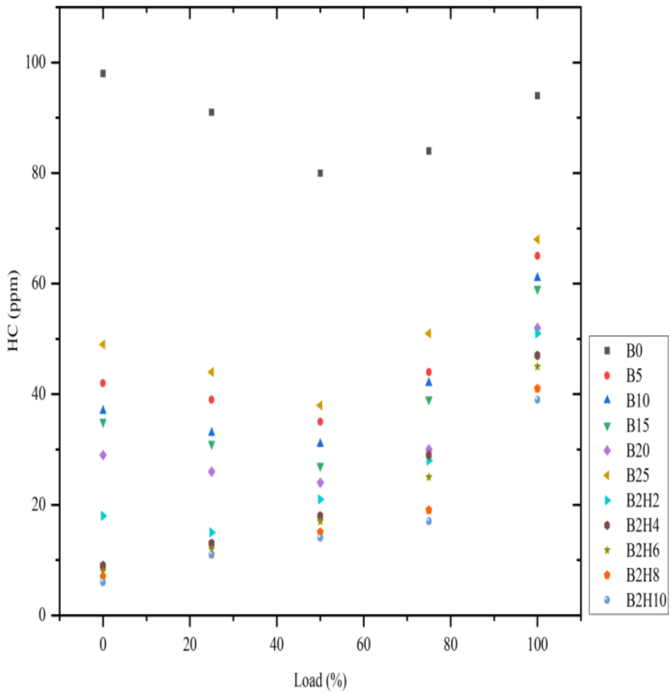


Figure 5. HC variation different fuel blends

4.2.2. CO emission

Carbon monoxide (CO) emissions for various diesel-biofuel blends is shown in Figure 6. The base diesel (B0) CO emissions at no load are recorded at 0.105%, which progressively decreases with the introduction of biofuels, down to 0.059% with a B25 blend—a reduction of nearly 44%. This decrease signifies the role of oxygenated biofuels in promoting more complete combustion. However, at 0% load, the B25 blend's CO emissions (0.089%) unexpectedly rise compared to the B20 blend (0.059%), suggesting a complex interaction between fuel properties and combustion dynamics, due to the biofuel's higher viscosity impacting atomization. The incorporation of graphene oxide (GO) nanoparticles and hydrogen significantly amplifies the reduction of CO emissions, with the B2H10 blend demonstrating a remarkable decrease across all load levels, culminating in a low of 0.029% at no load—a 72% reduction from the base diesel. This trend continues with increasing engine loads, with B2H10 blend achieving a 73% reduction in CO emissions at full load (0.033%) compared to the base diesel (0.124%). The consistent decrease in CO emissions with higher hydrogen flow rates, observed across the B2H series, underscores the synergistic effect of GO nanoparticles in enhancing fuel oxidation and hydrogen in improving the fuel-air mix, leading to a more efficient combustion.

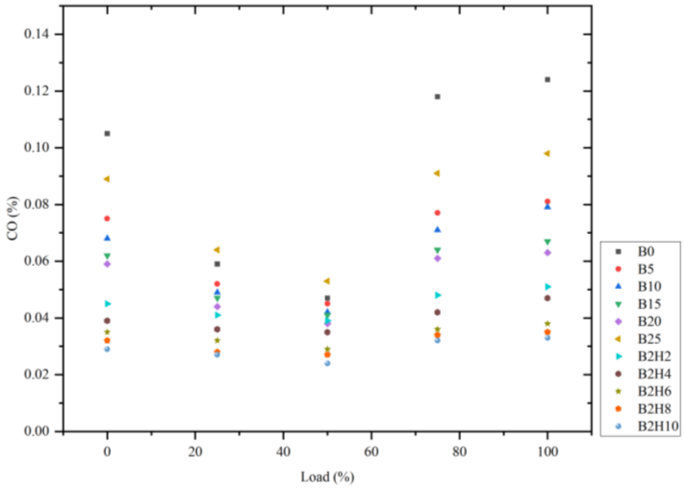


Figure 6. CO variation different fuel blends

4.2.3. CO_2 emission

Figure 7 gives the carbon dioxide (CO_2) emissions across varying fuel blends of biofuel. At idle, CO_2 emissions for the B0 Pure are observed at 1.51%, which marginally decreases to 1.5% upon the introduction of a 5% biofuel blend (B5). However, a noticeable increment occurs with the B25 blend, which indicates emissions at 1.76%, representing a 16.6% increase from B0, potentially indicative of the higher oxygen content in biofuels facilitating more thorough combustion. A contrasting reduction is seen with the B20 blend across the load variations, noting a significant decrease to 9.68% at 100% load, a drop of 0.4% from the B0 Pure. The integration of GO nanoparticles and incremental hydrogen flow rates with the B20 blend demonstrates a pronounced reduction in emissions; specifically, the B2H10 configuration yields the most considerable decrease, with CO_2 emissions reducing to 0.94% at idle, which is 37.7% lower than B0, and to 8.83% at full load, denoting a 9.2% reduction. This substantial drop can be attributed to the catalytic effect of GO nanoparticles enhancing fuel oxidation and the high combustion efficiency afforded by hydrogen.

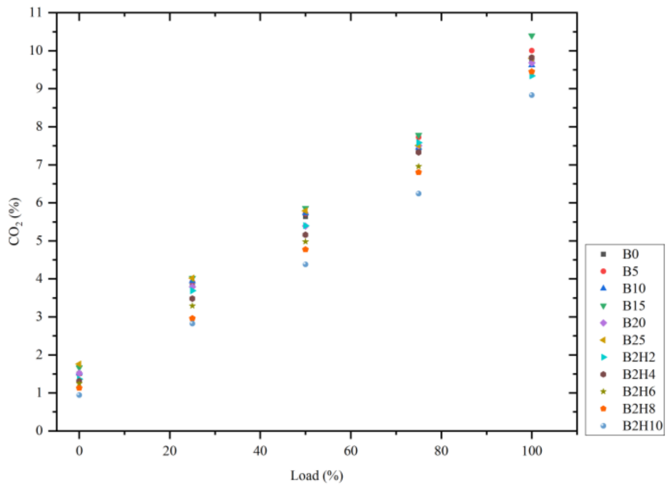


Figure 7. CO_2 variation different fuel blends

4.2.4. NOx emission

Figure 8 shows the NOx emissions for fuel blend used and the resultant emissions across different engine loads. The base diesel (B0) emits 46 ppm of NOx emissions at idle, and the inclusion of biofuels results in a noticeable increase, with a 41.3% rise for B5 at 65.20 ppm and a 53.8% increase for B10 at 70.76 ppm, due to the higher combustion temperatures from the oxygenated biofuels. This trend of increasing NOx emissions with higher biofuel content is consistent up to B25, which emits 80.86 ppm at idle, a 75.8% increase from B0. The graphene oxide (GO) nanoparticles and hydrogen introduction into a B20 blend. At idle, NOx emissions for B2H2 are at 84.40 ppm, but a higher hydrogen flow rate in B2H10 reduces NOx to 57.62 ppm, a 31.6% decrease from B2H2. At full load, B2H10 records NOx emissions of 1291.00 ppm, showing a 59.4% increase from B0, which shows impact of GO nanoparticles and hydrogen: while they initially contribute to higher NOx levels due to increased combustion temperatures, they subsequently promote more efficient combustion processes that can reduce NOx formation.

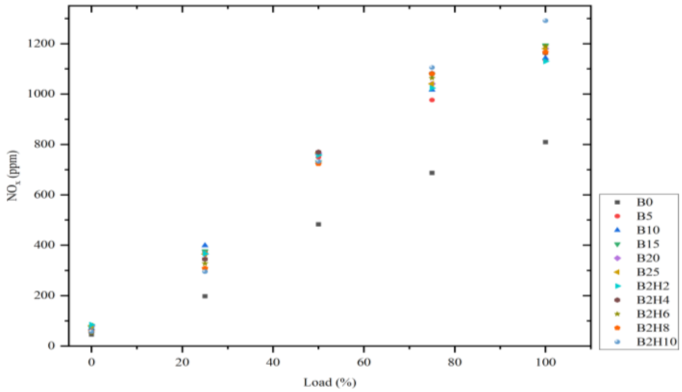


Figure 8. NO_X variation different fuel blends

4.2.5. Smoke opacity

Smoke opacity, a measure of particulate matter emissions that contribute to visible smoke, is shown to decrease with the incorporation of biofuels, given in Figure 9. Pure diesel (B0) starts at 8.5 Hartridge Smoke Units (HSU) at idle and increases to 85.3 HSU at full load. A marked reduction in smoke opacity is observed with B5, decreasing to 6.4 HSU at idle, and even further with B20, which records 3.9 HSU at idle—a 54% decrease from B0. However, an increase is observed with B25, emitting 4.9 HSU at idle, suggesting an optimal biofuel blend before smoke emissions begin to rise again. B20 blend enhanced with GO nanoparticles and hydrogen showed a consistent trend of reduced smoke opacity, with B2H10 displaying the lowest values across all load conditions, 2.5 HSU at idle. At full load, B2H10 exhibits 56 HSU, which represents a significant 34.4% reduction from B0, signifying the positive impact of additives on combustion and particulate reduction.

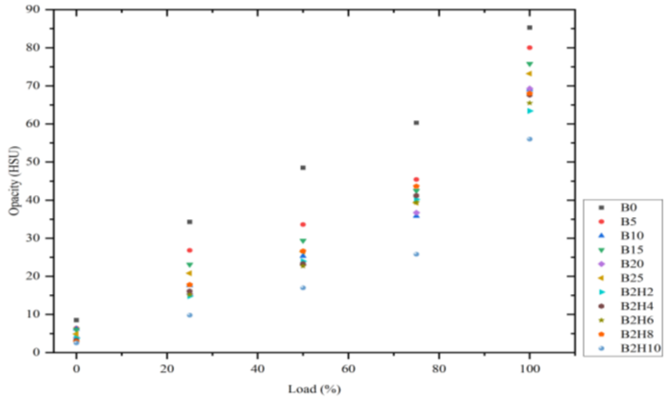


Figure 9. Smoke opacity variation different fuel blends

3. Deep LSTM prediction

In this work, a Deep Long Short-Term Memory (DLSTM) regression is employed to predict the emissions characteristics of the fuel blends. DLSTM is a type of artificial neural network that is widely used for prediction tasks, where the goal is to predict multiple output variables given a set of input variables. This model architecture is composed of several stacked LSTM layers, each capable of capturing long-term dependencies and patterns in the input data. The working of DLSTM regression involves feeding a sequence of inputs into the model which are then passed through a stack of LSTM layers, where each layer applies a non-linear transformation to the input data and captures the relevant patterns and dependencies. The output of the last LSTM layer is then passed through a dense layer, which produces a vector of predicted outputs. In DLSTM regression, the model is designed to predict multiple output variables simultaneously. Each output variable is associated with its own set of target values, which are used to train the model. During training, the model learns to adjust the weights of each layer and neuron in order to minimize the difference between the predicted outputs and the actual target values. One of the key advantages of using DLSTM regression for multi-output prediction tasks is its ability to capture complex dependencies and patterns in the data. The stacked LSTM layers allow the model to learn both short-term and long-term patterns, which can be useful in making accurate predictions.

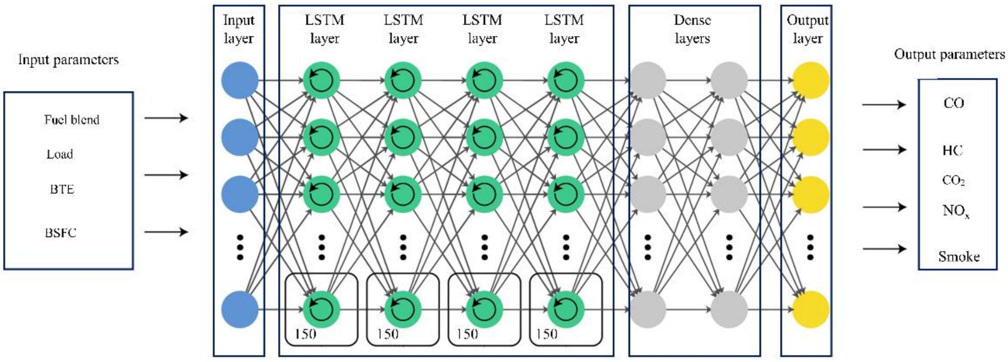
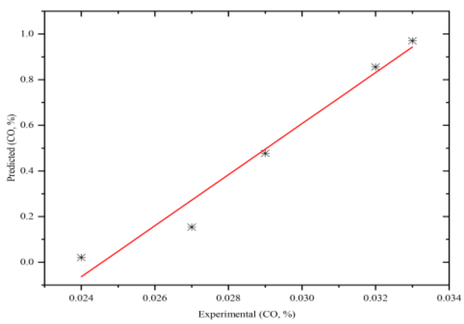
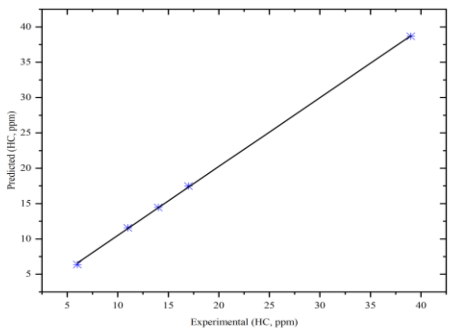


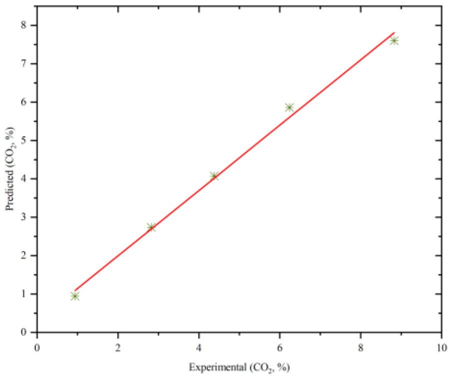
Figure 10. DLSTM model architecture

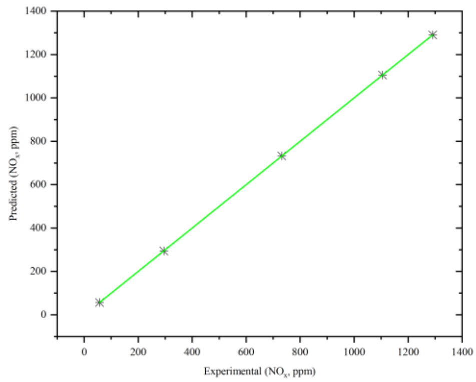
The DLSTM network architecture utilized in this study is depicted in Figure 11. Inputs to the DLSTM model include fuel blend, load, BTE, and BSFC. The model predicts five different emissions as outputs. The DLSTM model was developed using Python, with Keras and Scikit-learn libraries and is comprised of eight layers, which include an input layer, four LSTM layers, two dense layers, and an output layer. The dataset used for the model contained three input and five output variables and had a 13 × 6 dimension. The dataset was divided into 80% for training and 20% for testing. To evaluate the prediction performance of the DLSTM, root mean square error (RMSE) and mean absolute error (MAE) were used as metrics. Lower values of RMSE and MAE indicate better prediction accuracy. The DLSTM model featured four stacked LSTM layers, with each layer containing 150 neurons and training on 10 samples. A batch size of two and a hyperparameter setting of 200 epochs were employed. The obtained averaged RMSE values for CO, HC, CO_2, NO_x, and smoke opacity are 0.603, 0.443, 0.585, 0.422, and 0.417, respectively. The averaged MAE values for CO, HC, CO_2, NO_x, and smoke opacity are 0.478, 0.452, 0.405, 0.355 and 0.375, respectively. For representation, the observed and predicted values for B2H10 with correlation plot is shown in Figure 11.



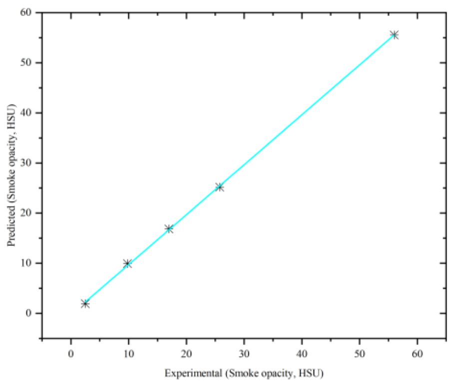


(a) (b)





(c) (d)



(e)

Figure 11. DLSTM model's correlation plot of B2H10 for: (a) CO, (b) HC, (c) CO_2, (d) NO_x, and (e) smoke opacity

4. Conclusion

This work investigates the combustion and emission characteristics of diesel engines powered by Corn oil biofuel blends, ranging from pure diesel to a 25% biofuel mixture particularly. Further, B20 enhanced with 100 ppm of graphene oxide (GO) nanoparticles and varying hydrogen flow rates from 2 to 10 liters per minute is evaluated. Additionally, a Deep Long Short-Term Memory (DLSTM) model is utilized to forecast the emission profiles of these blends. The major findings of this work are given below.

- Biofuel Blend Efficiency: The study found that BTE improved with increasing biofuel content up to the B20 blend, with a noted peak BTE of 28.39% at a 100% load—a notable enhancement from B0's 30% at the same load condition. However, the B25 blend's BTE dropped slightly at lower loads, a trend which reversed at higher loads, suggesting the existence of an optimal biofuel blend for maximum efficiency, with B20 emerging as the most efficient in this study.
- Emissions Reduction with Additives: Incorporation of GO nanoparticles and hydrogen, particularly in the B2H10 blend, led to a dramatic decrease in HC emissions, from B0's 98 ppm at idle to just 6 ppm—a 93.9% reduction. CO emissions also decreased substantially across all loads, with B2H10 showing a

reduction from B0's 0.124% at full load to 0.033%—a 73% decrease, highlighting the significant potential of these additives in reducing emissions.

- Smoke Opacity: A significant decrease in smoke opacity was observed with the addition of biofuels, with the B20 blend showing a 54% reduction at idle compared to B0. Furthermore, the B2H10 blend continued this trend across all loads, culminating in a 34.4% reduction at full load, indicating an improvement in particulate emissions management.
- NOx Emissions: NOx emissions presented a complex response; while initial biofuel blends increased NOx emissions due to higher combustion temperatures, the introduction of GO nanoparticles and higher hydrogen flow rates in B2H10 blend resulted in a decrease from B2H2's 84.40 ppm at idle to 57.62 ppm—a 31.6% reduction, suggesting the potential for controlled NOx emissions with the correct formulation.
- Combustion and Efficiency: Results shows the interaction between GO nanoparticles and hydrogen enhanced fuel efficiency. At full load, the B2H10 blend achieved the lowest BSFC of 0.27 kg/kWh, a significant improvement from the B0 baseline of 0.42 kg/kWh, indicating an improved combustion process and higher energy release from the hydrogen.
- DLSTM model was able to predict the emissions with an averaged RMSE and MAE of 0.498 and 0.413, respectively.

Refrences

[1] M. Elkelawy *et al.*, "Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends," *Fuel*, vol. 255, p. 115791, 2019.

[2] X. Zhang *et al.*, "Assessment of hydrogen and nanoparticles blended biodiesel on the diesel engine performance and emission characteristics," *Fuel*, vol. 307, p. 121780, 2022.

[3] M. Akcay, I. T. Yilmaz, and A. Feyzioglu, "Effect of hydrogen addition on performance and emission characteristics of a common-rail CI engine fueled with diesel/waste cooking oil biodiesel blends," *Energy*, vol. 212, p. 118538, 2020.

[4] F. R. M. França, L. dos Santos Freitas, A. L. D. Ramos, G. F. da Silva, and S. T. Brandão, "Storage and oxidation stability of commercial biodiesel using Moringa oleifera Lam as an antioxidant additive," *Fuel*, vol. 203, pp. 627–632, 2017.

[5] L. Wei, C. S. Cheung, and Z. Ning, "Effects of biodiesel-ethanol and biodiesel-butanol blends on the combustion, performance and emissions of a diesel engine," *Energy*, vol. 155, pp. 957–970, 2018.

[6] A. Abuhay *et al.*, "Opportunities for new biorefinery products from Ethiopian ginning industry by-products: Current status and prospects," *J. Bioresour. Bioprod.*, vol. 6, no. 3, pp. 195–214, 2021.

[7] A. Gaur, G. Dwivedi, P. Baredar, and S. Jain, "Influence of blending additives in biodiesel on physiochemical properties, engine performance, and emission characteristics," *Fuel*, vol. 321, p. 124072, 2022.

[8] I. M. R. Fattah, H. H. Masjuki, M. A. Kalam, M. Mofijur, and M. J. Abedin, "Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends," *Energy Convers. Manag.*, vol. 79, pp. 265–272, 2014.

[9] A. E. Elwardany, M. N. Marei, Y. Eldrainy, R. M. Ali, M. Ismail, and M. M. El-Kassaby, "Improving performance and emissions characteristics of compression ignition engine: Effect of ferrocene nanoparticles to diesel-biodiesel blend," *Fuel*, vol. 270, p. 117574, 2020.

[10] A. T. Hoang, "Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system," *J. Mar. Eng. Technol.*, vol. 20, no. 5, pp. 299–311, 2021.

[11] A. T. Hoang *et al.*, "Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: A review," *Renew. Sustain. Energy Rev.*, vol. 135, p. 110204, 2021.

[12] W. Zhu *et al.*, "Cassava stems: a new resource to increase food and fuel production," *Gcb Bioenergy*, vol. 7, no. 1, pp. 72–83, 2015.

[13] G. S. Aruwajoye, A. Kassim, A. K. Saha, and E. B. Gueguim Kana, "Prospects for the improvement of bioethanol and biohydrogen production from mixed starch-based agricultural wastes," *Energies*, vol. 13, no. 24, p. 6609, 2020.

[14] I. M. Rizwanul Fattah *et al.*, "State of the art of catalysts for biodiesel production," *Front. Energy Res.*, p. 101, 2020.

[15] B. Changmai, C. Vanlalveni, A. P. Ingle, R. Bhagat, and S. L. Rokhum, "Widely used catalysts in biodiesel production: a review," *RSC Adv.*, vol. 10, no. 68, pp. 41625–41679, 2020.

[16] K. Saoud, "Nanocatalyst for biofuel production: a review," *Green Nanotechnol. biofuel Prod.*, pp. 39–62, 2018.

[17] S. Bosu, R. P. Pooja, and M. Rajasimman, "Role of nanomaterials in enhanced ethanol production through biological methods–Review on operating factors and machine learning applications," *Fuel*, vol. 320, p. 123905, 2022.

[18] P. T. Sekoai *et al.*, "Application of nanoparticles in biofuels: an overview," *Fuel*, vol. 237, pp. 380–397, 2019.

[19] M. Mofijur *et al.*, "Impact of nanoparticle-based fuel additives on biodiesel combustion: An analysis of fuel properties, engine performance, emissions, and combustion characteristics," *Energy Convers. Manag. X*, p. 100515, 2023.

[20] V. Saxena, N. Kumar, and V. K. Saxena, "A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled CI engine," *Renew. Sustain. Energy Rev.*, vol. 70, pp. 563–588, 2017.

[21] A. T. Hoang, "Combustion behavior, performance and emission characteristics of diesel engine fuelled with biodiesel containing cerium oxide nanoparticles: A review," *Fuel Process. Technol.*, vol. 218, p. 106840, 2021.

[22] S. Khan, Y. Dewang, J. Raghuwanshi, A. Shrivastava, and V. Sharma, "Nanoparticles as fuel additive for improving performance and reducing exhaust emissions of internal combustion engines," *Int. J. Environ. Anal. Chem.*, vol. 102, no. 2, pp. 319–341, 2022.

[23] Ü. Ağbulut and S. Sarıdemir, "Synergistic effects of hybrid nanoparticles along with conventional fuel on engine performance, combustion, and environmental characteristics," *Energy*, p. 130267, 2024.

[24] E. Ettefaghi *et al.*, "A novel bio-nano emulsion fuel based on biodegradable nanoparticles to improve diesel engines performance and reduce exhaust emissions," *Renew. Energy*, vol. 125, pp. 64–72, 2018.

[25] M. El-Adawy, "Effects of diesel-biodiesel fuel blends doped with zinc oxide nanoparticles on performance and combustion attributes of a diesel engine," *Alexandria Eng. J.*, vol. 80, no. May, pp. 269–281, 2023, doi: 10.1016/j.aej.2023.08.060.

[26] A. A. Yusuf *et al.*, "Effect of low CeO2 nanoparticles dosage in biodiesel-blends on combustion

parameters and toxic pollutants from common-rail diesel engine," *Atmos. Pollut. Res.*, vol. 13, no. 2, p. 101305, 2022, doi: 10.1016/j.apr.2021.101305.

[27] A. Ranjan, S. S. Dawn, J. Jayaprabakar, N. Nirmala, K. Saikiran, and S. Sai Sriram, "Experimental investigation on effect of MgO nanoparticles on cold flow properties, performance, emission and combustion characteristics of waste cooking oil biodiesel," *Fuel*, vol. 220, no. August 2017, pp. 780–791, 2018, doi: 10.1016/j.fuel.2018.02.057.

[28] S. P. Venkatesan, P. N. Kadiresh, N. Beemkumar, and J. Jeevahan, "Combustion, performances, and emissions characteristics of diesel engine fuelled with diesel-aqueous zinc oxide nanofluid blends," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 45, no. 1, pp. 2922–2936, 2023, doi: 10.1080/15567036.2019.1666933.

[29] M. G. Bidir, N. K. Millerjothi, M. S. Adaramola, and F. Y. Hagos, "The role of nanoparticles on biofuel production and as an additive in ternary blend fuelled diesel engine: A review," *Energy Reports*, vol. 7, pp. 3614–3627, 2021.

[30] D. Yuvarajan, M. D. Babu, N. BeemKumar, and P. A. Kishore, "Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine," *Atmos. Pollut. Res.*, vol. 9, no. 1, pp. 47–52, 2018.

[31] P. Dimitriou, M. Kumar, T. Tsujimura, and Y. Suzuki, "Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine," *Int. J. Hydrogen Energy*, vol. 43, no. 29, pp. 13605–13617, 2018.

[32] H. Koten, "Hydrogen effects on the diesel engine performance and emissions," *Int. J. Hydrogen Energy*, vol. 43, no. 22, pp. 10511–10519, 2018.

[33] S. M. Hosseini and R. Ahmadi, "Performance and emissions characteristics in the combustion of co-fuel diesel-hydrogen in a heavy duty engine," *Appl. Energy*, vol. 205, pp. 911–925, 2017.

[34] B. A. Oni, S. E. Sanni, A. J. Ibegbu, and A. A. Aduojo, "Experimental optimization of engine performance of a dual-fuel compression-ignition engine operating on hydrogen-compressed natural gas and Moringa biodiesel," *Energy Reports*, vol. 7, pp. 607–619, 2021.