Research Article

Journal of Environmental Nanotechnology

Nano-enhanced Palmyra Palm Biodiesel for Improved Performance and Emission Control

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Received: 25.09.2024 Accepted: 12.12.2024 Published: 30.12.2024
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ABSTRACT

This research article describes an experimental study on the combustion characteristics of biodiesel produced from palmyra palm with multi-walled carbon nanotubes (MWCNTs) blended with diesel fuel in a single cylinder, four stroke, water-cooled diesel engine equipped with direct injection system which assists in measuring the performance of the engine precisely and its emissions. The work is based on palmyra palm biodiesel mixes of 20% and 40% with MWCNTs at 50 and 100 ppm at distinct engine load of 0%, 25%, 50%, 75% and 100%. The results highlighted the fact that brake thermal efficiency is almost similar to diesel while specific fuel consumption (SFC) reduced by about 18.46% and exhaust gases like CO, HC and smoke reduced to a maximum of 25.21%, 21.62% and 19.15%, respectively, while NO_x increased by 27.54% compared to neat diesel fuel. The results presented in this study show that the incorporation of MWCNTs in palmyra palm biodiesel increases combustion efficiency, resulting in lowered emission and increased performance.

Keywords: Biodiesel; Nano fuel; Emission; Palmyra palm; Multi-walled carbon nanotubes; Specific fuel consumption.

1. INTRODUCTION

Biodiesel is an environment friendly fuel, which is completely biodegradable. It is obtained indirectly from natural fats and oils such as vegetable oil or animal fat through transesterification. This procedure involves the conversion of the triglycerides to fatty methyl esters known as biodiesel and glycerine. The produced methyl esters are recommended to be used in diesel engines. Out of several feedstocks, the most favourable one is palmyra palm oils, due to their oil yield and the fact that they are relatively easy to source in tropical climates (Prasada *et al.* 2022). According to Shaafi *et al.* (2015), palmyra palm biodiesel is biodegradable, does not contain any toxic compounds and emits much lesser particulates, CO and unburnt hydrocarbon (HC). Also, biodiesel has a greater cetane number which causes better instances of burning and smooth running of the engine. The advantages associated with biodiesel are that it lowers the dependence on scarce fossil fuels and also minimises the impacts of extraction and burning of fossils (Sayyed *et al.* 2023). Moreover, it is viewed as a green resource of energy that can be generated on a local level, thereby cutting down on energy exports as well as improving the energy self-reliance (Singh *et al.* 2023). However, biodiesel encounters certain challenges (fluctuations in the cost of production, low-energy density compared to the traditional diesel and questions concerning the cold flow characteristics) which limit its application (Mesri *et al.* 2021).

Rajendran *et al.* (2024) analyzed the performance and emission profile of a CI DI diesel engine with jatropha biodiesel blends. The results showed that B25 is the optimal blend, showing improved fuel efficiency and low emission than higher mix like B50, B75 and B100 under certain circumstances. Saputro *et al.* (2023) studied the performance, combustion and emissions of biodiesel from waste cooking and B30 biodiesel. B30 showed better performance indicator than B100. Dhirendra *et al.* (2024) analysed biodiesel blends and demonstrated the performance, combustion and emission features of B20, B30, B40 and B100 soybean, algae, rapeseed and fish oils with varying loads. The findings showed that B20 and B40 showed reduced emissions and improved combustion characteristics when compared to pure diesel fuels, although they cause slight decline in brake thermal efficiency.

Biodiesel has lower oxidative stability, resulting in potential challenges in bulk storage and a slow degradative process of fuel (Senthilkumar *et al.* 2019). In order to overcome these challenges, nano additives are used. Due to their physio-chemical properties, particularly the large specific surface area of the nano additives, the performance and efficiency of the engine are significantly increased. Catalysts assist in improving combustion quality, reduce combustion pollutants and also maintain fuel (Prasada *et al.* 2022). Various metal oxide nanoparticles are generally used for this purpose. Out of them, zinc oxide (ZnO) and titanium dioxide (TiO_2) are used frequently. Consequently, these additives will enhance fuel atomization and enable burning and improve surface area coverage, hence causing near complete combustion and little emissions (Joy *et al.* 2023). Singh *et al.* (2023) demonstrated the application of TiO_2 nanoparticles that enhance the biodiesel's oxidative stability and flow characteristics at low temperatures. Of all the other nanomaterials, graphene and carbon nanotubes have high thermal and electrical conductive properties. These features enhance the combustible characteristics The antioxidant property is improved by the large surface area material like the graphene added to the biodiesel. Analyzing the existing literature, it can be stated that by using carbon nanotubes, it is possible to enhance the combustion efficiency and minimize the emission of particulate matter (Puchakayala *et al.* 2023).

Table 1 shows the performance and emission characteristics of biodiesel mixed with nanoparticles like zirconium dioxide, cerium oxide, aluminum oxide, copper oxide, which remain as oxygen carrier agents for enhancement of oxidation of fuels during combustion. They improve the process of combustion by enhancing the oxygen availability leading to more complete combustion of the fuel. This in turn leads to lower CO, HC and particulate matter (PM) emissions levels. Carbon nanotubes have a huge potential to enhance thermal and electrical conductivity of biodiesel. These extend the heat transfer rate and facilitate better combustion processes that increase engine efficiency, and hence, decreases fuel consumption levels. These nanoparticles also increase the lubricating property of the biodiesel. This overcomes the metallic wear and leads to better performance. Among all nano additives, MWCNTs are widely used because of their desirable mechanical, thermal, and electrical characteristics. It is found that MWCNTs possess a large surface area and high conductivity with regard to electrical current.

These properties can effectively promote the combustion process and fuel efficiency (Rao *et al.* 2022). The antioxidant properties of MWCNTs enhance the oxidative stability of biodiesel and extend its storage period (Sateesh *et al.* 2023). Addition of MWCNTs to biodiesel formulations addresses two major challenges, (high NO_x emissions and low energy content) (Rao *et al.* 2022; Şahin *et al.* 2023). The present study focuses on the production of biodiesel by combining palmyra palm oil with MWCNTs and evaluating its performance, emission characteristics, and associated benefits and drawbacks at concentrations of 50 ppm and 100 ppm in a single-cylinder diesel engine. This study will help gain an enhanced understanding of the improvement in the qualities of biodiesel and the efficiency of internal combusting engines and the minimization of the emissions by the addition of MWCNTs. The work would make a significant contribution to the subject of renewable energy, specifically regarding sustainable fuel.

Table 1. Diesel engine performance and emission characteristics of biodiesel mixed with nanoparticles

Type of fuel used	Nano particles	BSFC	BTE	CO	NOx	HC	Smoke	References
Jatropha Biodiesel, B20	Zr_2O_3, 25 ppm	↓	↑	↓	↑	↓	↓	(Venu and Appavu, 2021)
Cottonseed oil biodiesel, B10, B15	MWCNT, 100, 150 ppm	↑	↓	↓	↑	↓	↓	(Ninawe and Tariq, 2021)
Lemon and Orange Peel Oil, B20	CeO_2, 50, 100 ppm	↓	↓	↓	↓	↓	↓	(Sheriff *et al.* 2021)
Mahua Biodiesel, B20	Al_2O_3, 25, 50, 75, 100 ppm	↓	↑	↓	↓	↓	↓	(Mohan and Simhadri, 2022)
Waste Plastic Oil Biodiesel, B20	CuO_2, 25, 50, 75, 100 ppm	↓	↑	↓	↓	↓	↓	(Kalaimurugan *et al.* 2023)

2. MATERIALS AND METHODS

2.1 Production of Palmyra Palm Biodiesel

Palmyra palm oil from the kernel was obtained by mechanical extraction (yield 26%). The process of biodiesel production using palmyra palm oil was achieved through the transesterification process between the oil and methanol with a catalyst to produce biodiesel (methyl esters) and glycerol. Initially, the fruits obtained from palmyra palm underwent cleaning and drying. After some time, mechanical press was used in the extraction process of the fruits that produced crude palm oil. This was followed by cleaning up the extracted oil to minimize contamination problems and then removing the water content to enhance the effectiveness of subsequent oil reactions. During transesterification, the pretreated oil was heated to 60°C. A 6:1 molar ratio of methanol and sodium hydroxide was mixed with hot oil for 2 hours to convert the triglycerides to biodiesel and glycerol. The biodiesel was allowed to separate from glycerol and rinsed with warm water to eliminate the catalyst and glycerol. Finally, the biodiesel was evaporated and collected. Fig. 1 shows the process flow of biodiesel production. Palmyra palm biodiesel was mixed with neat diesel in the proportions of 20% and 40%, labeled as B20 and B40, respectively.

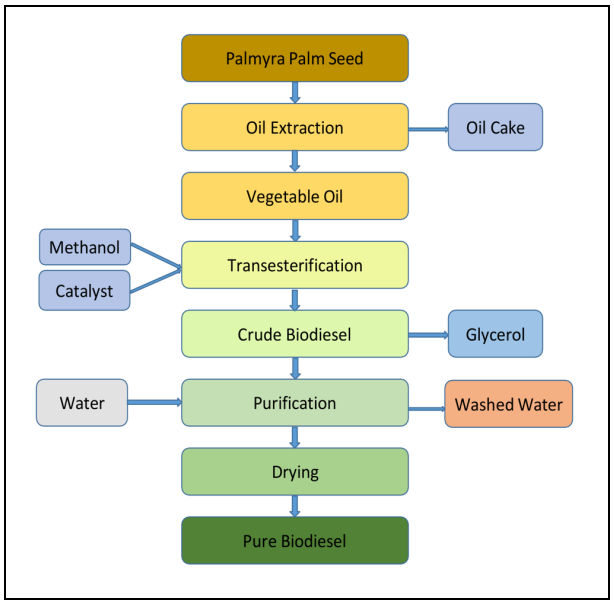


Fig. 1: Biodiesel production process

2.2 Details of MWCNTs

The MWCNTs (purity above 95 %) used in this study were purchased from Royal Scientific Suppliers. From the SEM analysis, it was concluded that the MWCNTs were of cylindrical structure and made up of several layers of graphene. The outside diameter varied between 10 and 30 nm. The length was 5 to 20 microns.

2.3 Preparation of MWCNT-blended Biodiesel

A sonication process was applied to disperse MWCNT in biodiesel. First, the MWCNTs were weighed and dispersed in a little amount of biodiesel for 30 min in an ultrasonic bath. Two different concentrations (50 ppm and 100 ppm) of MWCNTs were blended with biodiesel blends B20 and B40. After that, the dispersed immiscible MWCNT solution was stirred with the remaining biodiesel for an additional 1 hour in order to get more dispersion in biodiesel.

Table 2. Properties of the test fuels according to ASTM standards

Property	Diesel	Palmyra Palm	B20	B40
Density in kg/m^3, ASTM D-4052	832	874	838	851
Viscosity in cSt, ASTM D-445	4.1	31.6	6.9	9.7
Flash Point in °C, ASTM D-93	72	168	88	102
Cetane Number, ASTM D-13	46	48	47	51
Calorific Value in MJ/kg, ASTM D-224	42500	37740	41643	40594

Ultrasonication improved the homogeneity the blend and improved the qualitative and performance characteristics of biodiesel. Biodiesel derived from palmyra palm had a lower calorific value than diesel. Since the flash point of palmyra palm biodiesel is higher compared to crude diesel, the former can be dealt with safely. Different biodiesel blends were categorized as B20, B40, B20CNT50, B20CNGT100, B40CNT50 and B40CNT100. The properties of biodiesel were measured as per the ASTM standards (Table 2).

3. EXPERIMENTAL SETUP

Details of the engine test rig employed in the present experimental investigation are provided in the Table 3 and its schematic diagram is provided in Fig. 2. For determination of the engine performance, an eddy current type dynamometer was used. The configuration included a propeller shaft that had Universal joints in an attempt to enable the torque transfer. For air measurement purpose, an MS-built air box was used which consisted of an orifice meter and manometer for

effective air flow measuring. The gasoline system had a fuel tank capable of holding up to 15 liters of fuel and a glass fuel metering column for dewatering and evaluating the rationed fuel. Thermal energy measurement used a pipe-in-pipe calorimeter and temperature measurements were obtained using a K-type thermocouple connected to a digital multi-channel switchable temperature indicator. The engine speed was measured using a prompt digital speed sensor. Force measurements were obtained using a strain gauge load cell with a capacity of 0–50 kg, along with a force meter equipped with an LED display load indicator.

Table 3. Specifications of the test engine (Kirloskar Oil Engines Ltd., 2024)

Type	Horizontal single-cylinder 4-stroke DI CI engine
Make and Model	Kirloskar and TV1
Bore and stroke (mm)	88 and 110
Displace volume (cm^3)	661
Compression ratio	17.5:1
Injection timing	21° bTDC
Injection pressure	220bar
Rated power	3.7 kW @ 1500 rpm
Cooling type	Water cooled
Air intake	Naturally aspirated

4. RESULTS AND DISCUSSIONS

4.1 Analysis of Brake Thermal Efficiency (BTE)

Fig. 3 shows the effects of carbon nanotubes on the thermal efficiency of palmyra palm biodiesel tested under varying engine load conditions. The characteristics of BTE indicated in the graph were derived on different engine loads as varying fuel blends (Diesel, B20CNT50, B20CNT100, B40CNT50 and B40CNT100). This phenomenon is more common in diesel engines since increased loads typically improve combustion and hence, the thermal activity of the engines. When the load increased above 75%, the brake thermal efficiency slightly decreased. This may be caused by the higher friction losses and the problem of the optimal fuel-air mixture at high loads, and from this study, it was observed that diesel fuel outperforms biodiesel blends in brake thermal efficiency with a slight disparity, especially at higher load levels of 75% and 100%. The maximum decreases in brake thermal efficiency, compared with diesel fuel at full-load condition, were found to be 14.62%, 2.03%, 0.53%, 4.70%, and 3.50% for B100, B20CNT50, B20CNT100, B40CNT50, and B40CNT100, respectively. This could be attributed to the fact that biodiesel contains relatively less energy compared to traditional diesel fuel. Nanoparticles with improved surface area-to-volume ratio increases heat transfer coefficient. Incorporation of MWCNT nanomaterials into palmyra palm biodiesel resulted in greater peak in-cylinder pressure and faster heat rate delivery for better combustion efficiency and overall performance (Joy *et al.* 2023). The blend of B20CNT100 had a high level of performance whereby the load behavior closely resembled the BTE of diesel fuel.

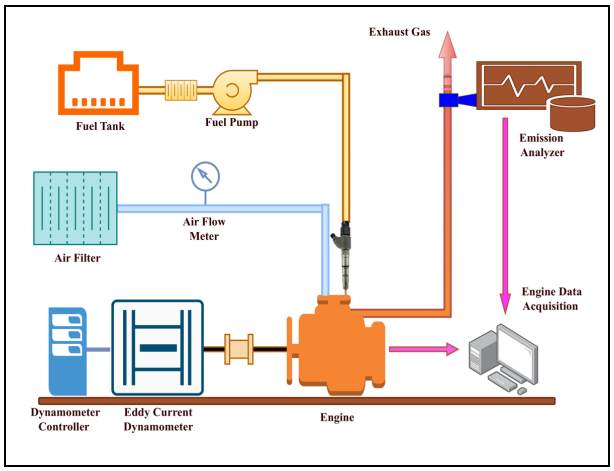


Fig. 2: Schematic diagram of the test engine layout

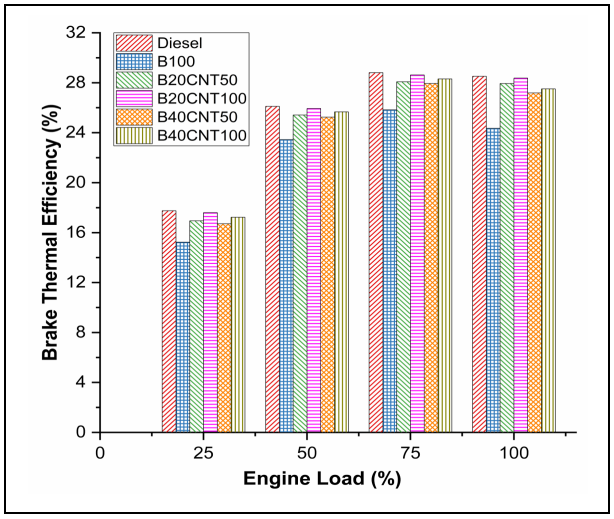


Fig. 3: Variation of BTE for all tested fuels at different load conditions

4.2 Analysis of Specific Fuel Consumption (SFC)

Fig. 4 reveals the effects of biodiesel blends supplemented with carbon nanotubes at 50 and 100 ppm on SFC. Specific fuel consumption decreases for all types of fuel and MWCNT content up to 75% load as the

engine load increases. The largest decrease in SFC values for B20CNT50, B20CNT100, B40CNT50, and B40CNT100 were observed as 15.38%, 18.46%, 3.08% and 5.23%, respectively, at 75% engine load. The SFC of B100 was increased by 12.31% for the same load. Most of the investigated blends hold considerably lower SFC compared to the neat compounds and it is important to mention that B20CNT100 displayed the most favorable SFC value among all the tested blends. This can be explained by the fact that engine efficiency increases at higher loads, resulting in lower fuel consumption per unit of energy produced. But if the load reaches the fuel blend of 100%, there is a slight increase in the SFC. This can be attributed to the increase in fuel demand, which is needed for satisfying the greater power demand at maximum load, hence less effective fuel consumption at maximum load. Commonly, it is seen that SFC reduces in the case of B20 blends as compared to the B40 blends. This can be attributed to the increased diesel content in B20 blends which improves combustion efficiency and therefore fuel economy. Multi-walled carbon nanotubes greatly enhance SFC. Engine fuels with 100 ppm of MWCNT have been found to show better performance in terms of specific fuel consumption compared with fuels containing 50 ppm of MWCNT, particularly at high loads. This observation serves to suggest that utilization of multi walled carbon nanotubes improves fuel atomization and also minimizes the ignition delay resulting in improved fuel utilization (Sayyed *et al.* 2023). Under all the engine loads, B20CNT100 repeats the least SFC achievement while at the same time maintaining the power output.

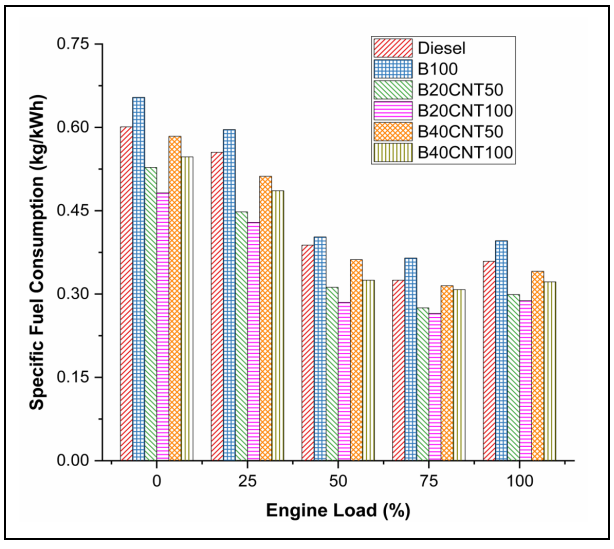


Fig. 4: Variation of SFC for all tested fuels at different load conditions

4.3 Analysis of CO Emission

Emission characteristics of the carbon monoxide at different engine loads for given fuel blends are depicted in Fig. 5. With increasing engine load, CO emissions tend to decrease for all fuel blends. This pattern is generalized as higher engine loads because of increased effectiveness in the combustion procedures, which leads to reduced carbon monoxide emission. When compared to neat diesel, the maximum reductions in CO emissions for four bio blends, B20CNT50, B20CNT100, B40CNT50, and B40CNT100 were reported at 16.33%, 25.21%, 20.20%, and 12.24% and for 100% biodiesel it was increased by 15.31% at 75 percent engine load. Out of the samples under test, B20CNT100 was found to have the least CO emission. At all engine loads examined in this study, CO emissions recorded with biodiesel blends were consistently lower than those recorded with the conventional diesel fuel. This may be due to the larger surface area and heat resistance of MWCNTs, which provide improved atomization and vaporization of the fuel. This results in more complete oxidation of the carbon molecules from which CO is formed, into CO_2 (Mesri Gundoshmian *et al.* 2021). When the dosage of MWCNT is raised from 50 ppm to 100 ppm, the CO emissions for both B20 and B40 blends are lower than those obtained from the first experiment. This implies that the MWCNTs improve the combustion process through the increased thermal conductivity and better distribution of the temperatures within the combustion chamber leading to better oxidation of CO (Sunil *et al.* 2020). The B40 blends containing 50 ppm and 100 ppm of MWCNT exhibited comparatively higher carbon monoxide emissions than the B20 blends. The above-discussed phenomenon can be linked with a higher biodiesel concentration present in B40 blends, which leads to a slight delay in combustion process of biodiesel as compared to conventional diesel fuel. This delay is caused by the higher viscosity and lower volatility of biodiesel as analyzed and concluded by Manigandan *et al.* (2021).

The range of HC levels associated with different engine loads for the blends of palmyra palm biodiesel with CNTs is depicted in Fig. 6. Hydrocarbon emission levels have a direct relationship with load levels in the engine with an increase in the emission levels across all fuel mixture some levels. This increase is expected, since greater loads can cause incomplete combustion at the engine, which in turn leads to elevated levels of hydrocarbon emissions. Comparing the above results, it

is observed that further rise in MWCNT concentration from 50 ppm to 100 ppm of both B20 and B40 blends reduces the hydrocarbon emissions irrespective of the differential engine loads. It is asserted that the incorporation of MWCNTs would improve the prospects of combustion efficiency due to better thermal conductivity and uniform heat distribution, which in turn, will lead to minimized hydrocarbon emission. The maximum reduction in hydrocarbon emission of B20CNT50, B20CNT100, B40CNT50, and B40CNT100 at 100% load were 16.22%, 21.62%, 4.05%, and 9.46%, respectively, and for B100 it was increased by 9.46%, in comparison to conventional diesel. While B20 blends show lowered HC emissions, B40 blends were observed to produce slightly greater hydrocarbon emissions. One likely reason for such an event is the presence of a significantly higher percentage of biodiesel in the B40 blend, which may result in increased viscosity and decreased volatility, which might lead to mechanisms that slightly slow down the combustion process (Sateesh *et al.* 2023). Across all speeds, the B20CNT100 blend consistently exhibits the lowest hydrocarbon emission level.

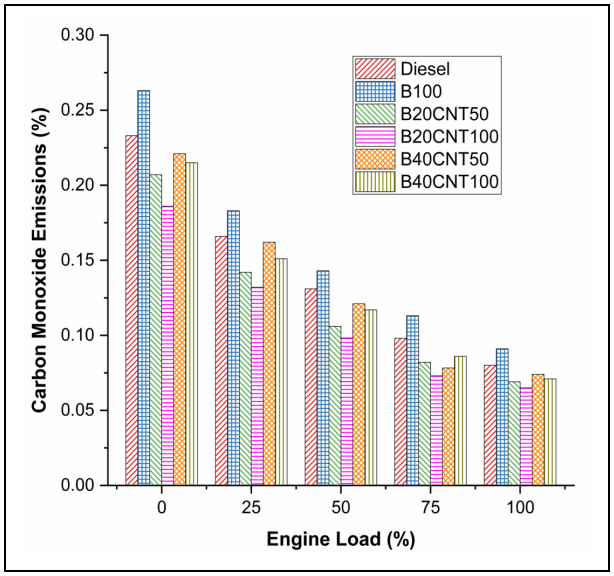


Fig. 5: Variation of CO emission for all tested fuels at different load conditions

4.4 Analysis of Unburnt HC Emission

Fig. 7 shows the variations of NO_x emission for all the fuels tested at various load conditions used in the present study. There is a direct relationship between engineering loads and the emission of NO_x for all fuel blends. This is expected to happen because high levels of engine load are known to lead to higher combustion temperatures that otherwise aid in the creation of NO_x. For most of the engine loads, the results on NO_x emissions indicated that diesel fuel has lower emission levels as compared to biodiesel blends. This can be due to increased oxygen concentration in biodiesel which increases combustion efficiency and combustion temperature leading to increased NOx formation. The maximum enhancement in NO_x emissions of B100, B20CNT50, B20CNT100, B40CNT50, and B40CNT100 as compared with diesel oil was determined as 22.03%, 13.48%, 27.54%, 6.52%, and 14.2%, respectively, at full loads. When MWCNT concentration is increased from 50 ppm to 100 ppm in both B20 and B40 blends, it leads to an increase in NO_x emission at all the engine loads.. When incorporated into biodiesel MWCNTs, they allow for the enhanced convection of heat within the combustion chamber as they have very high thermal conductivity. This assists in achieving uniform temperature levels throughout the combustion area rather than developing hot spots, and also shortens the ignition delay that in turn contributes to increased formation of NO_x. In most cases, B40 blends prove to have relatively higher NO_x emissions as compared to B20 blends. An increase in the concentration of biodiesel in the B40 blend increases combustion temperature, which also increases the formation of NO_x (Sunil *et al.* 2020). In particular, it can be stated that the B20CNT100 blend results in the highest value of NO_x emissions at the 100% load of the engine.

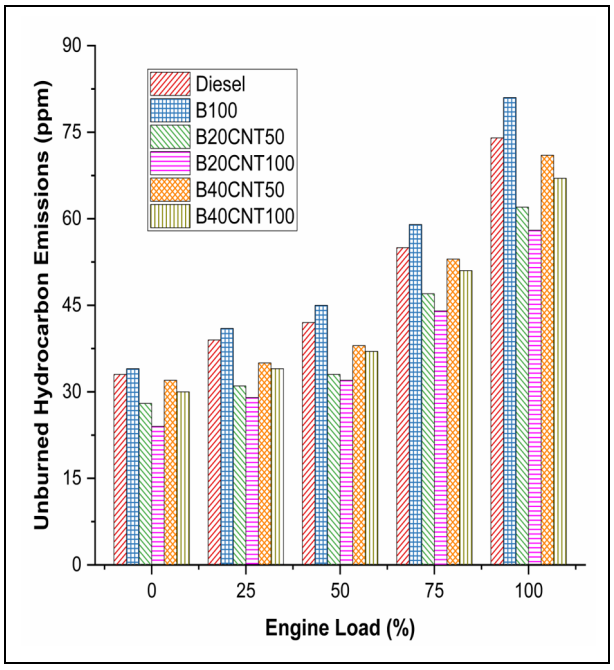


Fig. 6: Variation of HC emission for all tested fuels at different load conditions

4.5 Analysis of NO_x Emission

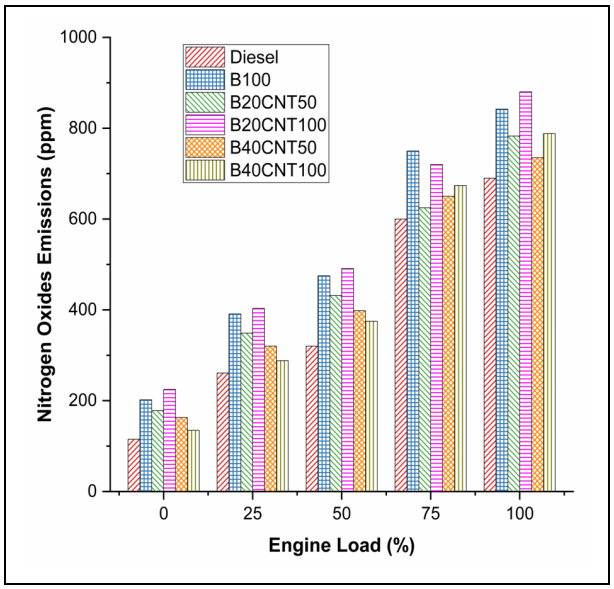


Fig. 7: Variation of NOx emission for all tested fuels at different load conditions

4.6 Analysis of Smoke Emission

As the engine load is raised, the smoke emission also rises in conjunction with all fuel mixes, a feature which can be attributed to the inherent nature of the diesel engines. The amount of smoke emissions is the highest for diesel fuel because of its high carbon content and the lack of oxygenated components. Compared to the blends containing carbon nanotubes, B100 has high smoke emissions than any blends of CNTs added, but it has low smoke emissions than the pure diesel (Fig. 8). In the biodiesel, oxygen is added to promote the combustion process, hence reducing smoke emissions. It has been concluded that the fuel blends B20CNT50 and B20CNT100 reduce smoke level by a considerable extent than the pure diesel and B100. The analysis and comparison of light extinction coefficient, smoke number, and thermal efficiency for the B20CNT100 blend indicate that it produced the lowest smoke emissions among the B20 blends. Furthermore, the superior thermal conductivity of MWCNTs enhanced the combustion characteristics of the blend.

The B40CNT50 and B40CNT100 samples show a general reduction in smoke emission, where B20CNT100 slightly outperforms B40CNT100 at the lower power output. Although all the optimization treatments resulted in a reduction in smoke density, the highest percentage improvement was achieved at three-fourths engine load with a higher concentration of MWCNT. At 75% engine load, the smoke emissions of B20CNT50, B20CNT100, B40CNT50, and B40CNT100 decreased by 10.64%, 19.15%, 6.38%, and 14.89%, respectively, compared with diesel fuel. Among these blends, B40CNT100 showed better results than B20CNT50. However, its performance was still inferior to that of B20CNT100.

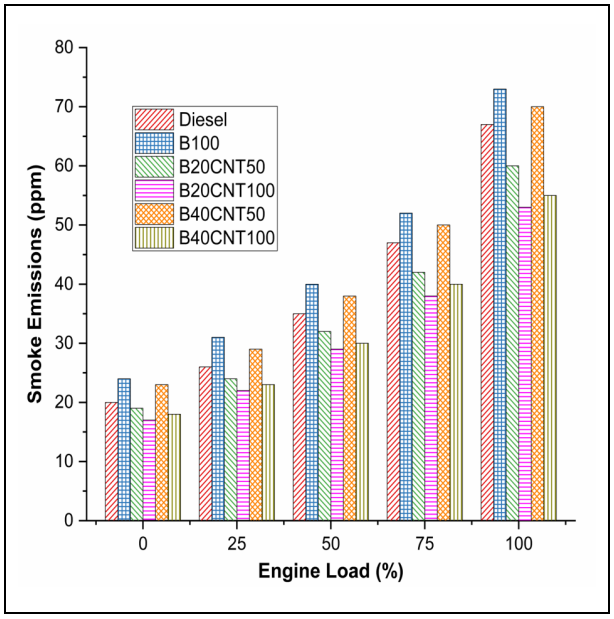


Fig. 8: Variation of smoke emission for all tested fuels at different load conditions

5. CONCLUSION

An investigation was conducted on the performance, combustion, and emission characteristics of palmyra palm biodiesel blends with varying MWCNT concentrations in a single-cylinder DI diesel engine at constant speed. Among the tested fuels, B20CNT100 showed the best overall performance, achieving BTE close to diesel (98.26% at 75% load) and reducing SFC by 18.46%. It also produced maximum reductions in CO, HC, and smoke emissions by 25.21%, 21.62%, and 19.15%, respectively. However, NO_x emissions increased by 27.54% due to improved combustion temperatures. Thus, the nano-enhanced biodiesel demonstrated improved efficiency, lower emissions, and greater sustainability potential compared to conventional biodiesel.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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