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ORIGINAL PAPER

Impact of injector nozzle diameter and hole number on performance and emission characteristics of CI engine powered by nanoparticles

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Abstract
To have energy sustainability and reduce emissions, it is essential to use alternative fuels in IC engines and improve their performance by using fuel combinations. In diesel engines, the fuel atomization process strongly affects combustion and emissions. The injector hole number of a fuel injector nozzle also plays a critical role in influencing the performance and emissions of diesel engines and is an important part of the diesel engine. In general, both parameters affect the spray parameters like droplet size and penetration length and thus the combustion process. In the present work, different injectors (4-hole injector with a nozzle diameter of 0.25 mm, 3-hole injector with a nozzle diameter of 0.20 mm) are used to study the performance and emissions characteristics of DI-CI diesel engine fuelled with a blend of Multi-Walled Carbon Nanotubes and Tallow Oil Methyl Ester. Multi-Walled Carbon Nanotubes were doped at 5, 10, 15, and 20 ppm into the test fuels. The experimental results revealed that the brake thermal efficiency of the engine slightly decreases when the engine is fueled by completely TOME biodiesel. Then the addition of Multi-Walled Carbon Nanotubes into the diesel-Tallow oil biodiesel blend improves the BTE. Furthermore, Multi-Walled Carbon Nanotubes lead to a noteworthy reduction in exhaust pollutants. Accordingly, all emissions (CO, HC, NOx, and smoke) were reduced with Multi-Walled Carbon Nanotubes in the test fuels thanks to the high surface area to volume ratio, higher energy content, catalyst role, accelerating chemical reactions, and oxidization of more unburnt fuels. Diesel–biodiesel blend with 20 ppm Multi-Walled Carbon Nanotubes exhibits superior performance and emissions characteristics among all blends. The BTE of the B40D60C20 blend was almost equivalent to that of diesel and has nearly equal emissions levels compared to diesel fuel under full and part load conditions. The B40D60C20 blend showed a maximum BTE of 30.9% which is 15.53% higher than raw TOME and 3.43% lower than diesel fuel. In addition to that, the blend B40D60C20 showed a significant reduction in CO emissions by 45.46%, HC by 17.29%, NOx by 15.25%, and smoke by 21.28% compared to the raw TOME. Therefore, the optimized fuel blend is B40D60C20 with a dose level of 20 mg/L, where a reasonable improvement in performance and emissions characteristics has been achieved. Additionally, a smaller nozzle diameter for injectors leads to better injection characteristics and a small size for atomized fuel droplets. Accordingly, better results in terms of engine performance and emissions characteristics are achieved for the injector having three-hole with a diameter of 0.20 mm. The optimized fuel combinations with the optimized nozzle geometry will lead to better IC engine performance. The response surface methodology and artificial neural network outcomes demonstrated that these two are excellent modelling techniques, with good accuracy. In addition, the artificial neural network's prediction performance was somewhat better than the response surface methodology.

Keywords Diesel engine · Biodiesel · Transesterification · MWCNT nanoparticles · Injector

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Abbreviations

INHN	Injector hole number
MWCNT	Multi-walled carbon nanotubes
BTE	Brake thermal efficiency
TOME	Tallow oil methyl ester
RSM	Response surface methodology
ANN	Artificial neural network
CO	Carbon monoxide

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NOx	Oxides of nitrogen
UBHC	Unburnt hydrocarbon
CNT	Carbon nanotubes
CRDI	Common rail direct injection
JME	Jatropha methyl ester
LPG	Liquefied petroleum gas
CR	Compression ratio
CH_4	Methane gas
JBD	Jatropha biodiesel

Introduction

In the recent energy era, biodiesel has been accepted as the best source to replace diesel fuel environmentally and economically. Nowadays, fossil fuels, especially diesel due to their parameters like fuel economy, resistance, reliability, and rigidity, have been used in all sectors such as transportation, energy, industrial, shipping, and agriculture. However, an increase in population, transportation, industrialization, agricultural utilization, fuel price, and limited oil reserves led to diesel exhaustion (Karagöz et al. 2022). Most of the diesel fuel is imported from Gulf countries with high exchange prices, which affects the economy of the country. The use of diesel fuel resulted in an increased carbon monoxide (CO), unburned hydrocarbons (UBHC), nitrogen oxides (NOx), and smoke emissions, which cause environmental pollution with greenhouse gases and lead to global warming and various health hazards.

To overcome the problems of diesel, it is necessary to produce environmentally and economically sustainable biodiesel. As stated by (Mohammed El-Kasaby, et al. 2013), the problems such as depletion of fossil fuels and environmental pollution can be overcome by using Biodiesel. Biodiesel is made up of mono-alkyl esters produced from edible and inedible oil, waste cooking oil, animal fat residue, bovine tallow, lard, castor, jatropha etc. (Hamaw et al. 2014). Compared to diesel, biodiesel has good lubricating properties, renewable, biodegradable, non-toxic, has a good cetane number, and has a high flash point (Nigam et al. 2011). Biodiesel use in engines contributes to a sustainable and eco-friendly environment by reducing the carbon particles from the emissions of diesel fuel (Mansir et al. 2018). When compared to vegetable oil, animal fat oil Biodiesel is less costly, which has motivated its use as a fuel for engine applications. The Animal waste produced from cattle, sheep, pigs, goats, birds (chickens), turkeys, and by-products of human consumption consists of organic matter and can be used as fuel in engine applications (Mora et al. 2019). The sources of tallow oil are cattle tissue beef, sheep lamb, pig lard, chicken feather, blood, skin, and meat processing industries (Barik and Vijayaraghavan 2018). The methods such as changing injection time, valve time, compression ratio, and supply of gaskets or wear seals to the internal parts are used to improve the diesel engine's performance. Techniques such as exhaust gas recirculation, exhaust gas withdrawal, catalytic converters, engine modification, fuel modification, and particulate filters are used to treat and control harmful emissions from diesel engines. Afshari presents an experimental investigation focused on the reduction of NOx pollutants in biodiesel fuels by means of a new method using nanoclay and nanofiltration together in the treatment of biodiesel. Rapeseed oil and methyl alcohol are converted into biodiesel by the esterification method. Subsequently, nanoclay is added to the mixture to separate the nitrogenous elements from the fuel (Afshari et al. 2018).

The experimental results revealed that the JBD + 40ppmFe_2O_3 + 40ppmCe_3O_4 mixture provides the highest BTE (32.5%) than pure diesel BTE (32%), improved BSFC (0.270 kg / kWh) compared to pure diesel (0.280 kg / kWh), and reduced exhaust gas temperature (245 °C) compared to pure diesel (310 °C) (Amit and Kumar 2015). Recently many researches carried out on fuel modification techniques by adding nanoparticles to the mixture of biodiesel and diesel used to improve performance and reduce emissions engine (Polat et al. 2022). Ahmed I. EL-Seesy observed that the addition of multi-walled carbon nanotubes (MWCNT) with optimized dose level to the mixture of biodiesel and diesel showed enhanced brake thermal efficiency with a notable reduction in emissions as NOx by 45%, CO by 50%, and UHC by 60% (Ahmed I. EL-Seesy et al. 2016). Sadhik and Basha found in their work that the addition of CNT to JME emulsified fuels showed significantly improved Brake thermal efficiency compared to that of pure JMEs and pure emulsion fuel due to improved combustion characteristics of CNT with brake thermal efficiency of JME2S5W100CNT (28.45%), which is higher than brake thermal efficiency of pure JME (24.80%) & emulsified JME2S5W (26.34%) (Sadhik and Basha et al. 2014). Prajwal et al. found that for better combustion and catalytic characteristics of MWCNTs the fuel mixture showed relatively superior brake thermal efficiency and lower CO, HC and smoke emissions compared to pure biodiesel fuel. Further, the reduced ignition delay, higher premix combustion fraction, and high temperatures cause relatively lower NOx emissions for fuel mixture multi-walled carbon nanotubes and biodiesel than diesel fuel (Prajwal et al. 2013). Deqing Meia et al. compared two nanomaterial's CNT and nano-M_0O_3 as additives in pure diesel in a CRDI engine in terms of performance, combustion and emissions characteristics with that of pure diesel. It found that CNT and MoO_3 diesel fuel mixture exhibits better fuel economy, combustion, and emissions than pure diesel due to the excellent thermal conductivity, surface deficits of the CNT, and the good catalytic oxidation function of MoO_3 (Mei et al. 2019). Basha and Anand et al. depicted combustion characteristics, performance, and emissions behavior of a CI engine operating with a mixture of carbon nanotube and Jatropha methyl ester. They found that the brake thermal efficiency of the Jatropha methyl ester with 100 PPM nano-carbon added in a 5% aqueous emulsion is 28.45% which is higher than Jatropha methyl ester (25%) and Jatropha methyl ester with 5% aqueous emulsions (26%) due to CNT combustion characteristics (Basha and Anand 2014). GhanBari et al. depicted that the addition of both multiwall carbon nanotubes and silver nanoparticles to the fuel mixture increases engine torque and power by up to 2% and reduces specific fuel consumption by 7.08% by improving the fuel mixture properties such as surface to volume ratio, flash point, kinematic viscosity, thermal conductivity, and fire point (Ghanbari et al. 2017). Vishwajit and Bhagwat et al. experimented with a DI-CI engine with a diesel fuel, Honge Oil Methyl Ester [HOME], and graphene nanoparticles. It found that the brake thermal efficiency for HOME 25 + 50 ppm mixed fuel was higher than that for HOME 25 + 25 fuel mixture due to the graphene nanoparticles at a higher dosage level to the biodiesel (Vishwajit A. Bhagwat et al. 2015). Ali MA Attia et al. analyzed the diesel engine performance emissions operating with a mixture of biodiesel, diesel, and alumina nanoparticle. It found that the dose of 30 mg /L gives optimized engine performance by 6%, a reduction in BSFC, by 7%, an increase in the BTE and a reduction in emissions CO by 75%, NOx by 70%, UHC by 55%, and smoke opacity by 5% (Ali MA Attia et al. 2014).

Prabu and Anand tried to use mixed ratio aluminum and cerium oxide nanoparticles in JME and found that BTHE is close to diesel, and there is a significant reduction of pollutants such as CO, HC, and smoke due to improved oxidation characteristics from the supply of oxygen from nanoparticles (Prabu and Anand 2015). Giulio Solero et al. compared the performance and emissions of pure diesel, biodiesel, and Al_2O_3 nanoparticles added to biodiesel. It found a lower emissions coefficient and improved combustion for diesel with Al_2O_3 nanoparticles added fuel, due to the better turbulence between air from Al_2O_3 nanoparticles and fuel droplets (Giulio Solero et al. 2012). Manibharathi et al. investigated the IC engine performance and emissions fuelled with rhodium oxide nanoparticles and Pongamia Biodiesel mixture. The rhodium oxide nanoparticles' addition increased brake thermal efficiency and reduced emissions levels by acting as an oxygen supplier (Manibharathi et al. 2014). N.R. Banapurmath et al. depicted the use of graphene, multi-walled carbon nanotubes, and silver nanoparticles with biodiesel in the diesel engine. The addition of these nanoparticles showed improved performance like increased Brake thermal efficiency and truncated hydrocarbon, carbon monoxide, and smoke emissions (N.R. Banapurmath et al. 2014). Moy et al. depicted that CNT addition to the diesel and biodiesel mixtures increases the fuel combustion rate, improves the cetane number, acts as an anti-knock additive, promotes clean combustion, and suppresses the smoke formations (Moy et al. 2002). Alias, et al. analyzed the carbon nanotubes (CNTs) effects on palm biodiesel and found an increase in the calorific value of palm biodiesel by 1.4% from 52.0 to 52.7 MJ / kg due to the maximum amount of CNT dispersion in the palm biodiesel (Alias et al. 2013). Amit and Kumar evaluated IC engine performance with a mixture of jatropha biodiesel, cobalt oxide, and iron oxide nanoparticles. Hosseini et al. examined the diesel engine performance and emissions operating with waste cooking oil and carbon nanotubes (CNT) fuel mixture. They found a decrease in specific fuel consumption (SFC) by 7.12% and increased BTE by 8.21%. Further, it was observed that there is a significant increase in torque, power with a reduction in emissions HC by 44.98%, Nox by 27.49%, smoke by 29.41%, and CO by 65.7% with the addition of nanoparticles in the WCO biodiesel (Hosseini et al. 2017). AnBarasu G et al. analyzed the performance and emissions behavior diesel engine fuelled with a mixture of CO_3O_4, TiO_2 nanoparticles, and Calophyllum inophyllum biodiesel. It found an increase in brake thermal efficiency and reduction in emissions such as CO, UHC, and smoke with nano-additives compared to a diesel with a high NOx emission (Anbarasu et al. 2016). Jayanthi and Rao found that copper oxide nanoparticle addition reduces the HC, smoke, $No_{x,}$ and CO emissions by increasing the BTE. The B20 + 80-ppm CuO blend showed engine optimization (Jayanthi and Rao 2016). Thirumal et al. investigated the effect of cerium oxide nanoparticles on diesel engine performance and emissions behavior. It was found from the results that CeO50ppm showed BTE increased by 6% and emissions reduced as NOx by 62.7%, smoke by 15%, CO by 35.65%, and HC by 56.5% (Thirumal et al. 2015). Kowthaman et al. investigated the carbon nanotube's addition effects on performance, combustion, and emissions behavior of DI-CI engine fuelled with Schizochytrium methyl ester-diesel blended fuel SCME 20 and SCME 40. It found that the addition of CNT increased the BTE by 2.5% and decreased the BSFC by 3.2% when compared to the neat SCME 20 blend. The emissions were reduced by UHC by 14.28%, CO by 23.07%, NOx by 5%, and smoke by 21.52%. The dose level of 50 ppm in SCME20 showed the optimized performance and emissions of the DI-CI engine (Kowthaman et al. 2021).

Based on the literature review, it can be summarized that less work has been presented by researchers on TOME biodiesel, which is the potential alternative diesel engine fuel and the addition of nanoparticles to biodiesel base improves the fuel properties in performance and emissions wise compared to pure biodiesel. The nanoparticles show better-improved properties in nano-scale form instead of in the bulk form. When added to biodiesel, the nanoparticles act as an excellent catalyst; exhibit a higher surface-to-volume ratio, high catalytic reactivity, and accelerate combustion reactions. Therefore, the present investigation was made with different dose levels of MWCNTs nano-additive to study the effect of MWCNTs nano-additive on the performance and emissions levels of a TOME-fuel blended diesel engine. The TOME oil is easily available and can be converted to biodiesel by transesterification. The different blends of the TOME biodiesel and diesel were tested in the diesel engine to evaluate performance and emission characteristics. Further, the experiment was carried out to improve performance and reduce emissions by the addition of multiwall carbon nanotubes. The RSM was used for the determination of the interaction between the independent variables, to carry out the mathematical modelling of the system. It helps in saving time and money by reducing the number of experiments. ANN (Artificial neural network) was used for prediction. It can learn and model nonlinear and complex relationships, which is important because, in an IC engine, many parameters between inputs and outputs are nonlinear and complex. On the other hand, it is noticed that the number of studies has focused on the injector nozzle diameter, and hole number is very limited in the literature. In this framework, the present study aims to contribute to this field by considering the changes in injector nozzle diameter and hole number on the engine performance, and exhaust pollutants.

Materials and methods

Fuel extraction and characterization

Fuel extraction

In this experiment, the biodiesel produced by alkali catalyzed the Transesterification process from waste tallow fat, including Single-Step Transesterification (SSTE) and Two-Step Transesterification (TSTE). Both methods of transesterification mixture of methanol and KOH or NaOH were used with reactions taking place at temperatures of 32 °C and 60 °C for 1-h time duration. The fuel properties of the Tallow Oil Methyl Ester (TOME) Biodiesel produced like viscosity, fire point, calorific value (C.V), flash point, and density are evaluated with the help of tools listed in Table 1. These evaluated properties met the specified limits according to ASTM standards and indicated that we could use tallow oil as a direct fuel in engine applications as compared to diesel fuel. The Transesterification reaction was monitored through a thin layer of Chromatography using a silica gel plate to optimize the biodiesel sample. The optimized sample was obtained by mixing 10%, 20%, 30% and 40% different volumetric percentages of biodiesel with the diesel.

Transesterification process

The required amount of tallow oil in the form of solid-state is filled in the drying tank and heated up to 60 °C. After heating, it will be liquefied and then transferred to the reaction tank. In the reaction tank, the oil was further heated to 60 °C, and the pump started for the recirculation of the oil. The 300 mL of methanol and 4.5 g of NaOH flakes for 1 L of tallow oil is taken, and NaOH flakes are dissolved in the methanol by continuously stirring it. The solution is added to the reaction tank by opening the reaction tank's valve and closing it. The pump is in the on condition continuously for recirculation of oil for up to 2 h. The oil sample is taken in the test tube every 30 min and kept in its steady-state condition to form separate layers of glycerine and biodiesel. After completing 2 h of recirculation, it is transferred to the drying tank and kept in a steady state for a minimum of 4 h to separate glycerine from biodiesel. After that, glycerine is wholly removed from the drying tank from the drain valve, and the water in the water tank is heated up to 90 °C and used to wash the biodiesel in the drying tank. Water settles down after 2 min and is drained out, and the same procedure is continued to remove the milky content of water until it completely goes off. After washing biodiesel, it is heated up to 125 °C to remove methanol and water content from the biodiesel. Finally, this biodiesel was kept to attain room temperature and stored in a container. Figure 1 gives a view of the transesterification unit.

Structure of multiwall carbon nanotubes

The multi-walled carbon nanotubes are made from graphene as multiple laminated layers. Compared to single-walled carbon nanotubes (SWCNT), multiwall carbon nanotubes (MWCNT) are not clearly defined due to their complex

Table 1 Properties of test fuel and the details of equipment used

Sl.No	Properties	Diesel	TOME biodiesel	Equipment used
1	Fire point (°C)	58	151	Cleveland apparatus
2	Kinematic viscosity (centistokes)	2.52	5.0	Redwood viscometer
3	Calorific value (kJ/kg)	45,843	38,350	Bomb Calorimeter
4	Flashpoint (°C)	55	127	Cleveland apparatus
5	Density (kg/m^3)	825	786.0	Mass/Volume

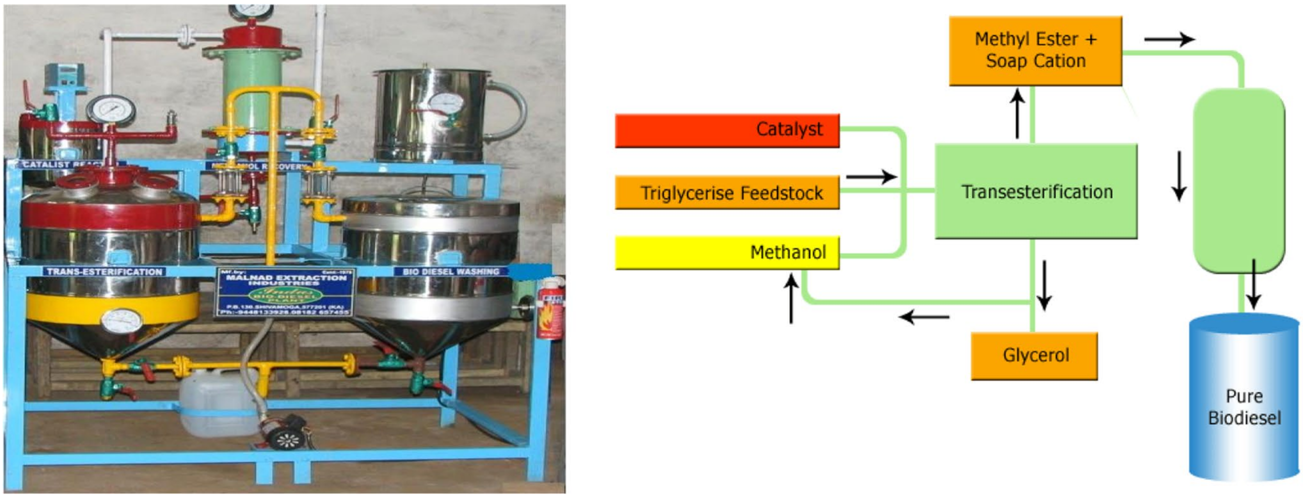

Fig. 1 Transesterification unit and process

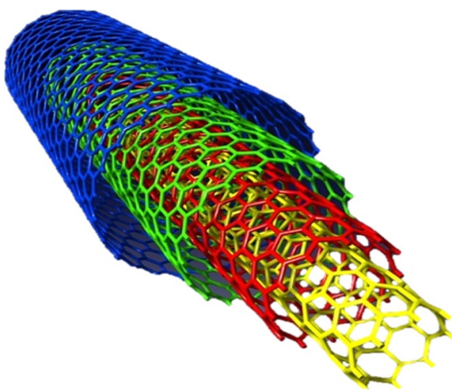

Fig. 2 Carbon nanotube powder

Table 2 Properties of multi-walled carbon nanotubes

Sl. No	Multi-walled carbon nanotube	Description
1	Production method	Chemical vapor deposition
2	Diameter	Avg. Diameter: 5–20 nm
3	Length	10 nm
4	Nanotubes purity	99%
5	Metal particles	< 1%
6	Amorphous carbon	< 1%
7	Specific surface area	3.30 M/G
8	Bulk density	0.20–0.35 G/Cm

structure (Karthikeyan et al. 2014). Carbon nanotubes are nano-sized multi-surface materials built in a cylindrical shape and made of pure carbon materials. Carbon nanotubes are used for numerous engineering applications due to their properties like the good surface area to volume ratio, high stiffness, and durability. In the present day, CNT used in biodiesel and diesel fuel blends will increase the carbon–oxygen ratio, act as an anti-knock additive, improve the combustion rate of the fuel, and reduce emissions. Figure 2 shows the morphology and real view of MWCNT nanomaterials, and Table 2 gives some significant properties of MWCNT nanomaterials.

Table 3 Technical specification of engine

Kirloskar TV1 Engine	Specifications
Number of cylinders	1
Number of strokes	4
Type Fuel used	H.S.Diesel
RPM	1500
Power	3.5 kW
Cylinder diameter	80 mm
Length of connecting rod	234 mm
Length of stroke	110 mm
Compression ratio	17.5:1
Orifice diameter	0.20 mm
Dynamometer arm length	185 mm
Load	Mechanical type
Cooling	Water cooled engine

Experimental setup

The experiments were conducted on a four strokes single-cylinder, water-cooled, Kirloskar TV1 type, diesel engine running under the uniform speed of 1500-RPM with a fuel mixture of MWCNT, TOME biodiesel, and pure diesel. The technical specifications of the experimental setup used for the investigation are given in Table 3 & depicted in Fig. 3

Fig. 3 Experimental test rig

(Kattimani et al. 2020). In this experiment, the variation of BTE, CO, HC, NO_X, and smoke concerning different loads is plotted and studied for all test fuel mixtures with different operating conditions like CR 17.5:1, injection pressure 240 and 260 Bar for 3- and 4-hole nozzle geometry orifices.

Fuel injector

The real and schematic views of fuel injectors and nozzle holes that are used in this study are shown in Fig. 4, and the specifications are given in Table 4.

Smoke meter

The MARS smoke meter SM-05 is shown in Fig. 5. It is used to measure the opacity of exhaust gases produced by diesel engines. The technical specifications are given in Table 4.

Experimental procedure

The following procedure was used to analyze the performance and emissions characteristics of a single-cylinder

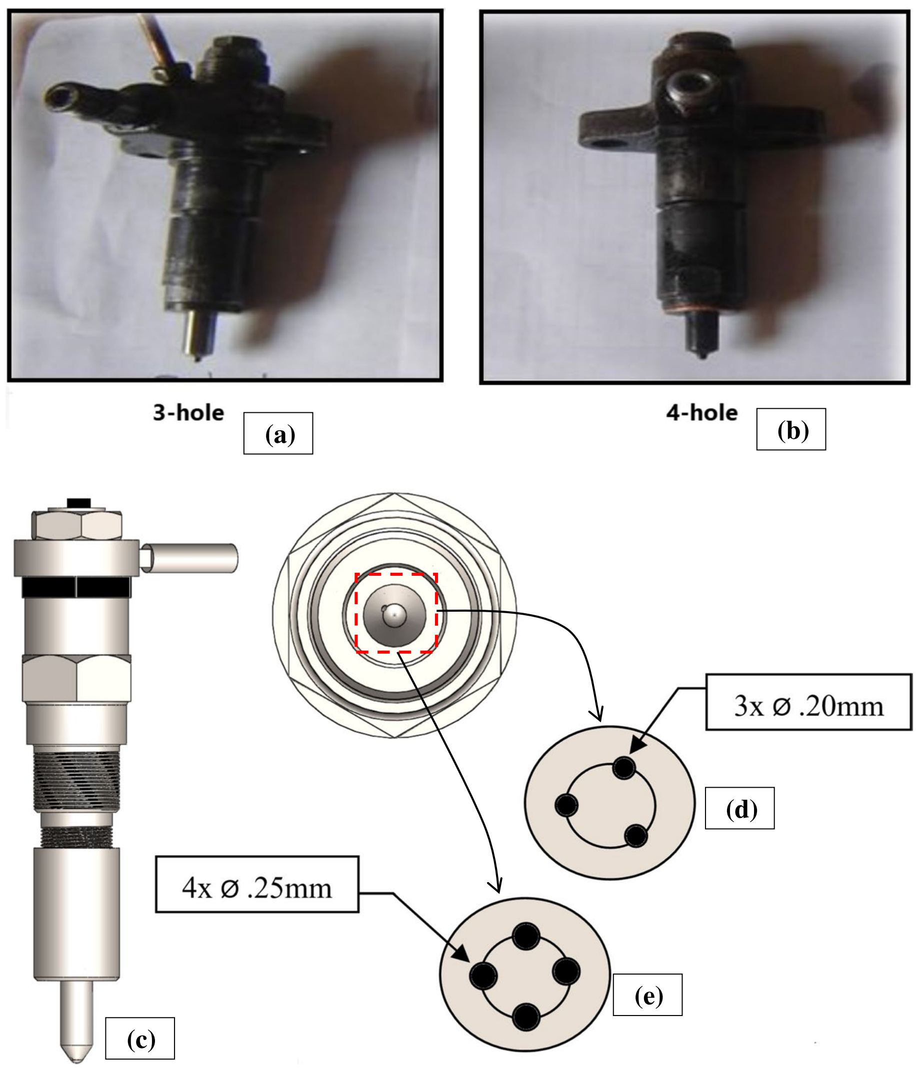

Fig. 4 Real view of fuel injector **a** 3 hole 0.20 mm **b** 4 hole 0.25 mm, **c** schematic view of fuel injector **d** 3 hole 0.20 mm **e** 4 hole 0.25 mm

Table 4 Smoke meter specifications

S.N	Smoke meter SM-05	Specification
1	Light Source	Green LED of 5 mm diameter
2	Detector	Photocell
3	Measuring RANGE	HSU = 99.9%, k = 9.99
4	Resolution	0.1/m
5	Linearity	0.1/m
6	Drift	Span:0.1/m, Zero:0.1/m
7	Response time	< 0.3 s
8	Engine temperature	2 sources between range 0–150 °C (± 1 °C)
9	Supply voltage	140–240 V, 50 Hz
10	Make	MARS Technologies Inc

Fig. 5 Smoke meter

diesel engine fuelled with a mixture of Multi-Walled Carbon Nanotubes (MWCNT) and Tallow Oil Methyl Ester (TOME) at 1500 rpm uniform speed. In Fig. 6, the nanodiesel preparation steps are followed to obtain a stable blend. Accordingly, the weight of nanoparticles and liquid fuels are measured by the precision scales. Then the nanoparticles dispersed into the diesel–biodiesel blends. In this step, a mechanical stirrer was used at 500 rpm for 30 min. Then the nanoparticles-added diesel–biodiesel blends were exposed to ultrasonication waves at 40 kHz for 120 min. The temperature of the ultrasonic bathwater was kept at 25 °C during all ultrasonication processes. Then the stable nano-diesel fuels were achieved and then poured into the fuel tank not to allow the nanoparticles into the liquid fuels to settle down. Then the properties of fuel such as flash point, viscosity, fire point, and density are found using various instruments listed in Table 1. The test fuels are prepared by blending different dose levels of multiwall carbon nanotubes into the mixture of diesel–biodiesel as listed in Table 5. Start the engine by cranking, it is waited for the stable data flow and then applies load and note down readings. Repeat the experimental procedure for all the above-mentioned different blends at different load conditions. Based on the experimental results collected and from the calculations, draw the performance and emissions graphs to identify the optimized biodiesel blend, giving better performance and reducing emissions. Finally, a conclusion suggests the optimized best blend with the highest thermal efficiency and lowest emissions characteristics.

The nanodiesel fuel preparation step followed in this paper is schematically depicted in Fig. 6.

Fig. 6 Nano diesel preparation step

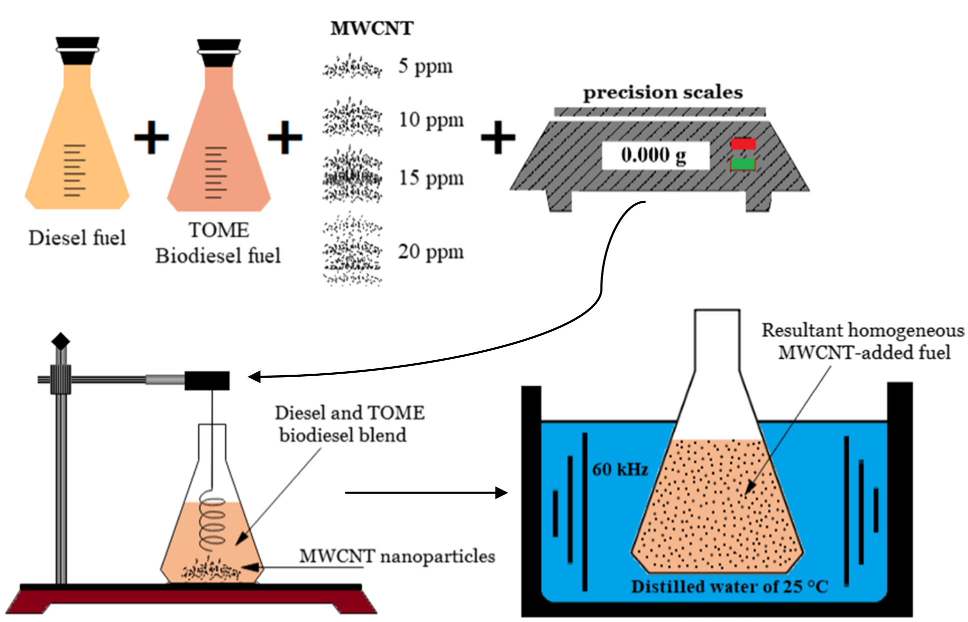

Table 5 Different blend proportions

Sl. No	TOME biodiesel (%)	Diesel (%)	MWCNT dosage, ppm	Blend code
1	10	90	5	B10D90C05
2	20	80	10	B20D80C10
3	30	70	15	B30D70C15
4	40	60	20	B40D60C20

Response surface methodology (RSM)

RSM is a statistical method for estimating the connection between dependent and independent variables. To analyze the statistical importance of the study factors and their interactions, it uses linear, quadratic or higher-order polynomial functions. In addition, the regression idea is used to forecast and optimize outcomes. The application of RSM in engineering domains has yielded positive results in the estimation of complex systems, over time. Engine load (kg), IOP (Bar) and blends were the parameters investigated in this research. User-defined discrete levels were used to generate the candidate population. There were two levels (high + 1 and low − 1) for all the input variables. BTE, CO, HC, and smoke density were the response variables that were measured. For a greater understanding of model features, the best-suited model for each response was chosen and analysis of variance (ANOVA) was used. The p-value is a statistical assessment of variants in samples of a given property in ANOVA. F is a probability distribution in distinct samplings, Df is degrees of freedom. A p-value of less than 0.05 was used as the determination rule for significance. The percentage contribution (PC%) of each model term was calculated, which is a ratio of an aggregate of squared deviations to an individual sum of squares (SOS). PC% is a tool that gives an approximate notion of how important study factors and interactions are in the design.

Results and discussions

The experimentally observed data was used for the evaluation of the variation of brake thermal efficiency, hydrocarbon, carbon monoxide, nitrogen oxide and smoke emissions levels concerning load for the conventional diesel fuel, raw TOME biodiesel and the CNT blended TOME nano-fuel according to the different injectors with varying nozzle diameter and hole number. Accordingly, the following sections are detailed based on the results achieved from the present study.

Performance comparison

Figure 7a depicts the brake thermal efficiency variation with Load for diesel, raw TOME, and TOME-CNT blended biodiesel fuel mixture for 3-hole nozzle geometry 0.20 mm diameter, 240 Bar injection pressure and 17.5:1 compression ratio. As the engine load increases, the BTE value for each test fuel improves. It can be attributable to the friction force, which is constant at low and high engine loads but is negligible as power increases at high engine loads. That is why the effect of loss from the friction forces is lower on piston motion at high engine loads, improving engine performance at high loads.

Another significant reason underlying the improvement of the brake thermal efficiency can be associated with the increment in-cylinder temperature at high engine loads. Compared to that low engine load, more fuel is required to

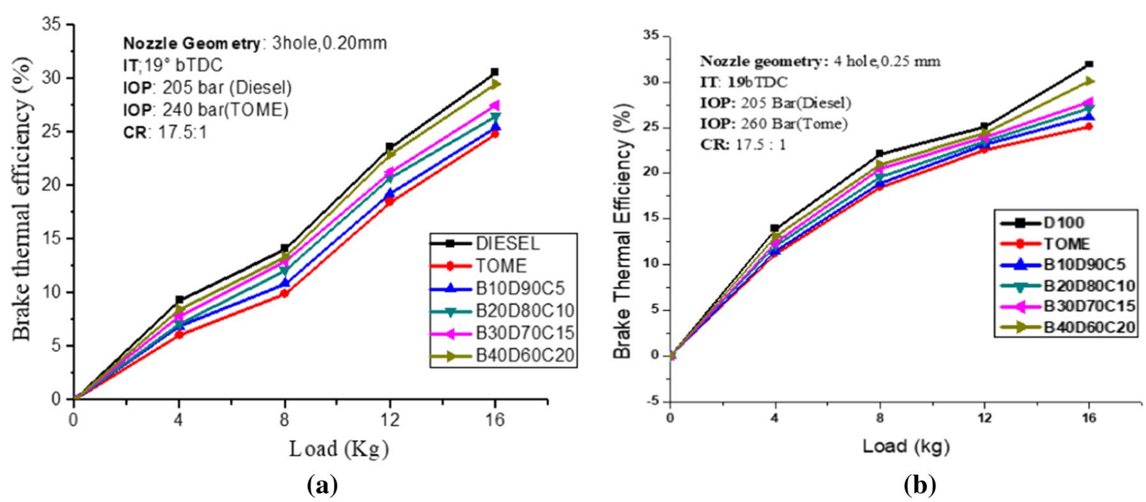

Fig. 7 Brake Thermal Efficiency variation with varying engine load for **a** 3 holes with the diameter of 0.2 mm **b** 4 holes with the diameter of 0.25 mm

reach high engine loads. Considering all test fuels together, it is noticed from the figure that a high BTE value is always achieved for conventional diesel fuel. Then the BTE sharply reduces when the engine is fueled by TOME biodiesel. The fundamental reason underlying these curves is probably explained by the calorific value of test fuels, as presented in Table 1. From the relevant table, it is seen that the conventional diesel fuel has a higher calorific value than that of TOME, resulting in a respectable reduction in the BTE value of TOME test fuel. Another reason why the BTE drops with TOME can be attributable to the kinematic viscosity of diesel and TOME fuels (See Table 1) (Ağbulut et al. 2020b). The kinematic viscosity of TOME is almost two times bigger than that of diesel fuel, leading to poor injection characteristics for TOME. That is because the fuel droplet diameters of test fuels with high viscosity are larger and the atomization is, therefore, worsens.

As a consequence of this case, the ignition delay period gets longer, and other combustion parameters also deteriorate. All these can refer to the reduction in BTE for TOME test fuel. Additionally, in Fig. 7a, the BTE improves with the presence of MWCNT in the test fuels. Then it is noticed that the improvement rate increases with the increment of the mass fraction of MWCNT in the test fuels. Accordingly, the most improvement in BTE is achieved at a given engine load when the engine runs with B40D60C20 test fuel. The reason behind the improvement of BTE with the addition of MWCNT nanoparticles can be explained by the large surface area to volume ratio, leading to increasing the catalyst role (Ağbulut et al. 2020a). In this way, the chemical reactions during the combustion process accelerate and ensure an extra duration for the unburnt fuels to burn (Ağbulut et al. 2021). Overall, the thermal efficiency enhances. Another reason can be attributable to the increasing energy content of test fuels with the addition of MWCNT nanoparticles into the test fuels. Accordingly, it was found that the B40D60C20 blend showed the maximum BTE of 29.2%, which found 14.04% higher than the pure TOME blend and 3.88% less than diesel at economic load.

On the other hand Figure, 7b depicts the BTE variation with varying engine load for diesel, raw TOME, and TOME-CNT blended biodiesel fuel mixture for 3-hole nozzle geometry 0.20 mm diameter, 260 Bar injection pressure, and 17.5:1 compression ratio. It was observed that due to an increase in injection pressure, there is an enhancement in brake thermal efficiency compared to these values at 240 Bar injection pressure. Due to its properties like proper air–fuel mixing, increased evaporation rate, and proper atomization, it was found that diesel showed higher brake thermal efficiency than the raw TOME and its blends (Dhana et al. 2018). When MWCNT is doped into TOME biodiesel and diesel fuel blend, CNT acts as an oxygen supplier due to its catalyst role and its properties like a high surface area to volume ratio, better atomization, and evaporation rate causes complete combustion and slightly increases BTE of all blends compared to the raw TOME biodiesel fuel (Muthusamy et al. 2018). Out of all these blends, the B40D60C20 blend showed the maximum BTE of 30.9%, which is 15.53% higher than the pure TOME blend and 3.43% less than diesel at economic load (Ahmed et al. 2017). Similar results were also noticed in the previous research (Ramesh et al. 2021; Ağbulut et al. 2019; Wei et al. 2021; Muruganantham et al. 2021; Ağbulut et al. 2021). It was observed that for 4-hole injector brake thermal efficiency decreased as compared to that of 3-hole injector due to the irregular geometry of 4-hole injector. On the other hand, there is an enhancement in brake thermal efficiency compared to these values at 240 Bars due to increased pressure. Out of all these blends, the B40D60C20 blend showed the maximum BTE of 30.1%, which is 14.28% higher than the pure TOME blend and 3.85% less than diesel at economic load. This BTE enhancement is due to the properties of added carbon nanotubes like the high surface area to volume ratio, better atomization and evaporation rate which causes complete combustion (Al-Kheraif, et al. 2021; Rastogi et al. 2021; Muthusamy et al. 2018; Ahmed et al. 2017; Ramachandran et al. 2021). The reason behind the improvement on the BTE with the injector of 3 holes having a diameter of 0.20 mm can be attributable to the injection parameters. The number of nozzles of the fuel injector and the diameter of these nozzles are very effective factors that strongly affect the injection parameter of the test fuels. In the smaller nozzle diameter, the fuel droplets have small diameters, as shown in Fig. 8.

Similarly, as the diameter of the injector nozzles increases, the diameter of fuel droplets increases. In that case, the sprayed fuel waits for a longer duration to evaporate, leading to a longer ignition delay. As the ignition delay period gets longer, the duration of the combustion decreases. Consequently, the fuel does not have a sufficient duration to be completely burned, worsening the brake thermal efficiency (Ağbulut et al. 2021). This case explains why the BTE drops for the injector nozzle have a smaller diameter. To draw a picture in the minds and increase intelligibility, the following schematic is presented in the study.

Emissions comparison

Carbon monoxide emissions

Figure 9 depicts the CO emissions variation with load for diesel, raw TOME, and TOME-CNT blended biodiesel fuel mixture for 4-hole nozzle geometry 0.25 mm diameter, 260 Bar injection pressure, and 17.5:1 compression ratio. It is observed that compared to 3-hole injectors, the CO emissions are high due to the irregular geometry of 4-hole injectors. From the graph, it observed that diesel fuel, due

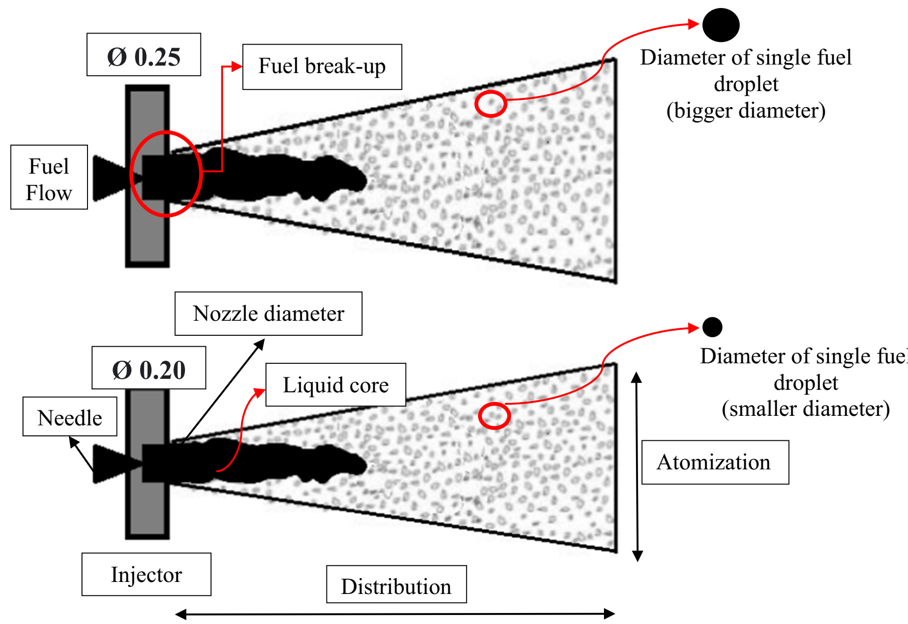

Fig. 8 Atomization and fuel droplet diameter according to the nozzle diameter

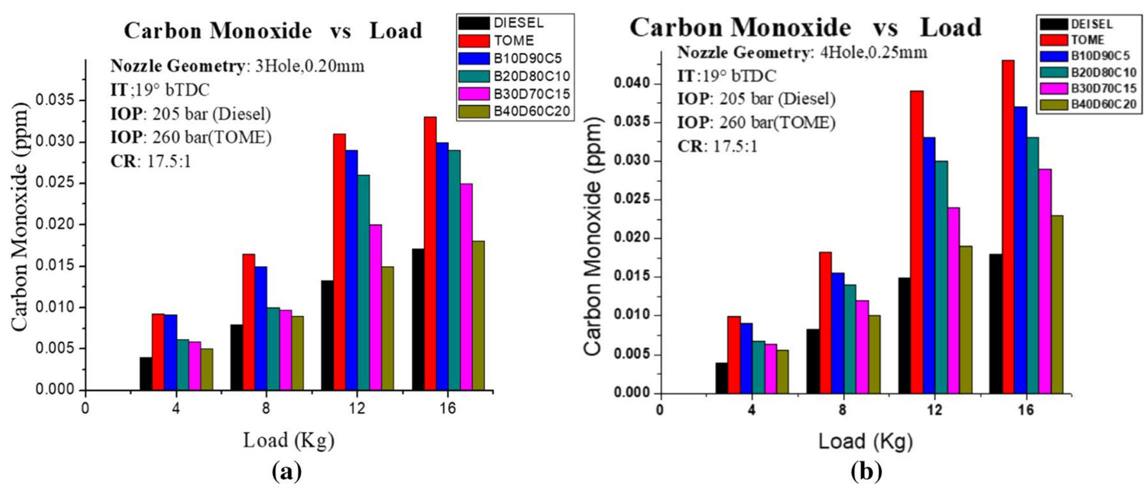

Fig. 9 CO emissions variation with varying engine load for **a** 3 holes with a diameter of 0.2 mm **b** 4 holes with a diameter of 0.25 mm

to its properties like high heat release rate, high calorific value, and poor viscosity, showed the lowest CO emissions and raw TOME due to its properties like high density, rich air–fuel mixture, and better viscosity showed the highest CO emissions at all loads (Hoseini et al. 2018, 2020). The blending of multi-walled carbon nanotube (MWCNT) to TOME improves calorific value, combustion, and oxidation rate of fuel mixture and reduces CO emissions. The blends B10D90C5, B20D80C10, B30D70C15, and B40D60C20 showed the reduction in the CO emissions by 12.82%, 15.38%, 25.64% and 47.05% compared to TOME. Additionally, the B40D60C20 blend showed comparable CO emissions to diesel fuel at all loads (Soudagar et al. 2019; Altun et al. 2011). The reason why CO emissions significantly drop with the addition of MWCNT nanoparticles is the high catalyst effect of the nanoparticles. The nanoparticles ensure a better surface area to volume ratio and fewer fuel consumption. Nanoparticles accelerate the chemical reactions due to their high catalytic effects during the combustion process, and they also decrease the activation energy required for the initiation of chemical reactions. Thus, during the combustion process, chemical reactions take place at lower temperatures, and along with the acceleration of these reactions, there is an opportunity for unburned fuels to be re-oxidized during the combustion duration.

As a consequence of this phenomenon, unburned fuels are oxidized a second time, and incomplete combustion products such as CO emissions are also reduced with nanoparticle addition. In parallel with the increase in nanoparticle dosage, the withdrawal in CO emissions was also more pronounced. The reason for this is that with increasing nanoparticle dosage, the number of free-circulating nanoparticles in the test fuel increased, and the catalytic effect increased accordingly. In other words, the lowest CO emissions were observed in the B40D60C20 test fuel, the highest dosage of MWCNT nanoparticles. The blends B10D90C5, B20D80C10, B30D70C15 and B40D60C20 showed a reduction in the CO emissions by 9.09%, 12.12%, 24.24%, and 45.46% compared to that of TOME. Additionally, the B40D60C20 blend showed comparable CO and emission to diesel fuel at all loads.

The fundamental reason underlying fewer CO emissions with the injector of 3 holes having a diameter of 0.20 mm can be attributable to the improving injection parameters. As the nozzle diameter gets smaller, the smaller diameter of fuel jet droplets can be sprayed. In this case, the surface area to volume ratio of test fuels gets larger, ensuring more fuel oxidization. Accordingly, CO emissions are recorded when the engine runs with a 3-hole nozzle of diameter 0.20 mm. Contrary, the bigger diameter of fuel droplets gets smaller the surface area to volume ratio, leading to less fuel to oxidize.

Additionally, it is noticed that the CO emissions are going to their maximum value for a given test fuel as the engine load increases. The reason behind it can be due to the increased fuel consumption at high engine loads. During the tests, the engine speed is constant, and the air intake is also constant. Therefore, as the engine load increases, the air–fuel ratio varies due to the increased fuel consumption. Therefore, the CO emissions are highly increasing at elevated engine loads due to the insufficient duration to oxidize and/or secondary oxidize entirely. Independent of the nozzle number and diameters, CO emissions follow similar trends according to the varying engine load. Similar trends were also noticed in the previous studies (Fayaz et al. 2021; Vigneswaran et al. 2021; Singh et al. 2021; Razzaq et al. 2021).

Hydrocarbon emissions

Like CO emissions, HC or unburnt HC emissions are incomplete combustion products and reduce with the complete combustion process. Figure 10 shows the variation of HC emissions according to the varying engine loads for different injectors. The most effective parameters on the HC emissions are counted as the appropriate air–fuel ratio, the chemical composition of the test fuel (C, H, and O), the presence of sufficient oxygen at the combustion duration for the fuel to oxidize during combustion, and the existence of sufficient time, other thermophysical properties of the fuel, its calorific value, cetane number, and viscosity, etc. (Ağbulut, Ü et. al 2020). All these are significantly essential parameters affecting the formation of HC emissions in internal combustion engines. With the varying engine loads, HC emissions exhibit a trend as in CO emissions. This means the incomplete combustion increases with an increment in the engine load, resulting in an increment in the incomplete combustion products such as CO and HC emissions. Therefore, the highest HC emissions are found where the highest CO emissions are recorded. The reason behind it can be attributable to the lower heating value, and high viscosity of TOME biodiesel, leading to worsening combustion and increasing fuel consumption for this test fuel. Then, increasing HC emissions are being pulled back with MWCNT nanoparticles in the test fuels. Probably, the main reason is the catalyst effect of the nanoparticles. Accordingly, the nanoparticles encourage

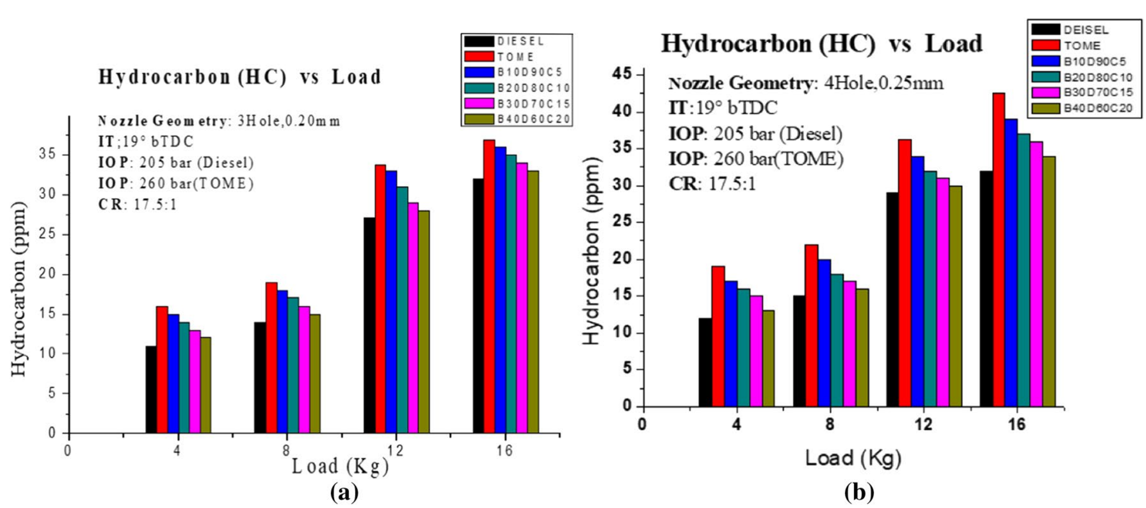

Fig. 10 HC emissions variation with varying engine load for **a** 3 holes with a diameter of 0.2 mm **b** 4 holes with a diameter of 0.25 mm

the test fuel to oxide, resulting in complete combustion and enhancing performance characteristics.

The MWCNT blending into the fuel mixture reduces HC emissions by burning carbon particles at cylinder wall temperature due to high surface catalytic activity and accelerating the burning of nonsymmetrical fuels with air (Annamalai et al. 2016; Vairamuthu et al. 2016; El-Seesy et al. 2019). It was found for the injector having 4 holes with a diameter of 0.25 mm that when compared to raw TOME biodiesel, B10D90C5, B20D80C10, and B30D70C15 blends, the B40D60C20 blend revealed the lowest HC emissions, which was 17.29% and 3.03% less as compared to those of TOME biodiesel and diesel fuel, respectively. On the other hand, it was found for the injector has 3 holes with a diameter of 0.20 mm when compared to raw TOME, B10D90C5, B20D80C10, and B30D70C15 blends, the B40D60C20 blend revealed the lowest HC emissions, which was 20.29% and 3.44% less as compared to TOME and diesel respectively. Previous researchers declared similar trends in terms of HC emissions (Leach et al. 2021; Jaikumar et al. 2021; Fayad and Dhahad 2021; Ardabili et al. 2021).

Nitrogen oxide emissions

The most critical parameter affecting the formation of NOx emissions is the in-cylinder temperature. Usually, conventional fuels do not have any nitrogen and oxygen atoms in their chemical composition, but the air should be intake into the combustion chamber to burn the fuel. When the nitrogen and oxygen atoms in the air taken into the combustion chamber reach high temperatures during the combustion process, the formation of NOx emissions increases. Because the reaction potential of nitrogen and oxygen atoms is very high at high temperatures (Ağbulut et al. 2019; Karagöz et al. 2020; Zeldovich et al. 1947; Khalife et al. 2017). For this reason, many studies in the literature make use of the in-cylinder temperature value or the exhaust gas temperature, which is a reflection of it, when explaining the formation of NOx emissions (Ağbulut et al. 2021; Sarıdemir et al. 2021; Rastogi et al. 2021; Emiroğlu and Şen, 2018). It can be seen from the study that NOx emissions were measured with the highest TOME biodiesel fuel. This is an expected result. In this study, the test fuel with the lowest energy density was TOME biodiesel. Therefore, when the engine is run only with TOME biodiesel, the fuel consumption will be higher than other test fuels. It is also possible to see this situation from the BTE graphic. Since the engine has to burn more fuel to reach the same engine load, the in-cylinder temperature values also increase when the engine is run with this test fuel, due to the excess fuel being burned. In this case, nitrogen and oxygen atoms in the combustion chamber participate in more chemical reactions, and the NOx level increases. Afterwards, significant reductions in NOx emissions were observed with the addition of nanoparticles as it is seen in Fig. 11. The most important reason for this can be associated with the increase in the energy density of the fuel and, accordingly, the decrease in fuel consumption in nanoparticle added test fuels (Ağbulut et al. 2021).

In addition, the high thermal conductivity values of the nanoparticles accelerated the heat transfer from the combustion chamber (Banapurmath et al. 2014) and restrained the formation of NOx. Accordingly, the highest reduction in NOx is noticed when the engine is fueled by 20 ppm MWCNT nanoparticles. For 3 holes with a nozzle diameter of 0.20 mm, the B40D60C20 fuel blend showed emissions, which was around 3.44% and 20.29% less than diesel fuel and TOME biodiesel, respectively. On the other hand, for 4 holes with a nozzle diameter of 0.25 mm, the B40D60C20 fuel blend showed emissions, which were around 3.95% and 24.30% less than diesel fuel and TOME biodiesel.

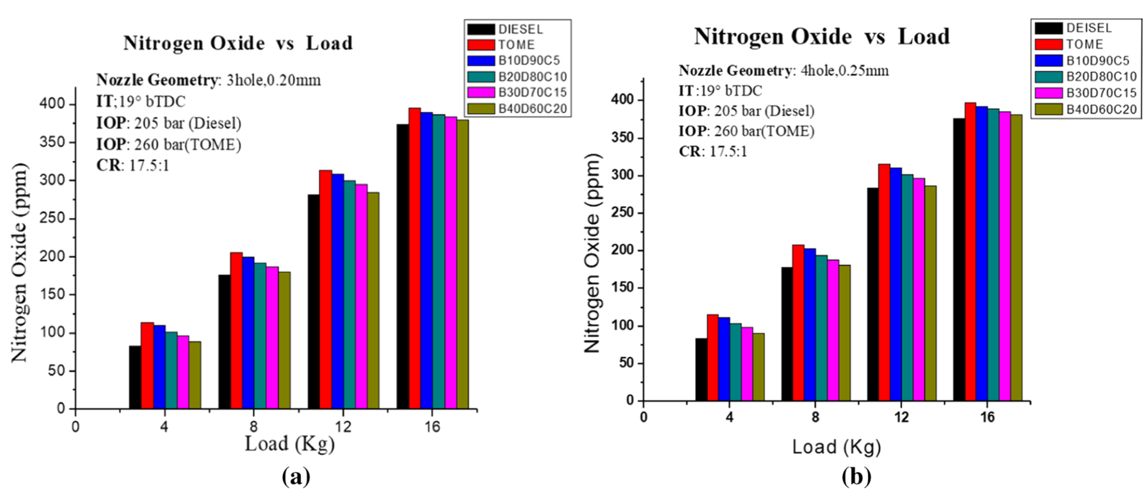

Fig. 11 NOx emissions variation with varying engine load for **a** 3 holes with a diameter of 0.2 mm **b** 4 holes with a diameter of 0.25 mm

Considering the nozzle number and hole diameter of the injector, it has been observed that lower NOx emissions are recorded when the engine is operated with an injector with a larger hole diameter. The reason for this can be attributed to the higher fuel droplet diameter in the fuel jets as a result of the atomization of the fuel at large nozzle diameters, and the shorter combustion duration as a result of the longer ignition delay. The large droplets of the sprayed fuels adversely affected the combustion process. Therefore, CO and HC emissions were recorded higher in the injector with a larger nozzle diameter. In addition, since the fuel could not burn completely, it was ejected from the exhaust without burning, and the temperature increase was measured relatively lower in this case. The low temperature also triggered a reduction in the formation of the NOx emissions for the injector with a large diameter.

Smoke density

Figure 12 illustrates the variation of smoke density concerning load for various diesel fuels, TOME & CNTs added TOME biodiesel blends at CR 17.5:1 for 3-hole fuel injectors having 0.20 mm diameter and for 4-hole fuel injectors having 0.25 mm. MWCNT nanoparticles have a large asymmetric surface area of 180 m^2/g and therefore act as an activated reaction site for air and fuel molecules (Soudagar et al. 2019). The higher thermal conductivity of MWCNT (5000 W/m.K) allows the nanoparticles to transfer sufficient heat to individual molecules of the combustion product placed on the additive surface and thus enhances the oxidation of carbonaceous particles, leading to a significant reduction in the smoke emissions. At higher engine loads, the smoke emissions increase due to a large quantity of smoke entering the combustion chamber. For maximum load, the smoke emissions for the B40D60C20 fuel blend showed emissions, which were around 3.63% and 21.28% less than that of diesel fuel and TOME biodiesel, respectively for 3 holes and the nozzle diameter of 0.20 mm.

On the other hand, the B40D60C20 fuel blend showed smoke emissions, which were around 3.86% and 22.97% less than that of diesel fuel and TOME biodiesel, respectively. Thus, the smoke emissions for B40D60C20 were comparable to neat diesel fuel at all loads. Furthermore, the lower ID period of the nano fuel blends also resulted in a faster-premixed combustion phase, which caused a reduction in smoke emissions.

Summary of the experimental results

The optimized fuel conditions were obtained for the blend B40D60C20, at nozzle geometry 3 holes, 0.20 mm diameter, injection of the pressure of about 260Bar, at 19 bTDC, where appreciable enhancement in Brake thermal efficiency and reduction is obtained. The B40D60C20 fuel blend showed smoke emissions, which were around 3.86% and 22.97% less than that of diesel fuel and TOME biodiesel, respectively.

Regression equations using response surface methodology (RSM)

Table 6 shows the ANOVA results and fit statistics for BTE. The model for BTE is significant, with an F value of 889.17 and a p-value of less than 0.0001. Furthermore, the R^2 value of 0.9940 (see Table 7) is near to a positive one, and the predicted and modified R^2 are in good agreement. The ANOVA table's p values reveal that both load and engine blends are significant. However, when compared to engine blends, the load contributes significantly to aggregated changes, with a

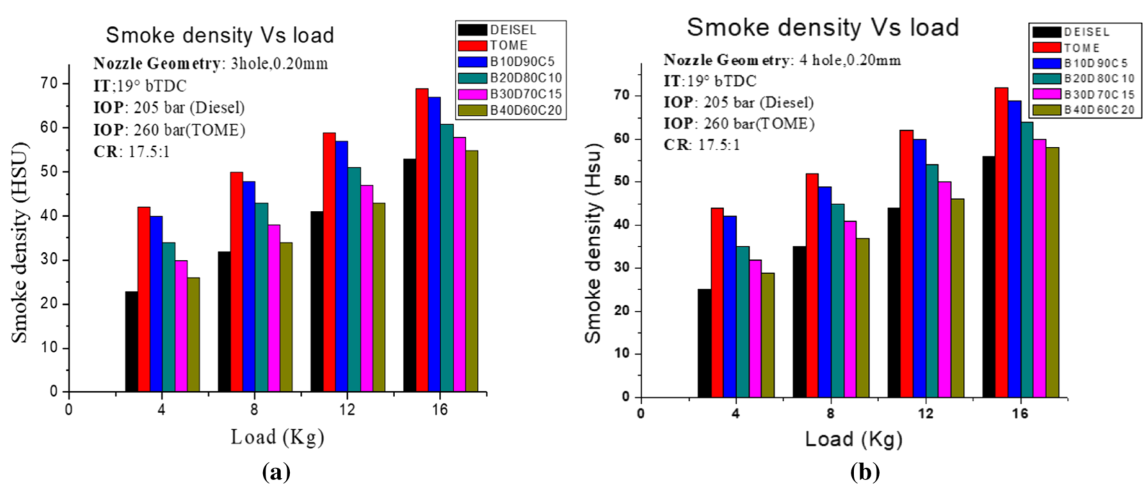

Fig. 12 NOx emissions variation with varying engine load for **a** 3 holes with a diameter of 0.2 mm **b** 4 holes with a diameter of 0.25 mm

Table 6 ANOVA Results (NOx emissions)

Source	Sum of squares	df	Mean square	F-value	p-value		PC (%)
Model	2.331E+05	3	77,706.76	889.17	< 0.0001	significant	99.4
A-Load (Kg)	2.227E+05	1	2.227E+05	2548.56	< 0.0001		94.6
B-IOP(BAR)	353.95	1	353.95	4.05	0.0161		15.09
C-blends	1015.32	1	1015.32	11.62	0.0036		43.29
Residual	1398.28	16	87.39				
Cor total	2.345E+05	19					

Table 7 Coefficient of determination for NOx emissions

Std. Dev	9.35	R^2	0.9840
Mean	246.85	Adjusted R^2	0.9829
C.V. %	3.79	Predicted R^2	0.9800
		Adeq Precision	73.8054

PC per cent of 94.6. Due to the poor fit and aliased nature of linear and cubic models, the best fitting quadratic model from the fit summary was chosen. Equation (1) is the actual regression equation for BTE. For other responses, Table 8 can be referred.

Using the regression equation and actual values of the experiments, Fig. 13 is plotted. It can be seen that there is a good agreement between the actual and predicted values.

Artificial neural network (ANN) modelling

The human brain is the source of motivation for the ANN. The brain is made up of a large number of processing units that are linked together like a network. "Brain Cells" or "Neurons" are the names given to these groups. An ANN is trained to find a connection between a system's inputs and desired output These networks, like human brain cells, are made up of structural elements called neurons. These are very basic computing elements that make up the layers, and the relationship between them defines the network's efficiency. Neurons are organized in such a way that the output of each layer's neuron is weighted and then serves as the input for the next layer. The number of hidden layers and neurons in each hidden layer can be calculated by trial and error (Kattimani et al. 2020), however, the number of dependent and independent variables is dictated by the problem at hand (Janardhana et al. 2021). An activation function, also known as a transfer function, is present in each neuron in the hidden and output layers. The hyperbolic tangent sigmoid transfer function is used in hidden layers instead of a linear function in the output layer. The neuronal outputs are calculated using these activation functions.

In this analysis, ANN was used to predict the performance and emissions characteristics of the various biodiesels used in the engine. The ANN architecture is shown in Fig. 14. It consists of an input layer for the input parameters, hidden layers and an output layer for the responses. An ANN model was created using the trained (feed-forward backpropagation) training algorithm, learned adaptation learning function, and hyperbolic tansig as the transfer function to train the large datasets. MSE was also employed as a performance metric. The stopping criterion for the generated ANN model training was "hundred" iteration, "zero" error $1{*}e^{-4}$ gradient value, and "hundred" validation error number. During the training of ANN, in this paper, both input and output quantities were inserted into the framework. By comparing the test outcomes with the output values of the modelled network, the MSE is determined. The weight values between the nodes in the network were modified based on this error statement. The network is trained when the weight values converge. Figure 15 depicts the trained network model's training, validation, research, and general regression analyses.

In Tables 9 and 10, the correlation coefficient of ANN models is shown for testing, training, and validation data.

Table 8 Regression equation of engine outputs

Brake Thermal Efficiency (%)	= 17.90029 + 1.64122*Load (Kg) -0.063556 *IOP(BAR) + 0.342031*Blends	(1)
Nitrogen Oxide (ppm)	= -177.82812 + 15.42822*Load (Kg) + 0.764990*IOP(BAR) + 106.68043*Blends + 0.037098*Load (Kg) * IOP(BAR) -0.201456*Load (Kg) * Blends-0.421119*IOP(BAR) * Blends	(2)
Carbon monoxide (ppm)	= -0.00374323 -0.00738058 * Load (Kg) -6.65867e-07 * IOP(BAR) + 0.0227391 * Blends + 4.1903e-05 * Load (Kg) * IOP(BAR) + -0.000255633 * Load (Kg) * Blends + -8.58074e-05 * IOP(BAR) * Blends	(3)
Hydrocarbon (ppm)	= -11.333 -2.60727 * Load (Kg) + 0.0542163 * IOP(BAR) + 26.4043 * Blends + 0.0214709 * Load (Kg) * IOP(BAR) -0.196606 * Load (Kg) * Blends -0.0990256 * IOP(BAR) * Blends	(4)
Smoke density (HSU)	= -96.1506 + -4.02181 * Load (Kg) + 0.499936 * IOP(BAR) + 74.305 * Blends + 0.0273758 * Load (Kg) * IOP(BAR) + -0.155589 * Load (Kg) * Blends + -0.29326 * IOP(BAR) * Blends	(5)

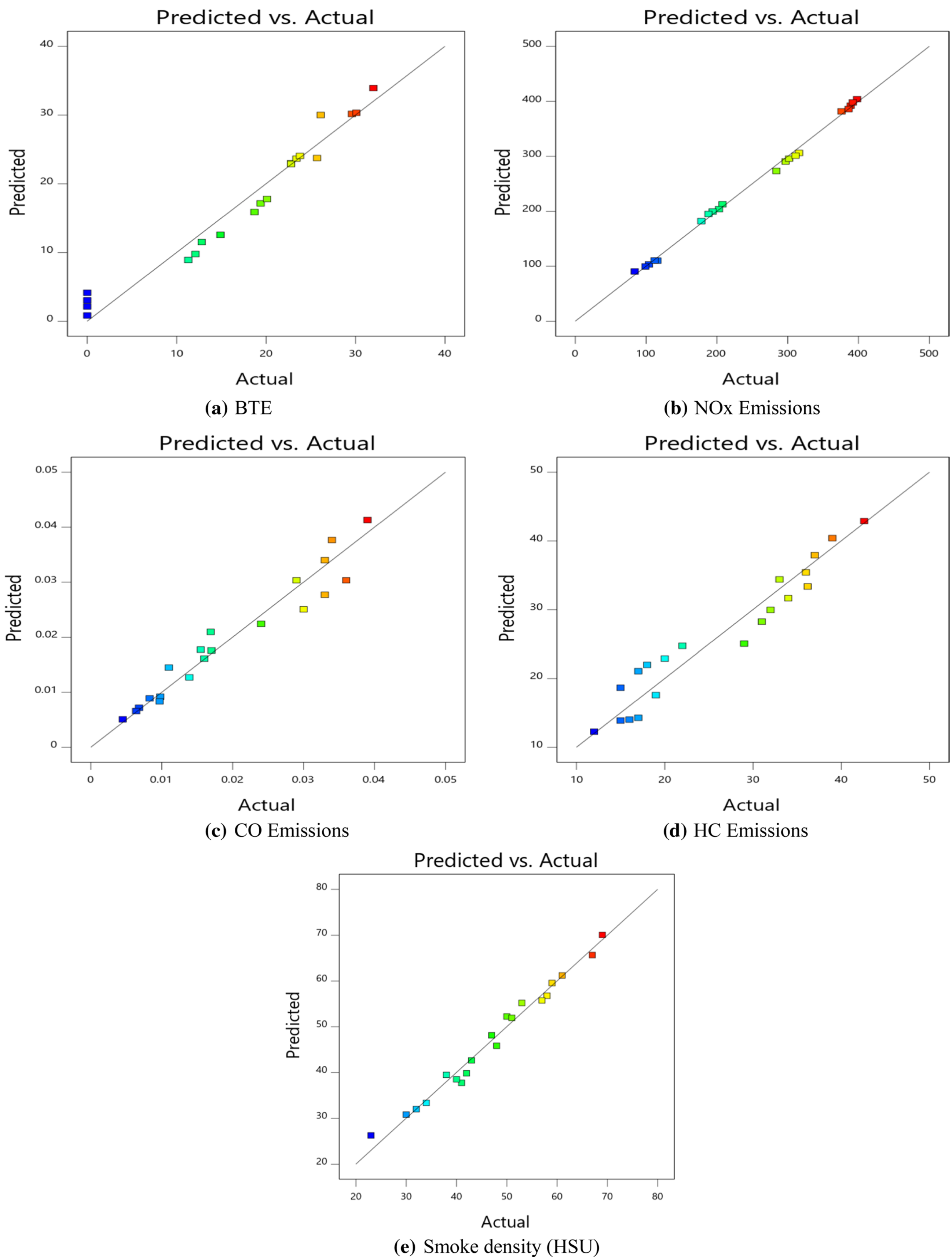

Fig. 13 **a–e** RSM modelling results vs. experimental results (efficiency and emissions)

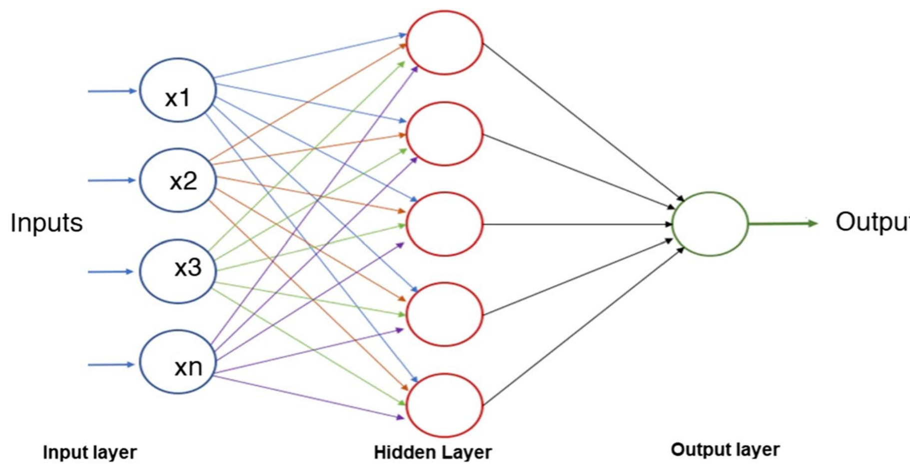

Fig. 14 ANN architecture

Table 9 ANN results for predicting *Brake Thermal Efficiency*

Number of Hidden layers	Neurons in the hidden layer	Modelling coefficient R^2			
		Training data	Validating data	Testing data	All data
1	10	0.98310	0.9930	0.98294	0.98435
1	15	0.98312	0.9932	0.98296	0.98437
1	20	0.98314	0.9934	0.98298	0.98441
1	25	0.98318	0.9938	0.98300	0.98445
1	**35**	**0.98321**	**0.9941**	**0.98303**	**0.984470.9840**
1	40	0.98320	0.9940	0.98302	0.98443

Bold values indicates the optimal network

Table 10 ANN results for forecasting *NOx emissions*

Number of Hidden Layers	Neurons in hidden layer	Modelling coefficient R^2			
		Training data	Validating data	Testing data	All data
1	10	0.99552	0.94894	0.99810	0.98230
1	15	0.99556	0.94896	0.99812	0.98234
1	20	0.99560	0.94898	0.99816	0.98236
1	30	0.99562	0.94900	0.99818	0.98238
1	**40**	**0.99566**	**0.94906**	**0.99822**	**0.98242**
1	50	0.99562	0.94902	0.99814	0.98240

Bold values indicates the optimal network

The ANN was trained iteratively to reduce the Mean Squared Error (MSE) performance function between the ANN outputs and the target data. It can be shown that ANN modelling with fewer neurons in the hidden layer correctly estimates the efficiency and emissions features in all cases (with the partial data). Nevertheless, 35 neurons and 40 neurons in the hidden layer framework were employed to simulate the ANN modelling outcome for Brake Thermal Efficiency (related to Fig. 7) for 3 holes and 240 Bar IOP and NOx emissions concerning load for various diesel, TOME & CNTs added TOME oil blends at CR 17.5:1 and 4-hole fuel injector having 0.25 mm diameter at 260 Bar IOP, respectively, due to the optimal value of the modelling coefficient as shown in Fig. 15. The test data is compared to the expected data obtained from ANN (Fig. 16). As can be seen, ANN's estimation of the results is significantly better.

Based on the results achieved from RSM and ANN results, it is noticed that the performance and emissions characteristics of the engine can be accurately predicted.

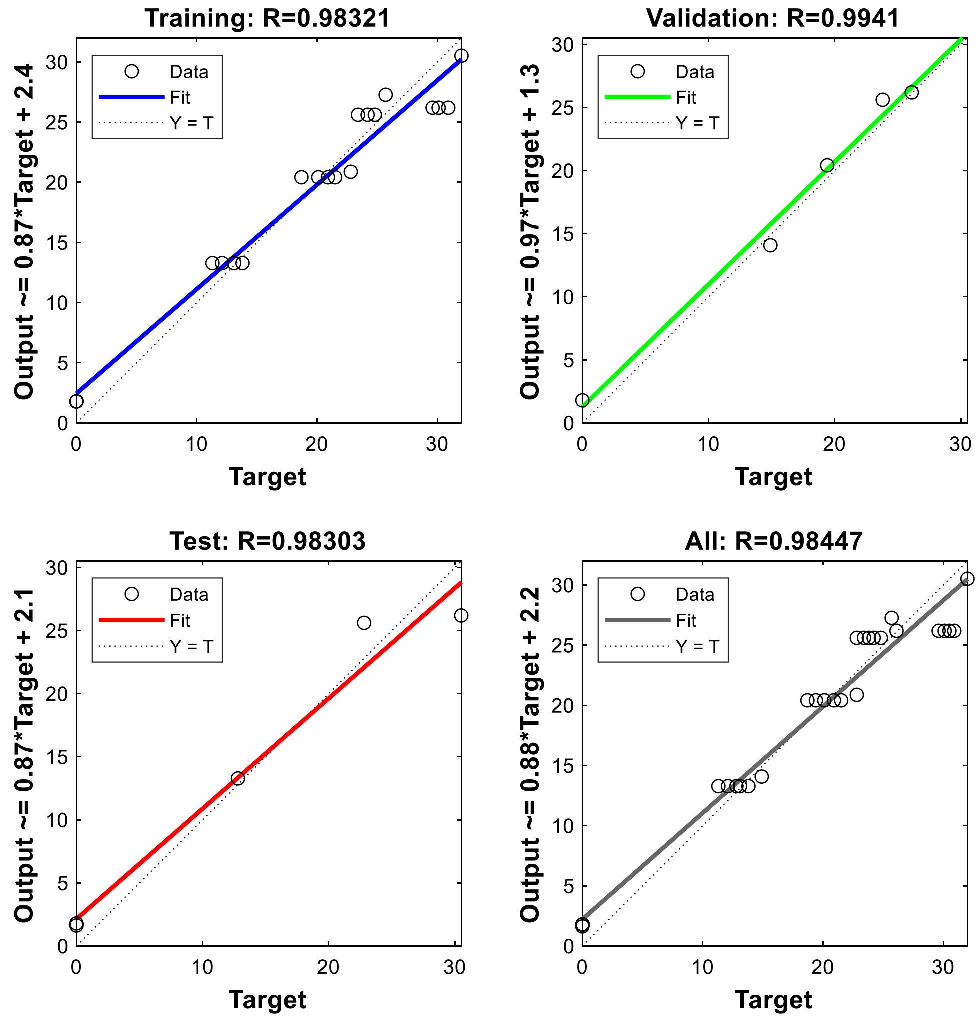

Fig. 15 Neural network training regression analysis (Optimal performance at 35 neurons in hidden layer for brake thermal efficiency)

Conclusions

From the research work, the following conclusions were drawn for the performance and emissions characteristics of single-cylinder diesel engine operation fuelled with a mixture of Multi-Walled Carbon Nanotubes (MWCNT) and Tallow Oil Methyl Ester (TOME) in different injector nozzle diameter and hole number.

1. Comparing fuel characteristics at different operating conditions, the optimized fuel conditions obtained for blending ratio B40D60C20 at nozzle geometry 3 holes, 0.20 mm diameter, injection of the pressure of about 260Bar, where a moderate increase in brake thermal efficiency and reduction in emissions were obtained.
2. Comparing brake thermal efficiency and emissions for 3-hole and 4-hole nozzle geometries showed that 4-hole nozzle geometry, due to its irregular nozzle geometry, decreased the brake thermal efficiency with an increase in emissions to 3-hole nozzle geometry.
3. As the injector nozzle diameter gets smaller, the injection parameters improve, resulting in an improvement in the test engine's performance and emissions characteristics.
4. When the engine runs with a big nozzle diameter, the NOx emissions are recorded as lower than that of smaller nozzle diameter. The reason behind it can be attributable to the worsening injection parameters, leading to deteriorating the combustion process. With the combustion process's deterioration, the fuels cannot be adequately burnt, and the in-cylinder temperature does not increase. Because of this case, NOx emissions are measured for the injector with a bigger nozzle diameter.
5. A small nozzle diameter ensures better atomization by getting a smaller fuel droplet diameter, leading to

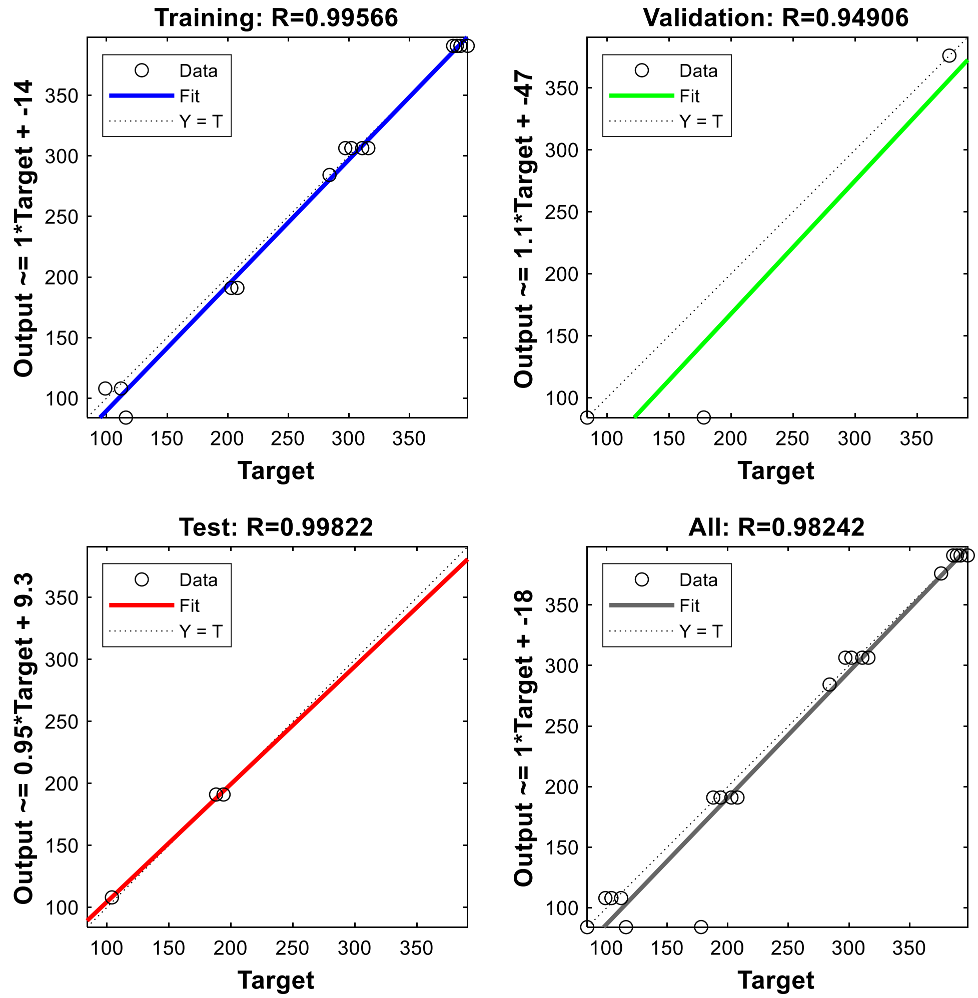

Fig. 16 Neural network training regression analysis (Optimal performance at 35 neurons in hidden layer No_x emissions

a better air–fuel ratio and improving the combustion process. Accordingly, a small nozzle diameter in the injector is reasonable for performance and emissions characterization.

6. MWCNT acts as an oxygen buffer and oxidizes more unburnt fuel in the combustion chamber. Accordingly, with the presence of MWCNT in the fuel, incomplete combustion emissions such as CO, HC, and smoke can be noteworthy reduced.
7. MWCNT improves the energy density of TOME biodiesel fuel and accelerates the chemical reactions during the combustion phase. Accordingly, TOME initially drops the brake thermal efficiency, but then it can be pulled back with the addition of MWCNT.
8. Thanks to higher thermal properties and lower fuel consumption due to the addition of MWCNT nanomaterials, NOx emissions are reduced compared to that of TOME biodiesel.
9. The engine's performance and emissions characteristics can be predicted with a high R^2 value, and future studies can use the given equation in comparing their prediction results.
10. The optimized diesel–biodiesel-CNT fuel blend B40D60C20 compared to the TOME fuel showed an enhanced brake thermal efficiency and was nearly equivalent to diesel fuel. The B40D60C20 blend, because of the catalytic effect of multiwall carbon nanoparticles, showed a maximum brake thermal efficiency of 30.9%, which is 15.53% higher than the pure TOME blend and 3.43% less than diesel at economic load.
11. The addition of 20 mg/L MWCNT in TOME blends, the B40D60C20 blend, revealed reduced Emissions as CO by 45.46%, HC by 17.29%, NOx by 5%, and smoke by 21.28% when compared with raw TOME. Further, the emissions were also comparable to neat diesel fuel

at all loads. The concentration of 20 ppm of MWCNTs in TOME shorter the ignition delay and increases the heat release.

12. Furthermore, fuel mixture MWCNT and TOME biodiesel characteristics show that they can be used in internal combustion engines without any modification in the engine configuration. The dual operation with the MWCNT and TOME biodiesel show improved performance with lower emissions. Also, we can notice similar results presented in the open literature.
13. RSM and ANN models were used for the output predictions with good accuracy without actually carrying out the experiments, saving time and money used to carry out the experiments. In addition, ANN's prediction performance was somewhat better than RSM's
14. The results of the ANOVA analysis demonstrated that all three parameters had a substantial impact on NOx emissions. RSM was used to create regression equations for NOx emission, which can be used as objective functions in optimization experiments.
15. The optimized fuel combinations with the optimized nozzle geometry will lead to better IC engine performance.

Limitations

In today's technology, the high cost of nanoparticles and the problem of sedimentation and agglomeration in the test fuel over time are limitations that prevent the widespread use of nanoparticles along with conventional test fuels.

Future scope

TOME biodiesel and diesel blends operation with some other additives to improve performance can be carried out. The other numerical methods (CFD) should be used to carry out complicated combustion analysis. Optimization algorithms of meta-heuristic nature can be used, integrated with ANN & RSM and can be explored for optimized prediction of the biodiesel performance and emission characteristics. Not even a single study addresses the optimized membership function, the number of neurons or hidden layers in the literature. This has to be explored in detail in future studies to obtain optimized biodiesel performance and emission parameters. Furthermore, future works may work on eliminating the problems of sedimentation and agglomeration for nanoparticles in the fuels.

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Declarations

Conflict of interest None.

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