

# Experimental investigation of CRDi diesel engine performance using neem biodiesel with a mixture of Al<sub>2</sub>O<sub>3</sub> and ZnO nano fuel additives

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## Abstract:

For many years, biodiesel has been seen as an alternative fuel with the ability to eventually replace diesel. Products that are emitted when engines undergo a complete combustion reaction provide no direct health risks to humans. Due to certain fuel characteristics, biodiesel performs poorer during combustion process than diesel fuel. As a result, smoke emissions, complete combustion products like CO<sub>2</sub>, and incomplete combustion products including HCs, CO, and NO<sub>x</sub> are released into surrounding. An attempt has been made to enhance combustion and emission performance of CRDi-VCR type diesel engine using B20 neem biodiesel with a novel nanoparticle mixture of Al<sub>2</sub>O<sub>3</sub> and ZnO as nano fuel additives for various dosing levels. B20 Neem biodiesel with nano additives was tested on a CRDi-VCR type diesel engine at a constant speed of 1500 rpm at various loads. Due to higher oxidation rate of hydrocarbon molecules, the nano additive reduced CO emissions in studies while improving the thermal conductivity, mass dissipation, and heat transfer of the tested nano fuels. Due to the improvement in the combustion reaction, CO<sub>2</sub> emission increased with product of complete combustion. Brake specific fuel consumption was reduced at full load condition with the addition of 25 ppm NPs. Also, neem biodiesel fuel results in appreciably improved brake thermal efficiency, lower values of smoke opacity, and lower CO, NO<sub>x</sub> and HC emissions.

**Keywords:** Nano-fuel additives; Neem biodiesel; Diesel engine performance; Emission characteristics; Combustion performance.

## 1. Introduction

Since their discovery, fossil fuels have powered most of mankind's energy needs, allowing us to flourish and prosper, especially in the decades after the Industrial Revolution. However, emissions from fossil fuels have surged due to their extensive or mostly unregulated usage, hastening the onset of climate change and global warming much beyond expectations. Scholars have engaged in discourse regarding the diminishing petroleum reserves juxtaposed with the escalating demand for energy supply in recent years. There is now a growing focus on energy sources that are sustainable, ecologically friendly, economical and efficient. The demand for sustainable energy sources has arisen due to the repercussions of escalating environmental contamination.

Diesel engines are essential in underdeveloped countries because they last longer, are more reliable, and get more mileage than SI engines [1-3]. The fuel needs of majority of transport vehicles are met by diesel, accounting for approximately 69%, while petrol accounts for 31% [4]. Fig. 1 demonstrates the quarter-wise sale of diesel and petrol through retail outlets across India between October 2020 to September 2021. The residual requirement is fulfilled by alternative fuels like liquefied petroleum gas (LPG), and compressed natural gas (CNG), which have continually experienced an increase in demand.

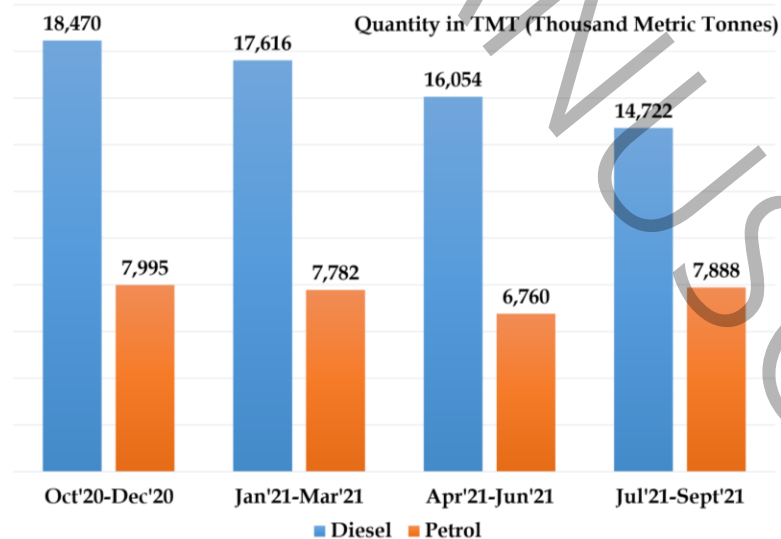
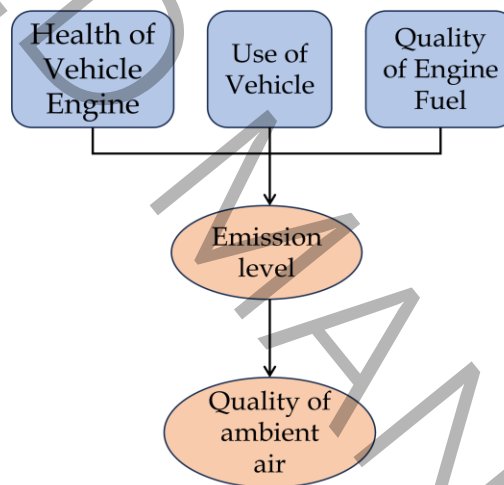


Fig. 1. Quarter-wise sale of diesel and petrol through retail outlets across India [4]

As per the Energy Information Administration of United State, the overall primary consumption in Asia accounted for 40% of the consumption during the preceding decade [5]. The substantial rise in global energy

demands suggests that the dependence on oil resources will persistently rise in the coming years. Furthermore, the accumulation of harmful contaminants in the environment is being worsened by the excessive usage of fossil fuels [6]. Globally, the automotive and energy industries are the primary contributors to atmospheric pollution [7].

According to studies conducted by the World Health Organization (WHO), three million people die every year as a result of air pollution [8]. Fig. 2 illustrates the elements responsible for generating air pollution because of the rising amount of on road vehicles [9]. In light of these difficulties, people are exploring potential alternatives to fossil fuels, such as renewable energy sources for use in areas such as internal combustion (IC) engines, transportation and mobility, and power generation.



**Fig. 2.** Factors affecting the quality of ambient air [9]

The seventeen objectives of the United Nations Sustainable Development Goals (UNSDGs) [10-12] are the following: sustainable and cheap energy; action on climate change; and responsible consumption and production. For the sake of progress in commerce, communication, education, healthcare, and transportation, society must ensure that all people have access to clean, inexpensive energy. Clean energy infrastructure and technology, investments in renewable energy sources, and energy-efficient practices can help governments speed up this process. It is necessary to implement the circular economy in order to decrease waste and make consumption and manufacturing more affordable. In this model, one process's trash is used as raw material for another's, or as a by-product that may be used for further purposes.

Amidst the G20 conference in New Delhi, India in September 2023, the Global Biofuels Alliance was formed. This initiative, led by India, seeks to unite governments, international organizations, and businesses in promoting the adoption of biofuels [13]. Biofuel is a phrase that describes hydrocarbons produced from organic materials through certain methods. Biodiesel and bioethanol are the two predominant kinds of biofuels, with the former being the main focus of this study.

The use of biodiesel fuels as a viable and environmentally friendly substitute for traditional petroleum diesel has received significant attention in more recent research studies [14]. A multitude of researchers are now investigating various facets of biodiesel production and use in response to the growing need for clean and sustainable sources of energy [15, 16]. Methyl ester is extracted from several sources, including animal fats such as lard, and both edible and non-edible oils and waste cooking oils.

The making process of biodiesel leads to the enhancement of fuel characteristics and combustion performance. Differences in the biodiesel manufacturing procedures and compositions of catalysts can lead to variations in fuel qualities, including density, viscosity, cetane number, flash point, fire point and decreased calorific value [17]. Considerable disparities in generation of torque and power, ignition delay time, exhaust emissions characteristics, and even pressure and temperature of the engine combustion chamber can be observed depending on the type of biodiesel utilised [18].

Modi and Gosai [19] conducted an experimental study using a low-heat rejection diesel engine coated with Partially stabilized zirconia (PSZ) fueled with Palm biodiesel. Utilizing palm biodiesel led to reduced emissions of particulate matter, carbon monoxide, and, unburned hydrocarbons while there was a slight rise in emissions of nitrogen oxides. Hwang et al. [20] performed a thorough examination of the microstructure of soot produced by burning waste cooking biodiesel in a compression ignition engine. The researchers found that the level of aggregation of the soot particle is lower with biodiesel.

Modi and Patel [21] conducted an empirical investigation utilizing a low-heat rejection diesel engine that was coated with Magnesium Zirconate ( $MgZrO_3$ ) and fueled with Neem biodiesel. They witnessed a decrease in the release of particulate matter, carbon monoxide, and unburned hydrocarbons with the application of Neem biodiesel. In addition, they noted a significant rise in nitrogen oxides (NOx). Despite

the renewable nature of biofuels and their potential to lower emissions from engines compared to fossil fuels, comprehensive life cycle assessments are necessary for environmentally responsible growth [22].

To reduce exhaust emissions, Modi et al. [23] ran an experiment to see how different rates of exhaust gas recirculation (EGR) affected emissions of nitrogen oxides (NO<sub>x</sub>) and smoke from an adiabatic diesel engine that ran on a mixture of diesel and neem biodiesel. At 5% EGR with TB10, the results indicated a reduction of smoke opacity and emission in nitrogen oxides by 15% and 26% correspondingly. Moreover, the combination of TB20 with 10% EGR proved to be effective in decreasing smoke opacity and emission in nitrogen oxides by 30% and 34% correspondingly, in comparison to CI engine without EGR.

Biodiesel fuel is currently garnering growing global interest as a constituent of oil blends or as a direct substitute for diesel fuel in automobile engines. Almost all diesel machinery, including distribution and storage vehicles, is said to be compatible with biodiesel blends up to B20 [24]. Typically, no engine modifications are required for these low-level blends. However, many engines built with little or no modifications can utilize heavier mixes or B100 oils [25]. Oxygen content of 10% in biodiesel enhances combustion and decreases hydrocarbon, carbon monoxide, and soot emissions, while to some extent raising NO<sub>x</sub> emissions.

To address these concerns, recent studies on the subject have focused on using non-edible plant oils. There are an enormous variety of nonedible oil crops in environment such as jatropha tree (*Jatropha curcas*), palm (*Elaeis guineensis*), linseed (*Linum usitatissimum*), castor (*Ricinus communis*), karanja (*Paullinia pinnata*), mahua (*Mangifera indica*), rice bran (*Oryza Sativa*), neem (*Azadirachta indica*), rubber plant (*Hevea brasiliensis*), microalgae, kusum (*Schlechera trijuga*), and tobacco seed (*Nicotiana tabacum L.*) [26]. Considerable study has been conducted on the jatropha oil and palm oil in connection to the production and performance of biodiesel from non-edible oils [19, 27-32].

Edible oils cannot be utilised in the manufacturing of biodiesel in India because the country is net importer of vegetable oils. India is a major international producer of neem oil. Neem seeds contain more than 30% of the oil content. It represents an unexplored reservoir in India [33-36]. The principal focus of the present work will be on biodiesel derived from the oil of the neem tree (*Azadirachta indica*). The use of biodiesel

in India has numerous potential benefits, such as reforestation of degraded land, bolstering of rural economies and agriculture, less reliance on foreign crude oil, and less air pollution [35]. Neem tree is a rapidly developing agricultural plant with a productive lifespan of 150-200 years. The neem tree exhibits remarkable resilience in the face of drought and arid soil conditions, withstanding temperatures as high as 44°C and as low as 4°C as concluded by Karmakar et al. [37]. The seeds of the neem tree have a substantial oil content ranging from 39.7% to 60% [38]. The annual fruit yield of a well-grown neem tree ranges from 30 to 50 kg [39]. The above-described attributes of neem oil plants and the fatty acid makeup of the oil render it a valuable renewable resource for the industry of biodiesel generation. These features largely influence the choice of neem biodiesel for the present study. Table 1 summarizes some of the important research on the performance and emissions of diesel engines running on mixes of biodiesel derived from neem oil.

**Table 1.** Summary of the literature on neem oil-based biodiesels

Reference	Blend of neem oil-based biodiesel utilised	Observations
Karmakar and Mukherjee [37]	B20, B50 and B100	<ul style="list-style-type: none"> <li>The rate of decrease in CO, HC, and Smoke opacity was increased with increase in biodiesel blend.</li> </ul>
Nair et al. [40]	B10, B20 and B30	<ul style="list-style-type: none"> <li>Compared to diesel, a 34% rise in BTE was realized with B10.</li> <li>The rate of decrease in CO, HC, and Smoke opacity was increased with increase in biodiesel blend.</li> </ul>
Rathinam et al. [41]	B80 with 20% butanol, B90 with 10% butanol, B100	<ul style="list-style-type: none"> <li>Inclusion of 20% of butanol, reduces the CO, HC, NOx, and Smoke, by 5.9%, 8.6%, 10.4%, and 6.8% respectively.</li> </ul>
Chaudhary [42]	B45 with 5-15% diethyl-ether	<ul style="list-style-type: none"> <li>Inclusion of 15% diethyl-ether in B45, raised exergy efficiency by 6.8% and demonstrated 56% reduction in NOx emission.</li> </ul>
Vinod and Karthikeyan [43]	B20 with 10% hexanol, B20 with 20% hexanol, B20 with 30% hexanol	<ul style="list-style-type: none"> <li>A significant rise in CO, HC, smoke, and NOx caused the BTE to decrease as the concentration of hexanol in neem oil biodiesel (B20) increased.</li> </ul>

Researchers are now exploring the possibility of using biodiesel and other partially added clean-burning supplemental fuels in a dual-fuel configuration. Recently, there has been a surge in interest in using nano-additives to reduce emissions [44-46]. Various fuel additives were employed to enhance oxidation stability, cold flow properties, corrosion resistance during prolonged fuel storage, deposit formation, and

contamination prevention [47, 48]. Gosai et al. [49] represents a classification, and examples of various types of fuel additives, including their corresponding characteristics. Typically, fuel additives are mixed with the fuel in a small amount, usually between 20 and 500 parts per million (ppm). However, due to their small size, additives face difficulties during settling particles, clumping together, and the uneven distribution of particle sizes. Siltation, aggregation, and uneven particle size distribution are some of the problems that microscale additions face.

The blend of biodiesel and conventional diesel fuels with nano additives show great potential for future enhancements in their effectiveness. [6, 50, 51]. Different numerical and experimental studies were performed by various researchers to explore thermo-fluid characteristics of nanofluids comprising  $Al_2O_3$ , ZnO, CuO,  $SiO_2$ , and  $AgO_2$  nanoparticles [52-57]. They evaluated various characteristics involved in augmenting thermo-fluid performance like thermal conductivity, and viscosity. In comparison to more traditional fluids, nanofluids exhibit greater stability due to size-dependent processes and the erratic movement of nanoparticles.

The nanoparticles in the biodiesel improve ignition characteristics and serve as a catalyst. Table 2 summarizes the results of the comparisons concerning the effects of biodiesel incorporated with various nanoparticles on the engine and emission performance running under various conditions.

**Table 2.** Summary of the nanoparticles affecting the performance and emission characteristics of a CI engine

Ref.	Engine type	Base fuel (Diesel / Biodiesel)	Nano-particles	Operating condition (RPM)	Engine performance		Emission performance			
					BTE	BSFC	CO	HC	NOx	Smoke
Gosai et al. [9]	2-cylinder 4- stroke, DI, WC	Diesel	$Al_2O_3$ , ZnO	1500	Rise (29.33% - 34.5%)	Reduce (14.98% - 11.91%)	Reduce (4.69%- 20.04%)	Reduce (1.15%- 7.17%)	Reduce (10.25%)	Reduce (4.44%- 20%)
Sadhik and Anand [58]	4-stroke, Single Cylinder, DI, AC	Jatropha	$Al_2O_3$ , CNT, $Al_2O_3$ + CNT (25 ppm, 50 ppm)	1500	Highest for $Al_2O_3$ + CNT blend	Decrease	Decrease	Decrease	Decrease	Lowest for $Al_2O_3$ + CNT blend
Prabu [59]	4-stroke, Single Cylinder, DI, AC	Jatropha	$Al_2O_3$ , $CeO_2$ (30 ppm)	1500	Increase (3-4%)	Decrease (1-2%)	Decrease (40-50%)	Decrease (33%)	Decrease	-
Sajith et al. [60]	4-stroke, Single	Jatropha	$CeO_2$ (20-80 ppm)	1500	Increase (1.5%)	Decrease	Decrease	Decrease (25-40%)	Decrease (30%)	-

	Cylinder, DI, WC										
Vellaiyan and Partheeban [61]	4-stroke, Single Cylinder, DI	Soya-bean	ZnO (100 ppm)	-	-	-	Decrease (40%)	Decrease (33.3%)	Decrease (41.4%)	Decrease (28.3%)	
Agbulut et al. [62]	4-stroke, Single Cylinder, DI, AC	Waste cooking oil	TiO <sub>2</sub> , SiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> (100 ppm)	2000	-	-	Decrease	Decrease	Decrease	Decrease	
Youssef and Ibrahim [63]	4-stroke, Single Cylinder, DI	waste cooking oil biodiesel	ZnAl <sub>2</sub> O <sub>4</sub> (100 ppm)	-	Increase (2-5%)	Decrease (3%)	-	-	-	-	
Ozgun et al. [64]	4-stroke, 4-Cylinder, DI, WC	Rape-seed	MgO (25 ppm, 50 ppm)	1200-1300	Increase (6.8% for 25 ppm, 4.4% for 50 ppm)	-	Decrease	-	Decrease	-	
Aalam, Saravanan, Kannan [65]	4-stroke, Single Cylinder, DI, WC	Zizipus Jujube	Al <sub>2</sub> O <sub>3</sub> (25 ppm, 50 ppm)	1500	Increase (2.5%)	Decrease (6%)	Decrease	Decrease	Decrease	-	
Chandra-sekaran et al. [66]	4-stroke, Single Cylinder, DI, WC	Mahua (B20)	CuO (50 ppm)	1500	Increase	-	Decrease (15-20%)	Decrease (5-10%)	Decrease (2-5%)	Decrease (15-25%)	
Devarajan et al. [67]	Twin cylinder, DI, WC	Mahua	Magnetite (1% vol)	1300	Increase (2.27%)	Decrease (5.11%)	Decrease (32.6%)	Decrease (16.7%)	Decrease (9.02%)	Decrease (14.28%)	
Yuvarajan et al. [68]	4-stroke, Single Cylinder, DI, AC	Musturd	TiO <sub>2</sub> (100 ppm, 200 ppm)	1100	-	-	Decrease (8-13%)	Decrease (4.2%)	Decrease	Decrease	
Prabakaran and Udhoji [69]	4-stroke, Single Cylinder, DI	Diesel, Biodiesel, Ethanol	ZnO (250 ppm)	1500	Increase	Decrease	Decrease	Decrease	Decrease	Decrease	
Jayanthi and Rao [70]	4-stroke, Single Cylinder, DI	Linseed oil	CuO (40 ppm, 80 ppm, 120 ppm)	1500	Increase (3-4%)	Decrease	Decrease	Decrease	Decrease	-	
Annamalai et al. [71]	4-stroke, Single Cylinder, DI, WC	Lemongrass Oil	CeO <sub>2</sub> (30 ppm)	1500 RPM	Increase (17.2%)	Decrease	Decrease (15.6%)	Decrease (24.8%)	Decrease (6.4%)	-	

Integration of NPs into biodiesel or conventional diesel can optimize fuel characteristics like kinematic viscosity, caloric value, flash point, density, and cetane number, therefore achieving full combustion.

Aluminum is considered as the most suitable metal option, whereas carbon nanotubes are the preferred

choice for non-metal NPs. The presence of an ample supply of oxygen and the beneficial effects of NPs on the fuel properties can significantly enhance combustion efficiency, leading to decreased specific fuel consumption and dangerous air emissions. Wei et al. [72] experimentally investigated the use of aluminum oxide nanoparticles mixed with diesel-methanol. The addition of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) nanoparticles into the diesel-methanol mixture effectively mitigates the release of hydrocarbons,  $\text{CO}_2$ , and smoke, while somewhat augmenting the emission of  $\text{NO}_x$ . Furthermore, the engine's performance and fuel combustion are marginally improved. Experimental evidence demonstrates that the inclusion of  $\text{Al}_2\text{O}_3$  NPs in diesel-methanol fuel enhances the engine's overall performance and contributes to environmental cleanliness.

In their study, Gavhane et al. [73] found that the use of zinc oxide ( $\text{ZnO}$ ) nanoparticles in soybean biodiesel enhances crucial fuel characteristics. Furthermore, it improves the engine performance and decreases the BSFC by 20.37%. The addition of oxygen leads to a modest rise in  $\text{NO}_x$  emissions, whereas  $\text{CO}_2$ , smoke, HC, and CO emissions are reduced by 21.66 percent, 22.54 percent, 30.83 percent, and 41.08 percent correspondingly. Also, Table 3 summarizes the results of the previous studies on neem oil biodiesel with various types of nanoparticles.

**Table 3.** Summary of the literature on neem oil-based biodiesels with different nanoparticles

Reference	% Blend of neem biodiesel	Type of Nanoparticles	Observations
Senthil et al. [74]	B25	MnO FeCl <sub>3</sub>	<ul style="list-style-type: none"> <li>• Marginal rise in cylinder pressure and heat release rate with NPs.</li> <li>• Inclusion of MnO and FeCl<sub>3</sub> significantly lowers emissions of Nox, CO, and HC.</li> </ul>
Devarajan et al. [75]	BD100	Ag <sub>2</sub> O (5 and 10 ppm)	<ul style="list-style-type: none"> <li>• Rise in BTE was observed with the inclusion of Ag<sub>2</sub>O (10 ppm) from 26.6% to 28.4%.</li> <li>• Emissions reduced appreciably.</li> </ul>
Sakthivadivel et al. [76]	BD40 + Ethanol	Al <sub>2</sub> O <sub>3</sub> (25–50 ppm)	<ul style="list-style-type: none"> <li>• Significant improvement in an ignition temperature and the ignition delay with the inclusion of Al<sub>2</sub>O<sub>3</sub></li> <li>• Al<sub>2</sub>O<sub>3</sub> augment the performance and anti-knocking ability of the neem biodiesel.</li> </ul>
Balaji and Cheralathan[77]	BD100	Al <sub>2</sub> O <sub>3</sub> (100–300 ppm)	<ul style="list-style-type: none"> <li>• Maximum BTE was observed with 200 ppm</li> <li>• Emissions reduced appreciably.</li> </ul>
Sivasaravanan et al. [78]	B10, B20	Rice husk NPs (0.1%)	<ul style="list-style-type: none"> <li>• Inclusion of 0.1% NPs, augment BTE by 8.3% for B20</li> <li>• BSFC reduced by 6.1%.</li> </ul>

			<ul style="list-style-type: none"> <li>•With 0.1% of NP, About 10%, 11.2%, and 11.9% reduction in NO<sub>x</sub>, HC, and CO were observed, respectively.</li> </ul>
Durairaj et al. [79]	B10, B20, B30, B40	CeO <sub>2</sub> (5%)	<ul style="list-style-type: none"> <li>•An appreciable reduction in emission and BSFC observed for B20 with the inclusion of CeO<sub>2</sub> (5%)</li> </ul>
Rathinam et al. [80]	BD100	CeO <sub>2</sub> (100 ppm)	<ul style="list-style-type: none"> <li>•Compared with BD100, the reduction in HC, NO<sub>x</sub>, and CO by 3.6%, 3.6%, and 4.2%, respectively was observed with BD100 + CeO<sub>2</sub></li> </ul>
Devaraj et al. [81]	B100	TiO <sub>2</sub> (100 and 200 ppm)	<ul style="list-style-type: none"> <li>•Inclusion of TiO<sub>2</sub> significantly lowers emissions of No<sub>x</sub>, CO, and HC.</li> </ul>
Ramakrishnan et al. [82]	B10	CNT (50 and 100 ppm)	<ul style="list-style-type: none"> <li>•Inclusion of CNT (100 ppm) lowered HC, smoke, CO, and NO<sub>x</sub> by 6.7%, 7.8%, 9.2%, and 5.9%, respectively compared of B10.</li> </ul>
Ramesha et al. [83]	B20	CNT (25, 50, and 100 ppm)	<ul style="list-style-type: none"> <li>•B20 with 50 ppm of CNT had the highest BTE with lower emissions compared to other fuels.</li> <li>•Inclusion of CNT (50 ppm), enhanced BTE by 8.1%.</li> <li>•Emission of CO and HC reduced by 0.078% and 8.15% respectively.</li> </ul>

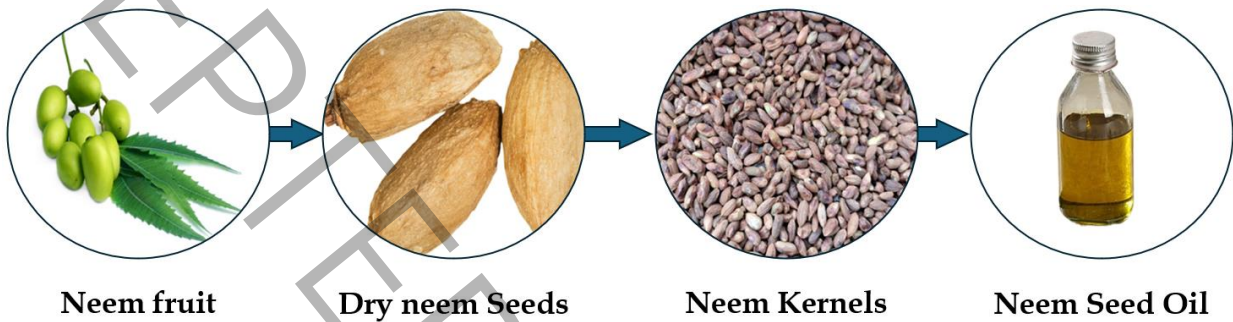
According to the reviewed literature, there is a lack in information regarding investigated neem biodiesel with a mixture of Al<sub>2</sub>O<sub>3</sub> and ZnO nanoparticles. Furthermore, there is a dearth of data on the efficiency of combustion and emissions from a Common Rail Direct injection (CRDi) engine that is a single-cylinder, four-stroke diesel engine of the Variable Compression Ratio (VCR) type and runs on transesterified neem biodiesel with a mixture of Al<sub>2</sub>O<sub>3</sub> and ZnO nanoparticles added to the fuel. This motivated the authors to conduct the current study. The following are the primary aims of the current experimental investigation:

1. To study the effects on diesel engine performance of adding a mixture of Al<sub>2</sub>O<sub>3</sub> and ZnO NPs to B20 Neem biodiesel. This will be done by looking at metrics like BSFC and BTE.
2. To evaluate the efficiency of the combustion process by looking at combustion characteristics like in-cylinder pressure and exhaust gas temperature rate.
3. To analyze the emission characteristics of a CI engine by measuring smoke density, CO, CO<sub>2</sub>, HC, and NO<sub>x</sub> emissions from the exhaust gases.

## 2. Materials and Methods

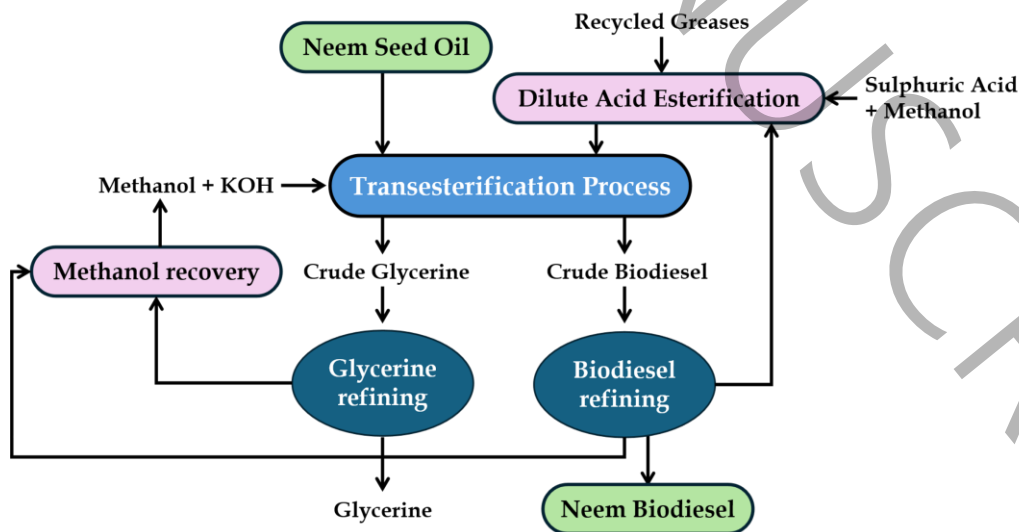
### 2-1- Biodiesel preparation

Biodiesel is traditionally synthesized by the process of transesterification of vegetable oil feedstock, which can be either edible or non-edible. For the current study, neem seed oil is extracted from the dried neem seed kernel as shown in Fig. 3.



**Fig. 3.** Neem seed oil extraction

In this study, biodiesel was synthesized in a laboratory setting using non-edible neem oil using a transesterification process with methanol, with potassium hydroxide (KOH) serving as the catalyst. Fig. 4 depicts the transesterification process utilised in current study to produce neem biodiesel. The biodiesel was prepared in the laboratory at Chemical Engineering Department, Government Engineering College, Bharuch. The characteristics of petroleum diesel and Neem biodiesel examined for the experimentation are presented in Table 4.



**Fig. 4.** Neem biodiesel production using transesterification process

**Table 4** Characteristics of diesel and Neem biodiesel [84]

Properties	Unit	Diesel	Neem Biodiesel	Standard
Specific gravity @ 15°C	gm/cc	0.8396	0.8589	ASTM D3142
Net calorific value	MJ/kg	44.421	39.095	ASTM F976
Cetane number	-	54.6	57.1	ASTM D613
Kinematic viscosity @ 40°C	cSt	4.84	5.21	ASTM D445
Flash point	°C	52	127	ASTM D976
Pour point	°C	-33	9	ASTM D97

## 2-2- Nano fuel preparation

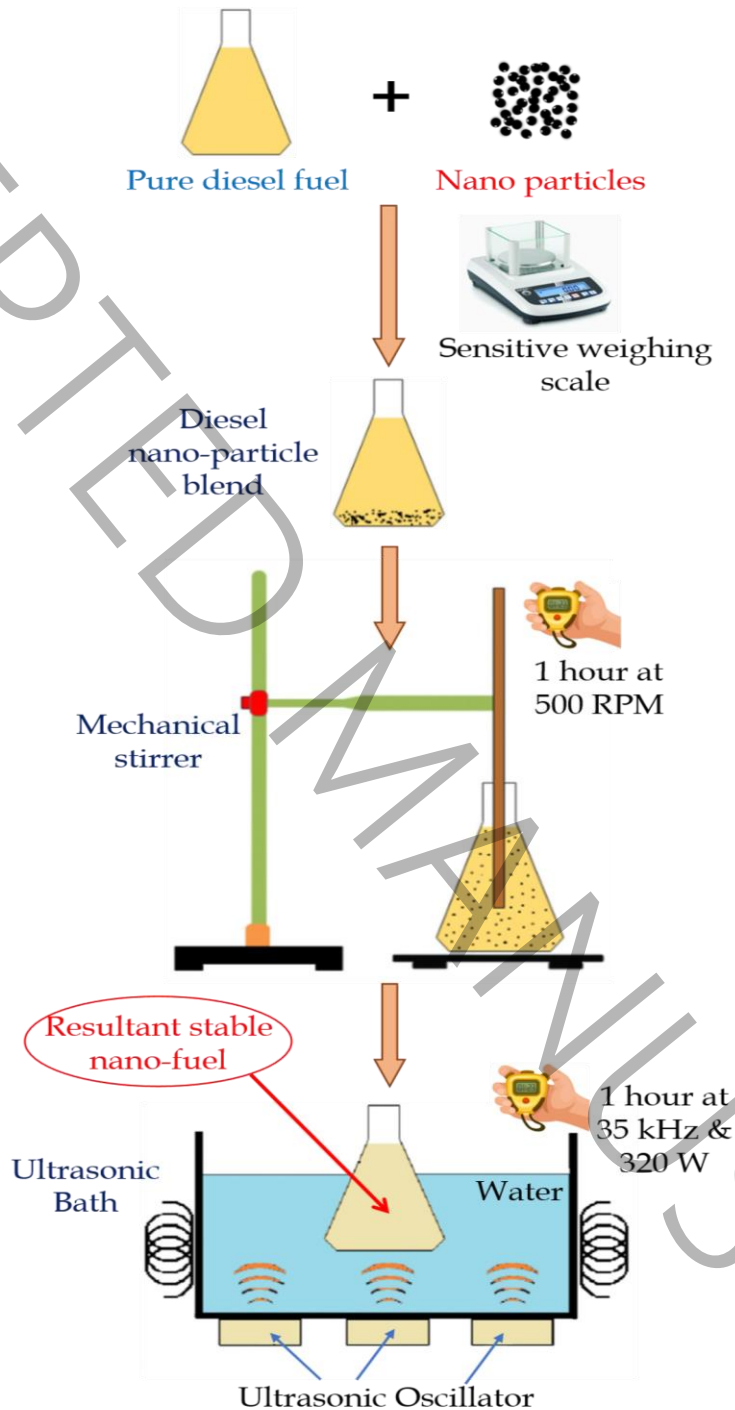
The base fuel for the diesel engine in this study is Neem biodiesel. sonication apparatus available at the Ankleshwar Research and Analytical Laboratory (ARAL) in Gujarat, India, is utilised to combine nanoparticles with major fuel in the current work. The steps needed for manufacturing nano fuel are shown in Fig. 5. Al<sub>2</sub>O<sub>3</sub> and ZnO nanoparticles were acquired from M/s. Adnano Technologies, located in Karnataka, India. The characteristics of nanoparticles are presented in Table 5.

**Table 5.** Characteristics of Nanoparticles [85, 86]

Properties	Unit	Al <sub>2</sub> O <sub>3</sub>	ZnO	Standards
Physical appearance	-	Fine grains	Fine grains	-
Shape of particles	-	Globular	Globuler	-
Visual appearance	-	White	Milky white	-
Purity	%	99.9	99.9	-
Mean grain size	Nm	30-50	30-80	ASTM D6913
Specific surface area of NPs	m <sup>2</sup> /g	110	100-120	ASTM C1069
Bulk density	g/cm <sup>3</sup>	0.6	0.54	ASTM D1895
Melting point	°C	2055	1975	ASTM D3418
Molecular weight	g/mol	101.96	81.408	ASTM D6474

The mass fraction of each individual nanoparticle is 100 parts per million (ppm). Particularly, NPs weighing 100 mg (50mg Al<sub>2</sub>O<sub>3</sub> and 50mg ZnO) were introduced into 1 kilogram of neem biodiesel. The precision reading of the Radwag brand precision scales (Model: AS 110.R2 PLUS Analytical Balance) was ± 0.001g, which was used to determine the mass of the suspended nanoparticles [95]. Afterwards, a

Bandelin Sonorex ultrasonic bath (Model: Digitech DT 514 H) [96] working at 35kHz and 320W power for one hour was used to evenly distribute the nano-fuel mixture.



**Fig. 5.** Nano fuel preparation process [9]

In the present study, four experimental fuel cases were prepared by mixing a B20 blend of Neem biodiesel with nanoparticles in varied concentrations (25 ppm, 50 ppm, 75 ppm, and 100 ppm). For each

instance of test nanofuel, an equal weight of Al<sub>2</sub>O<sub>3</sub> and ZnO nanoparticles is utilised. A nanofuel mixture was subsequently synthesized by combining diesel fuel with a mixture of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) and zinc oxide (ZnO) nanoparticles. The volume of the mixture prepared for all four cases was 9 liters.

Visual sedimentation of the biofuel mixtures was checked up to 30 days, and zeta potential analyzer (Zetasizer - UK made) was utilised for analyzing stability of the biofuels made from Al<sub>2</sub>O<sub>3</sub> and ZnO mixture. The primary properties of the considered test fuels are listed in Table 6. The prepared modified nano fuel was characterized, investigated for fuel properties and then utilized for experiments.

**Table 6.** Properties of B20 Neem biodiesel fuel and modified nano fuels

Properties	Density (@ 15 °C)	Calorific value	Flash point	Fire point	Cetene number	Kinematic viscosity (@ 40 °C)
Unit	kg/m <sup>3</sup>	MJ/kg	°C	°C	-	cSt
<b>B20 Neem biodiesel (without NPs)</b>	835	42.28	50	55	47	2.20
<b>B20 Neem biodiesel with 25 ppm NPs</b>	838	43.41	54	62	54	3.10
<b>B20 Neem biodiesel with 50 ppm NPs</b>	842	43.62	55	64	57	2.95
<b>B20 Neem biodiesel with 75 ppm NPs</b>	849	43.81	56	66	59	2.84
<b>B20 Neem biodiesel with 100 ppm NPs</b>	855	43.89	58	69	61	2.76
<b>ASTM standard</b>	D1298	D240	D93	D93	D613	D446

### 2-3- Experimental Test-rig

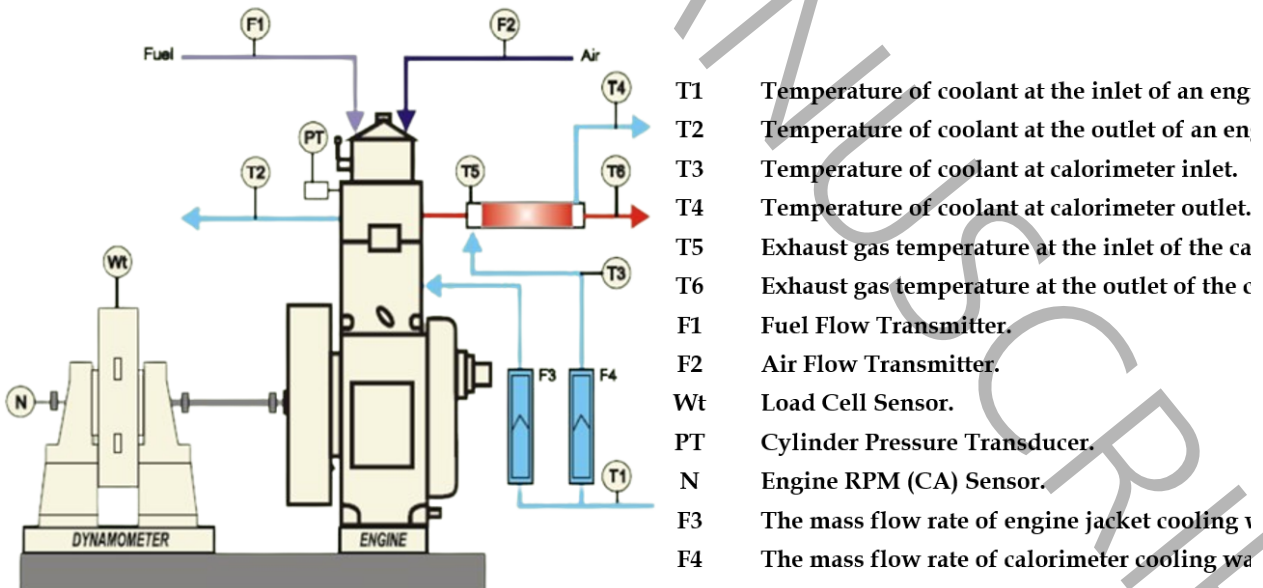
The experiments were conducted using a Kirloskar made Common Rail Direct injection (CRDi) engine with Variable Compression Ratio (VCR) type single-cylinder four-stroke diesel engine as mentioned in Table 7. Once the engine and other installed measuring devices reached a steady state condition, the experiment measurements could begin. Fig. 6 depicts the schematic configuration of the experimental test rig. The configuration includes an independent control panel featuring two fuel tanks and an air tank, as well as a transmitter for monitoring air and fuel flow.

The flow of cooling water to the engine and calorimeter is quantified using rotameters. The setup incorporates LabVIEW for real-time performance evaluation, enabling the collection, monitoring, and

analysis of experimental data, as well as the estimation of various performance test parameters. The engine was put through its paces at a steady speed of 1500 rpm under varied loads, starting with no load and progressing to maximum load. At each step of the process, the values of several parameters were recorded.

**Table 7.** Engine specification [87]

Specification	Unit	Value
Manufacturer	-	Kirloskar Oil Engines Ltd.
Engine model	-	TV1
Engine type	-	VCR-CRDI type diesel engine
Engine position	-	Vertical
No. of cylinder	-	1
No. of stroke	-	4
Compression ratio	-	17.5:1
Compression pressure	Bar	60
Bore × Stroke	mm	87.5 × 110
Rated speed	RPM	1500
Rated output	HP	7
Engine weight	Kg	160
Dynamometer	-	Eddy current type
Rotation of flywheel	-	Clockwise
Cooling type	-	Water cooled



**Fig. 6.** Schematic diagram of experimental test rig

Measurements were taken for the engine's BSFC, BTE, and emission characteristics such as emissions of HC, CO<sub>2</sub>, CO, NOX, and smoke opacity of exhaust gases at each operating point. Importantly, before recording engine speed, air and fuel consumption, load on the dynamometer load for every operating condition.

In order to ascertain the measurement apparatus's error, the investigations must be conducted under known conditions. It is imperative to ascertain the sources of measurement error and the magnitude of each in order to estimate the overall measurement uncertainty [88]. Bias and precision are the two types of errors that can occur in measuring apparatus. Bias errors are the errors that persist throughout the experiment and can only be eliminated through calibration. The direct quantification of numerous experimental study results is challenging due to their dependence on multiple independent parameters [89]. The specific uncertainty associated with each instrument is presented in Table 8. Based on instruments uncertainty, overall uncertainty in engine efficiency was found below 5%.

**Table 8.** Percentage uncertainty.

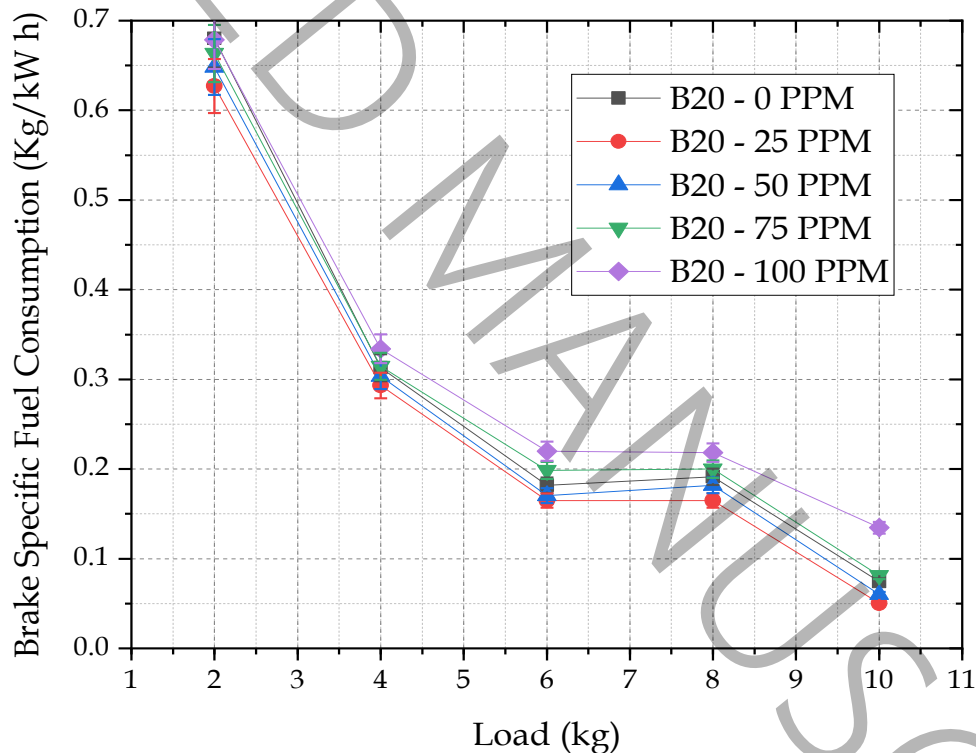
<b>Parameter / Instrument</b>	<b>Unit</b>	<b>Range</b>	<b>Uncertainty(%)</b>
Engine speed (Digital Techometer)	RPM	0-15000	± 2.0
Temperature of cooling water (K type thermocouples)	°C	0-1300	± 0.2
Temperature of lubricant (K type thermocouples)	°C	0-1300	± 0.2
Consumption of fuel	g/kWh	-	± 0.8
Pressure (Pressure gauge)	Bar	0-100	± 0.5
NOx	ppm	0-5000	± 0.8
HC	ppm	0-30000	± 1.0
CO	ppm	0-20	± 0.8
CO <sub>2</sub>	ppm	0-10000	± 0.8

### 3. Results and Discussion

#### 3-1- Engine Performance

##### 3-1-1 Brake specific fuel consumption (BSFC)

One way to compare the efficiency of various engine sizes is by looking at their specific fuel consumption. How much energy the engine produces is directly proportional to how fast it consumes fuel. Increased fuel consumption is an indicator of an inefficient engine, since it indicates that more fuel is required to generate the same amount of power. The correlation between variations in engine load and brake specific fuel consumption (BSFC) is seen in Fig. 7. Outcome have demonstrated that BSFC decreases to a minimum as braking power increases to the optimum load, subsequently rising marginally under overload conditions.



**Fig. 7.** Variation in BSFC with varying engine load

Fig. 7 shows that compared to pure biodiesel, the BSFC of  $\text{Al}_2\text{O}_3$  and ZnO NPs blended neem biodiesel was more at higher dosages (75 ppm and 100 ppm), but it was reduced at lower dosages (25 ppm and 50 ppm). With a dose adjustment from 25 ppm and 50 ppm, respectively, BSFC decreased by about 7.8-32.21% and 2.9-19.01%. At 80% load, the brake specific fuel consumption might be reduced by as much as 0.07 kg/kWh when the addition amount was 25 ppm. This indicates that neem biodiesel with

nanoparticles at lower doses (25 ppm and 50 ppm) likely had a higher surface area/volume ratio, which improved the catalytic effect and decreased consumption of fuel.

### 3-1-2 Brake thermal efficiency (BTE) (%)

Brake thermal efficiency (BTE) of a diesel engine is calculated using the brake power and the calorific value of the fuel. BTE is the reciprocal of BSFC. Fig. 8 illustrates that the Brake Thermal Efficiency of all analyzed fuels is higher than B20 blend of neem biodiesel fuel. Also, it can be observed that the thermal performance of the brake enhances with increasing loads.

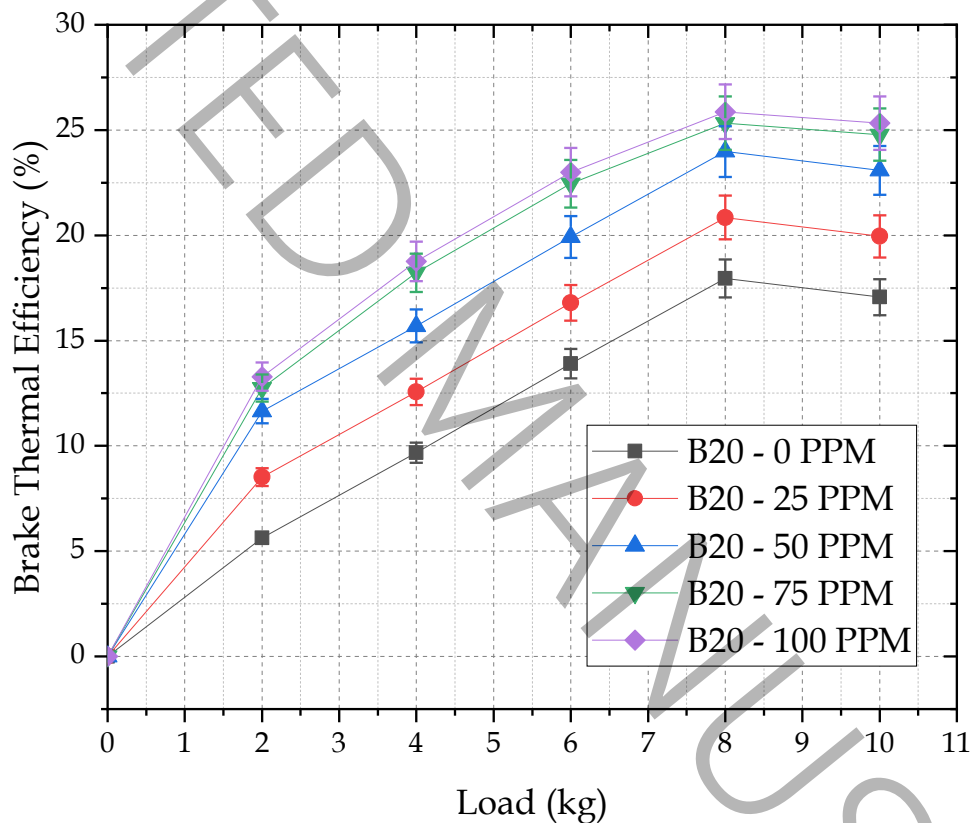


Fig. 8. Variation in BTE with varying engine load

According to Devrajan et al. [75], conventional diesel fuel has a larger calorific value and lesser viscosity, hence it has a lower BTE than plain neem biodiesel. It has been noted by Devrajan et al. [90] and Yuvarajan et al. [91] that fuels with a lower viscosity and a higher calorific value enhance the mixing of air and fuel, allowing for complete combustion. Adding nanoparticles (NPs) to neem biodiesel at concentrations of 25, 75, and 100 ppm has compensated for the fuel's diminished efficiency. According to Afshari et al. [92], Dhinesh et al. [93], and Gunasekar et al. [94], NPs shorten the time it takes for

combustion to begin. Supplementing neem oil biodiesel with NPs improves BTE by raising the thermal conductivity of fuel, which in turn improves heat transfer during combustion.

Fig. 8 presents the outcomes of the experiment carried out on the engine utilizing a B20 blend of neem biodiesel alongside modified cases of nanofuel. The findings indicate that the BTE of neem oil biodiesel is further enhanced by increasing the  $\text{Al}_2\text{O}_3$  and ZnO NPs from 0 to 100 ppm. The ratio of surface area to volume is larger in nanoparticles. Because of these nanoparticles act as an oxygen buffer, increasing efficiency, adding  $\text{Al}_2\text{O}_3$  and ZnO NPs to fuel makes combustion last longer and be more thorough than with the basic fuel without these nanoparticles. It was shown that the efficiency improvement usually increases as the nanoparticle dosage increases.

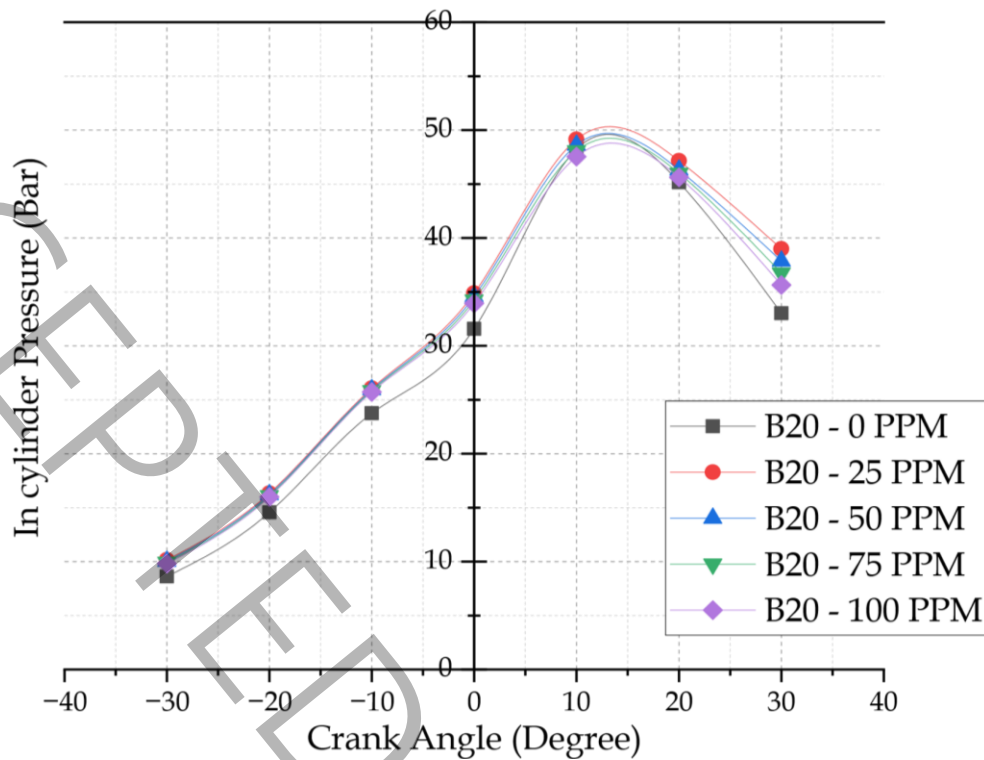
### **3-2- Combustion Performance**

The combustion mechanism is among the most complex parts of any engine. Cylinder pressure and heat release rate are generally utilised to highlight the behaviour and characteristics of the combustion process.

#### **3-2-1 In cylinder pressure (bar)**

The most useful way to learn about combustion is to measure the pressure inside the cylinder. In cylinder pressure is utilised to calculate the heat release rate and provide enough data for the combustion study. Fig. 9 shows the variation in cylinder pressure with varying crank angle operating at full load.

In a mixture of  $\text{Al}_2\text{O}_3$  and ZnO NPs, the ignition timing exhibited a concentration-dependent delay. This is because modified nanofuels have a lower heating value and a higher viscosity. The cylinder pressure will drop and the ignition delay will occur as a result of the improper air and fuel mixture. Although the ignition delay of biodiesel was reduced with the addition of  $\text{Al}_2\text{O}_3$  and ZnO NPs to the fuel, it is still slightly longer than that of pure conventional diesel. Biodiesel with added  $\text{Al}_2\text{O}_3$  and ZnO NPs had improved combustion due to increased thermal conductivity and decreased viscosity. Since the faster rate of viscosity rise cancels out the impact of improved thermal conductivity, increasing the concentration of  $\text{Al}_2\text{O}_3$  and ZnO NPs from 25 ppm to 100 ppm slightly lengthened the igniting delay. As a result, although there is a small delay in ignition timing compared to B20 with 0 ppm NPs, maximum cylinder pressure is achieved with B20 with 25 ppm NPs.



**Fig. 9.** Variation in cylinder pressure with varying crank angle

It is observed that during the combustion process, the cylinder pressure increases with increasing crank angle for all the cases. The trend is consistent across all cases of modified nano fuels, with the exception of very small variations in pressure levels at lower crank angles. Case B20 with 25 ppm NPs has a peak pressure that is 39% more than the other modified fuels that were tested.

### 3-2-2 Heat release (KJ)

How quickly the diesel engine's combustion process releases the chemical energy of the fuel is known as the rate of heat release. The combustion process of a diesel engine consists of two stages: the premixed phase and the diffusion phase. The rate of heat emission is determined by means of the first law of thermodynamics [95]. However, compared to B20 with 0 ppm, the fuel with a mixture of  $\text{Al}_2\text{O}_3$  and ZnO NPs had a maximum higher heat release rate, even if the ignition delay was considerable. This may have occurred because incomplete combustion led to a higher oxygen level in the fuel.

Fig. 10 displays the differences in the heat release rate for B20 neem biodiesel combined with the mixture of  $\text{Al}_2\text{O}_3$  and ZnO NPs with varying crank angle. Here, heat release rate increases with increase in crank angle and with increase in dose level of nano particles. The reason behind this is because modified

biodiesel contains an excessive amount of oxygen. There are consistent patterns in the heat release rate curves across all instances. When compared to other nanoparticle blends, the peak heat release rate at 25 ppm mixture of  $\text{Al}_2\text{O}_3$  and ZnO nanoparticles is marginally higher.

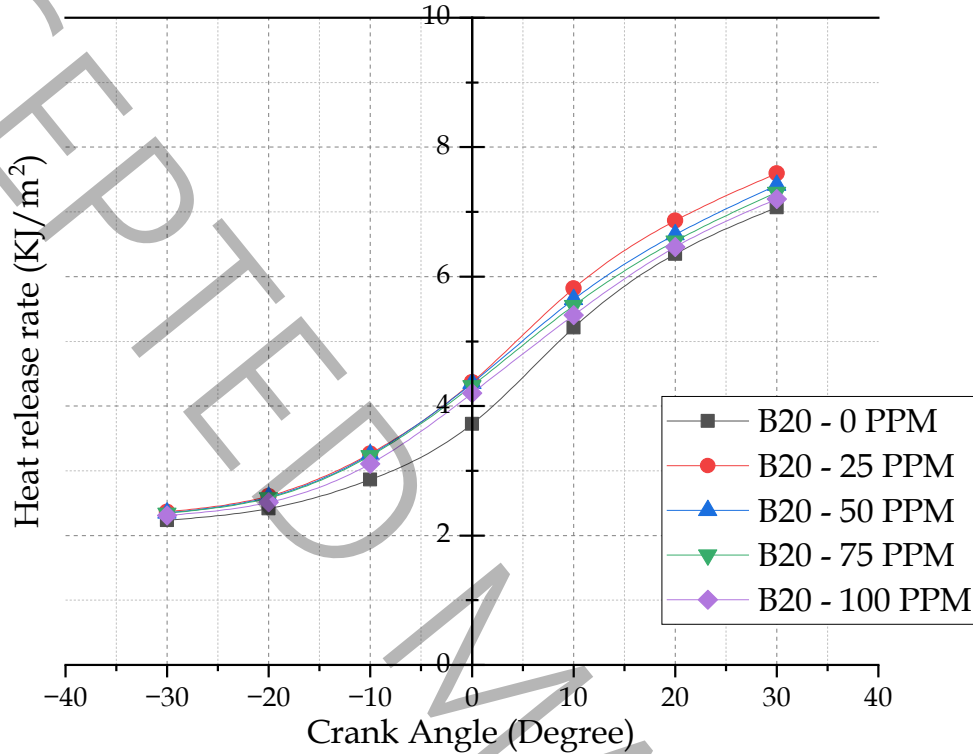


Fig. 10. Variation in rate of heat release with varying crank angle

### 3-3- Emission Performance

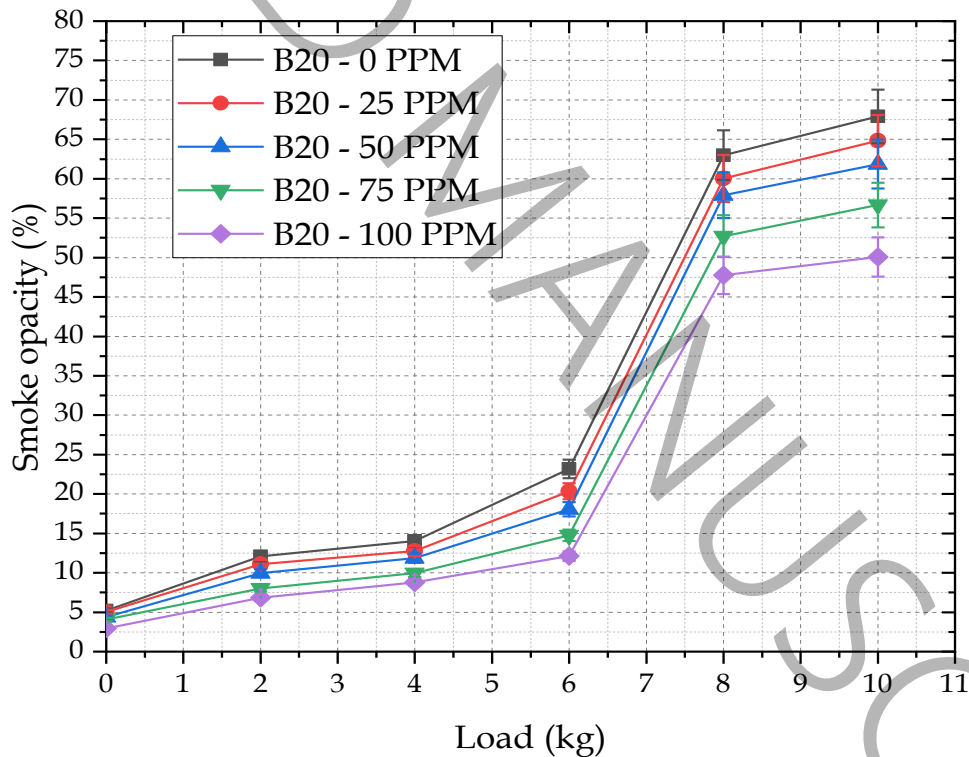
#### 3-3-1 Smoke opacity

The variation in smoke opacity with varying engine load is demonstrated in Fig. 11. The opacity of the smoke is one measure for its output. There is a lot of smoke coming out of diesel engines. It is possible for smoke to be exacerbated in cases of improper repair or malfunctioning diesel engines. The outcome of the test will depend on how old the engine is and how obscure the area is.

Because of the lean combination, the evaluated fuels produce little smoke emissions when braking with less power. An increase in braking power causes an increase in fuel supply, which in turn causes a rich mixture, which in turn causes incomplete combustion and increases smoke emissions [96]. Smoke emission from neem oil biodiesel is lesser than diesel as observed by Devarajan et al. [75]. The inherent oxygen content of neem oil biodiesel promotes combustion process and reduces smoke emissions [97, 98]. A

significant decrease in smoke emissions is noted when 25 and 100 ppm of  $\text{Al}_2\text{O}_3$  and ZnO nanoparticles are added to neem oil biodiesel. Nanoparticle seeding increases the rate of evaporation of B20 fuel, which contains oxygen by nature [99]. Adding 25–100 ppm of  $\text{Al}_2\text{O}_3$  and ZnO NPs to neem oil biodiesel further lowers its smoke emissions. An increase in the percentage of  $\text{Al}_2\text{O}_3$  and ZnO improves combustion efficiency and decreases smoke emissions.

In comparison to pure biodiesel (B20 - 0 ppm), the smoke density of all instances involving nanoparticles in biodiesel reduced as depicted in Fig. 11. A reduction in smoke opacity of approximately 3.6-13.9%, 8.7-28.9%, 19.47-51.03%, and 31.8-78.12% was noted as the dosage of nano particles varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively. The decrease in smoke density indicates that nanofuel combustion efficiency is improved by adding  $\text{Al}_2\text{O}_3$  and ZnO nanoparticles.



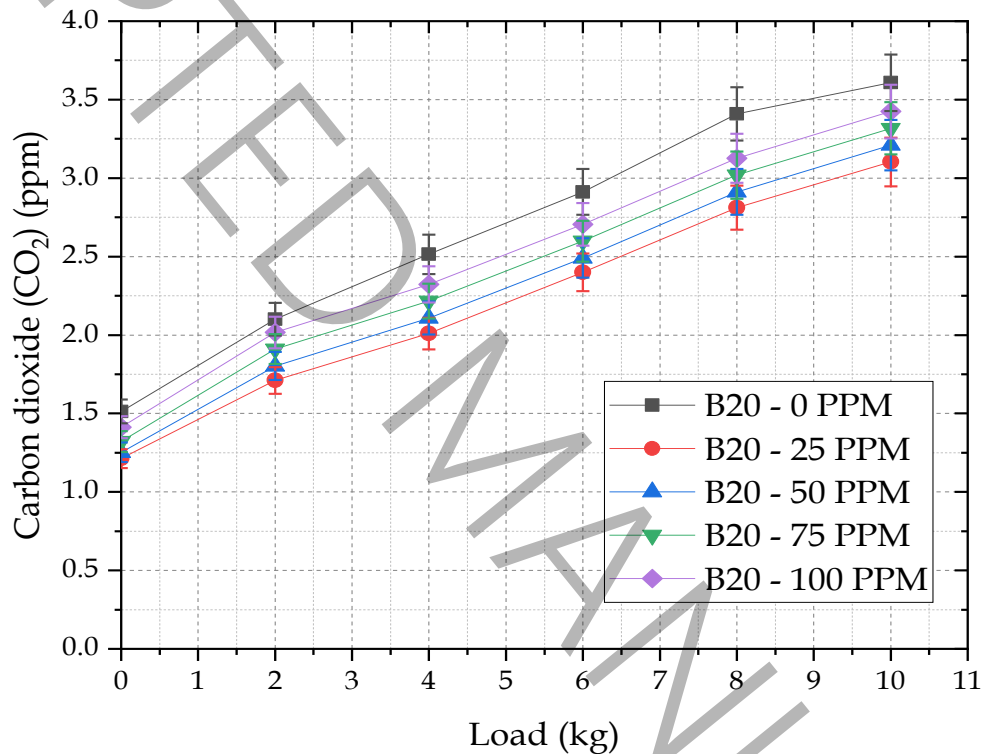
**Fig. 11.** Variation in smoke opacity with varying engine load

In addition, it has been noted that a significant increase in smoke density is associated with a rise in engine load. The general excess of fuel in the air mixture is likely responsible for this behaviour. Variables like temperature, period of the diffusion in combustion, and diminished levels of oxygen affect the quantity of

smoke that is developed. The incomplete combustion that results from atomizing the fuel could be the reason for this.

### 3-3-2 Carbon dioxide (CO<sub>2</sub>)

One carbon atom and two oxygen atoms together create a structure of molecules called carbon dioxide (CO<sub>2</sub>). As a greenhouse gas, carbon dioxide is present in Earth's atmosphere in trace levels. Dry ice is the name given to it when it is solid. In the carbon cycle, it is an essential component.



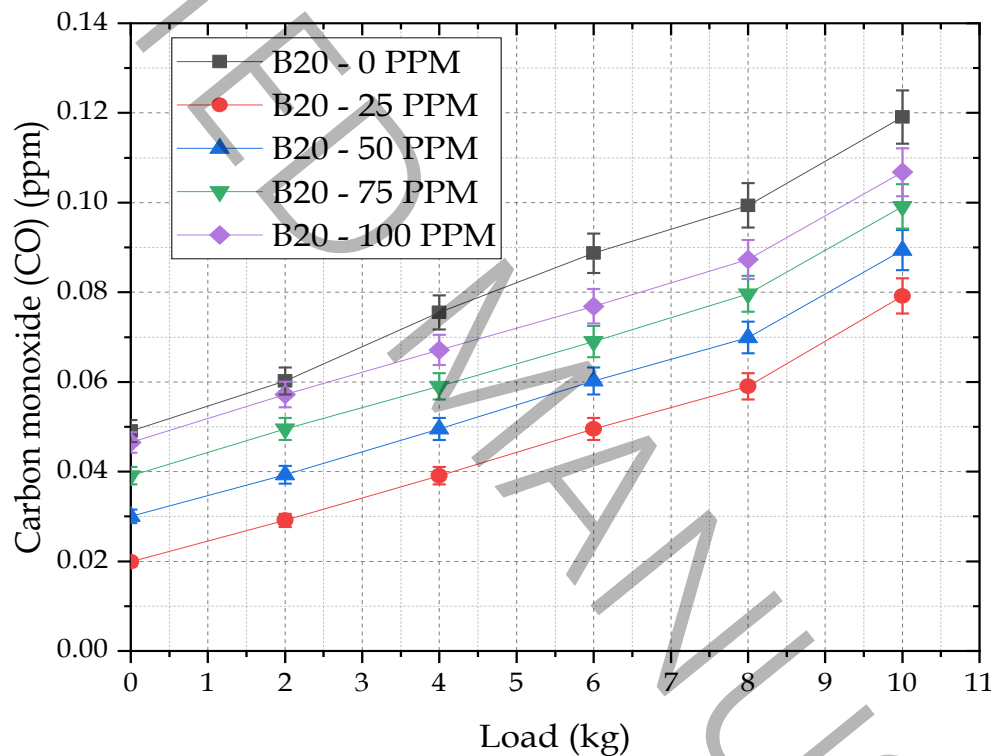
**Fig. 12.** Variation in carbon dioxide with varying engine load

With the application of Al<sub>2</sub>O<sub>3</sub> and ZnO NPs, soot particles can be more easily oxidised at lower temperatures. Soot can be converted into CO<sub>2</sub> through oxidation with the help of these NPs, which act as catalysts. The relationship between engine load and CO<sub>2</sub> emissions is shown in Fig. 12. Adding Al<sub>2</sub>O<sub>3</sub> and ZnO NPs to B20 neem biodiesel in every considered proportion reduces CO<sub>2</sub> emissions in exhaust fumes. Compared to pure biodiesel (B20 - 0 ppm), the carbon dioxide emissions in every case with nanoparticles in biodiesel decreased by approximately 19.84-13.99%, 17.2-11.02%, 12.64-8.04%, and 6.61-5.09% as the

nanoparticle dosage varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively, from low to high engine load. The most significant drop is observed in the case of B20 – 25 ppm.

### 3-3-3 Carbon monoxide (CO)

Carbon monoxide, a flammable gas, is somewhat denser than air and lacks colour, smell, and taste. Emissions of carbon monoxide will rise as engine loads increase. More pollution from emissions might result from incomplete combustion. Additional pollution could be caused if the burning is not extinguished. Possible causes include a slow-burning pre-mixed and a high-viscosity diesel mixture, both of which led to a rise in droplet volume and poor dissolution.



**Fig. 13.** Variation in carbon monoxide with varying engine load

Because of the reduced fuel input and lean mixture, the generation of CO emissions from the investigated fuels is in the lower range at decreased brake power. Venkata Ramanan and Yuvarajan [100], and Pandian et al. [101] both noticed the same pattern. Increasing the brake power of engine leads to an increase in fuel intake, which in turn causes incomplete combustion and higher CO emissions. Conventional diesel produces more carbon monoxide than neem oil biodiesel [75]. The reason behind this is because neem oil biodiesel naturally contains oxygen [102, 103]. Nanoparticles are added to neem oil biodiesel to lower its CO emission. Inclusion of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  NPs to neem oil biodiesel increased combustion oxygen and

decreased carbon monoxide emissions. Praveen et al. [104] and Seela et al. [105] found a similar pattern when adding nanoparticles to biodiesel in their respective investigations.

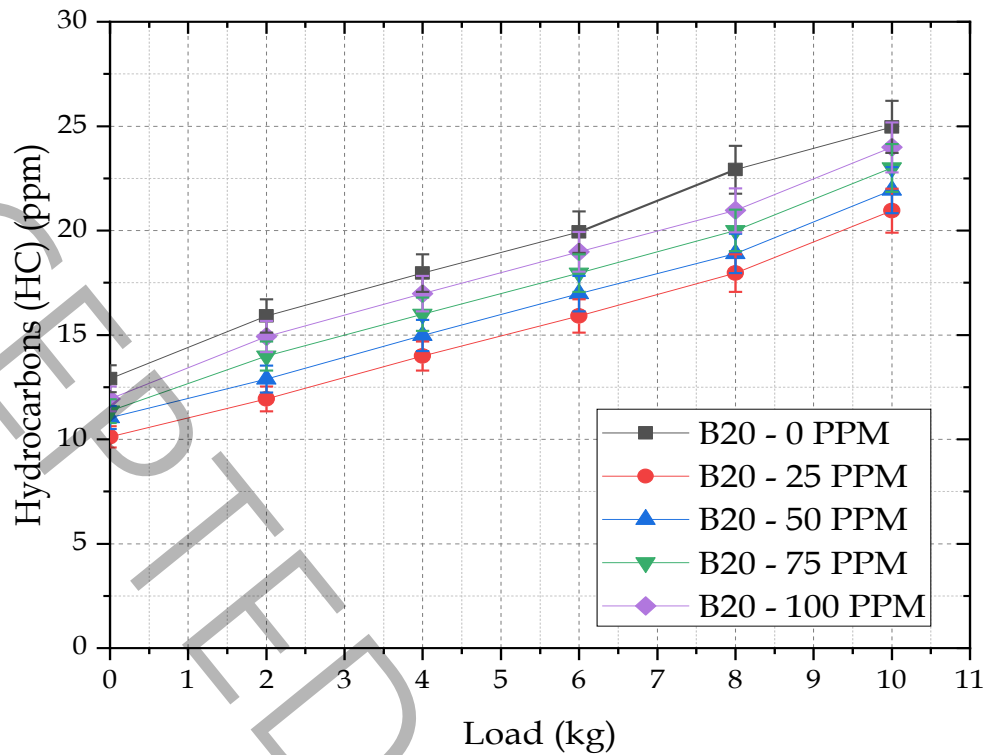
The relationship between engine load and CO emissions is shown in Fig. 13. Enhanced engine combustion is achieved with the integration of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  nano additives into modified nano-fuel in terms of significant reduction in CO emissions compared to pure biodiesel (B20 - 0 ppm). Compared to pure biodiesel (B20 - 0 ppm), the carbon monoxide emissions in every case with nanoparticles in biodiesel decreased by approximately 60.62-33.17%, 38.7-25.1%, 21.08-16.72%, and 5.32-10.62% as the nanoparticle dosage varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively, from low to high engine load. The most significant drop is observed in the case of B20 – 25 ppm.

From experimentation, it was observed that with increase in concentration of nanoparticles (e.g., 50, 75 and 100 ppm) leads to higher aggregation of nanoparticles inside engine which affects the injection process of fuel inside the engine cylinder. This will result in incomplete combustion compared to 25 ppm case. Thus, from overall performance analysis, 25 ppm case found more optimum than other higher NP concentration cases with respect to CO, HC and  $\text{NO}_x$  emission.

### **3-3-4 Hydrocarbons (HC)**

The relationship between hydrocarbon (HC) emissions and engine load is seen in Fig. 14. Many important energy sources rely on hydrocarbons, which are organic substances made up of carbon and hydrogen atoms. These include coal, natural gas, crude oil, and many more. As development progresses, the number of hydrocarbons rises. The properties of diesel mixtures including high viscosity high density, and low volatility may prevent it from being adequately dissolved, leading to the excessive amounts of hydrocarbons (HC).

The addition of NPs lower particulate matter (PM) emissions by reducing soot production and increasing its oxidation [74]. The breakdown of fuel into smaller and more uniformly dispersed droplets during injection could be improved by nano-additives. It increases combustion efficiency by improving atomisation, which results in a more homogeneous air-fuel mixture, improves the combustion process to increase efficiency and lower carbon monoxide (CO) and hydrocarbon (HC) emissions.



**Fig. 14.** Variation in hydrocarbons with varying engine load

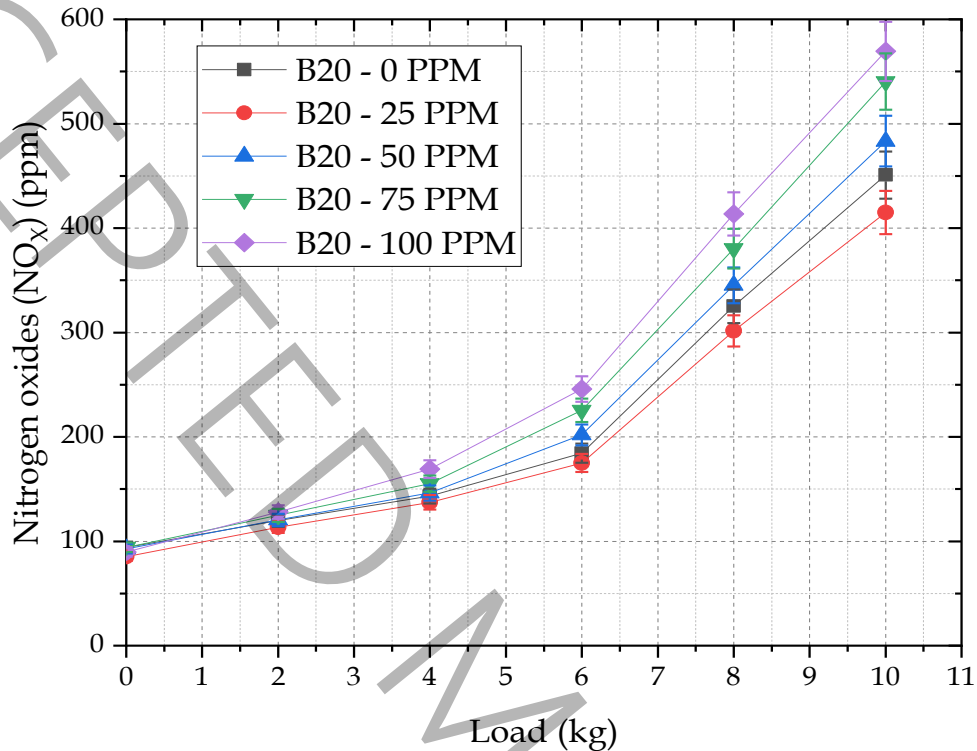
Fig. 14 shows that when nanoparticles are added to generate modified nano fuel, the hydrocarbon emissions significantly decrease, which means that the combustion process is perfect. The emission of hydrocarbon in every case with nanoparticles in biodiesel decreased by approximately 16.08-24.97%, 12.14-19.05%, 7.87-12.69%, and 3.93-7.43% as the nanoparticle dosage varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively, from low to high engine load as compared to pure biodiesel (B20 - 0 ppm), The most significant drop is observed in the case of B20 – 25 ppm.

### 3-3-5 Nitrogen Oxides (NO<sub>x</sub>)

The relationship between engine load and emission of Nitrogen oxide is shown in Fig. 15. A common abbreviation for NO<sub>x</sub> is nitric oxide and nitrogen dioxide. Chemical reactions involving gaseous nitrogen oxides result in smoke and acid rain. They also play a crucial role in the creation of hazardous air pollutants like particulate matter and ground-level ozone, which can have negative impacts on mankind's health.

Emission of NO<sub>x</sub> emissions rises with the rise in engine load. According to Anderson et al. (2017), Joy et al. (2017), and Arul Gnana Dhas et al. (2018), this is caused by the cylinder temperature rising during

combustion. When compared to diesel, neem oil biodiesel has demonstrated higher NO<sub>x</sub> emissions [75]. The primary cause of increased NO<sub>x</sub> generation at all engine loads is the B20's intrinsic oxygen content [106].



**Fig. 15.** Variation in nitrogen oxides with varying engine load

Fig. 15 shows that when Al<sub>2</sub>O<sub>3</sub> and ZnO NPs are added to B20 blend of neem biodiesel in dosage of 25 ppm, NO<sub>x</sub> emission is greatly reduced at all loads, which determines similar trend as concluded by Sakthivadivel et al. [76]. Here, about 4.98-8.31% higher reduction was obtained in the case of B20 – 25 ppm compared to B20 – 0 ppm. It was observed that low dosage of Al<sub>2</sub>O<sub>3</sub> and ZnO NPs improves the combustion process by lowering the combustion temperature and delay time [102, 103] which shortens the combustion time and lowers NO<sub>x</sub> emissions [107]. However, the higher concentration of NPs (i.e. 50, 75, and 100 ppm) greatly increases the NO<sub>x</sub> emission compared to B20 – 0 ppm case. About 17.89%, 25.04%, and 28.85% increase was observed in NO<sub>x</sub> emission as compared to the case of B20 – 0 ppm.

#### 4. The conclusion

The present study aims to study engine performance; combustion performance and emission performance of a Common Rail Direct injection (CRDi) engine with Variable Compression Ratio (VCR) type single-

cylinder four-stroke diesel engine fuelled with transesterified neem biodiesel using novel nanoparticle mixture of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  as fuel additives. The results show that B20 neem biodiesel with a combination of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  nanoparticles (NPs) can improve the thermal efficiency of CI engines at dosage levels ranging from 25 ppm to 100 ppm. BSFC and BTE increases whereas exhaust gases from diesel engines show reduction in smoke opacity,  $\text{NO}_x$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and unburned HC emissions, which proves that the fuel has been completely burned. From the results of the experiments that, it can be concluded that:

1. Compare to higher dosages (75 ppm and 100 ppm), BSFC was reduced appreciably at lower dosages (25 ppm and 50 ppm). About 7.8-32.21% and 2.9-19.01% reduction was observed with a dose of 25 ppm and 50 ppm, respectively. About 0.07 kg/kWh reduction was observed at 80% load for 25 ppm nano additives.
2. About 16-51%, 33-106%, 41-126%, and 44-136% increase in BTE was observed for the dosing levels of 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively.
3. Due to excess amount of oxygen content in modified nano-fuel, rise in heat release rate was observed with increase in the crank angle. Compare to other cases heat release rate at 25 ppm mixture of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  nanoparticles is marginally higher.
4. During the combustion process, the cylinder pressure increases with increasing crank angle for all the cases. B20 with NPs dose level 25 ppm demonstrated highest cylindrical pressure which was about 39% more than other considered cases.
5. About 3.6-13.9%, 8.7-28.9%, 19.47-51.03%, and 31.8-78.12% reduction in smoke opacity was recorded as the dosage of nano particles varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively. The down fall in smoke density indicates improvement in the nanofuel combustion efficiency with addition of  $\text{Al}_2\text{O}_3$  and  $\text{ZnO}$  nanoparticles.
6. Compared to pure biodiesel (B20 - 0 ppm), the carbon monoxide emissions in every case with nanoparticles in biodiesel decreased by approximately

7. About 60.62-33.17%, 38.7-25.1%, 21.08-16.72%, and 5.32-10.62% reduction in carbon monoxide emissions was noted as the nanoparticle dosage varied from 25 ppm, 50 ppm, 75 ppm, to 100 ppm, respectively, from low to high engine load. The most significant drop is observed in the case of B20 – 25 ppm.
8. Addition of NPs in B20 neem biodiesel resulted in appreciable reduction in various emission parameters like CO, CO<sub>2</sub>, HC and NO<sub>x</sub>. Highest 60.62-33.17% and 19.84-13.99% reduction in CO and CO<sub>2</sub> were obtained for the case of B20-25 ppm, respectively.
9. Maximum 4.98-8.31% reduction was obtained with B20 – 25 ppm compared to B20 – 0 ppm. However, about 17.89%, 25.04%, and 28.85% increase was observed in NO<sub>x</sub> emission as compared to the case of B20 – 0 ppm. This was due to higher aggregation of nanoparticles inside engine at higher concentration (e.g., 50, 75 and 100 ppm) which affects the injection process of fuel inside the engine cylinder and leads to incomplete combustion.

Overall, experimental results exhibit that B20 blend of neem biodiesel with 25 ppm Al<sub>2</sub>O<sub>3</sub> and ZnO nanoparticles dosage (B20 – 25 ppm) found best as compared to other considered cases.

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