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Impact of carbon quantum dot nanoparticles on combustion, performance and emissions in diesel/microwave-assisted canola oil biodiesel blend

Yaşar Önder Özgören[1], Ahmet Uyumaz[2,*], Hamit Solmaz[3], Fatih Aksoy[1], Alper Calam[4], Mustafa Babagiray[5], Seda Şahin[6], and Laçine Aksoy[7]

[1] Afyon Kocatepe University, Faculty of Technology, Automotive Engineering Dep., 03200, Afyonkarahisar, Turkey
[2] Burdur Mehmet Akif Ersoy University, Faculty of Engineering Architecture, Mechanical Engineering Dep., 15200, Burdur, Turkey
[3] Gazi University, Faculty of Technology, Automotive Engineering Dep., 06500, Ankara, Turkey
[4] Gazi University, High Vocational School of Technical Sciences, Machinery and Material Technologies Dep., 06374, Ankara, Turkey
[5] Afyon Kocatepe University, Graduate School of Natural and Applied Sciences, 03200, Afyonkarahisar, Turkey
[6] Selçuk University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, 42140 Konya, Turkey
[7] Afyon Kocatepe University, Faculty of Science and Arts, Department of Chemistry, 03200, Afyonkarahisar, Turkey

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Abstract. Usage of biodiesel produced with conventional transesterification methods decreases the conversion of biodiesel from vegetable oil. Microwave-assisted production enables higher reaction efficiency, providing better conversion of vegetable oils. It also causes to obtain poorer characteristics of biodiesel, such as higher viscosity and density. It was aimed to improving the properties of biodiesel with microwave-assisted production and mixing it with nanoparticles to investigate the performance, combustion and emission characteristics. The influences of nanoparticle addition (carbon quantum dot) on engine performance, combustion and emissions have been analyzed in a direct injection CI engine. A single cylinder water cooled CI engine was used in the experiments. Experiments were performed at 4.12, 9.61, 15.10, 20.60 Nm and 2200 rpm. Canola biodiesel was obtained *via* the microwave-assisted transesterification method and mixed with diesel at the ratio of 20% (B20). 50, 100 and 150 ppm nanoparticle were added to the obtained B20 and tested in a CI engine. Specific Fuel Consumption (SFC) raised by 2.03%, 4.83%, 4.40% and 1.69% with B20, B20CQD 50 ppm, B20CQD 100 ppm and B20CQD 150 ppm respectively compared that diesel at 15.10 Nm. Remarkable reduction was found on CO, HC with B20CQD 50 ppm, B20CQD 100 ppm and B20CQD 150 ppm according to B20. In addition, an impressive reduction was realized on soot emissions with the usage of nanoprticle addition. But, NO_x increased using fuel blends. As a result, the usage of quantum dot nanoparticle improved the poor properties of canola oil biodiesel and test fuels were used easily without modification in a diesel engine.

Keywords: Canola biodiesel, Nanoparticle, Carbon quantum dot, Engine performance, Exhaust emissions.

Nomenclature

Al_2O_3	Aluminum oxide
A_2	Heat transfer surface area
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
B20	80% diesel and 20% microwave assisted canola oil biodiesel
CA	Crank angle
CA50	Crank angle location of 50% accumulated HRR (°CA)
CD	Combustion duration
CI	Compression ignition
COV_{imep}	Cyclic variations of imep
CQD	Carbon quantum dot
dQ_{gr}	Gross heat release rate
dQ_{heat}	Transferred heat
$d\Theta$	The variation of crank angle
CO	Carbon monoxide
CO_2	Carbon dioxide

* Corresponding author: auyumaz@mehmetakif.edu.tr

DI	Direct Injection
h_c	Heat transfer coefficient
HC	Hydrocarbon
HP	Horsepower
ID	Ignition delay
ITE	Indicated thermal efficiency
imep	Indicated mean effective pressure
k	Polytropic index
m_f	Consumed fuel
MgO	Magnesium oxide
MPRR	Maximum pressure rise rate
MTBE	Methyl tert-butyl ether
n	Engine speed
NO_x	Nitrogen oxides
P	In-cylinder pressure
RI	Ringing intensity
Q	Heat release rate
Q_{LHV}	Calorific value of fuel
RI	Ringing intensity
RSM	Response surface method
SFC	Specific fuel consumption
θ	Crank angle
σ_{imep}	Average indicated mean effective pressure
T_g	Averaged in-cylinder gas temperature
T_w	In-cylinder wall temperature
V	Cylinder volume
W_{net}	Network
$\bar{X}$	Standard deviation
ZnO	Zinc oxide
TiO_2	Titanum dioxide
UHC	Unburned hydrocarbon

1 Introduction

Biodiesel, a renewable, non-toxic, and eco-friendly fuel with high oxygen content, has gained widespread attention as a promising alternative to conventional diesel fuel in Compression Ignition (CI) engines. This alternative fuel, which can be derived from sustainable sources like waste oils and various plant and animal products, offers significant environmental benefits, such as lower emissions of carbon monoxide (CO) and hydrocarbons (HC), which contribute to cleaner air and a reduced carbon footprint. Biodiesel's ability to be produced from waste materials also contributes to waste reduction and promotes energy independence, making it an ideal candidate in the global shift toward renewable energy sources. However, despite its advantages, the practical application of biodiesel in CI engines is hindered by several significant drawbacks. These include poor injection and atomization characteristics, suboptimal cold-start performance, and lower calorific energy when compared to conventional diesel fuels. The high viscosity and density of biodiesel lead to inefficient fuel atomization, resulting in inhomogeneous combustion, which further contributes to the generation of particulate matter and other undesirable emissions [1–5]. Furthermore, a critical limitation of biodiesel is its inability to simultaneously reduce both soot and nitrogen oxide (NO_x) emissions in CI engines. This dual-emission challenge poses a significant barrier to meeting stringent regulatory standards, such as the Euro emissions standards, which are of major concern for engine manufacturers and researchers [3–11].

To overcome these challenges, researchers have increasingly turned to the use of additives to improve the properties of biodiesel and optimize its performance in CI engines. Among the various additives explored, nanoparticles have emerged as a promising solution due to their unique physical and chemical properties. Nanoparticles offer a high surface area-to-volume ratio and exceptional thermal conductivity, which enable them to promote oxidation reactions more effectively than conventional additives. This catalytic effect not only improves combustion efficiency but also enhances essential fuel characteristics such as cetane number, flash point, and viscosity, all of which contribute to improved fuel injection and atomization [12–14]. In addition, nanoparticles act as combustion catalysts, accelerating oxidation reactions and improving overall combustion quality, which results in higher engine efficiency and a reduction in harmful emissions [15–25]. Studies across various fuel types have consistently shown that adding nanoparticles such as zinc oxide (ZnO), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3) to biodiesel can significantly enhance both engine performance and emission profiles, making nanoparticles a highly attractive option for biodiesel applications [18, 19].

Recent research studies have highlighted the positive effects of nanoparticles on biodiesel performance, offering valuable insights into their potential as additives [20, 26–29]. For instance, Gunaydin *et al.* [25] explored the effects of adding dibutyl maleate to diesel fuel and observed that this combination reduced in-cylinder pressure while increasing Ignition Delay (ID). Although the study noted a decline in Indicated Thermal Efficiency (ITE) by 20.18% with D90DBM10 and 24.25% with D90DBM20, it underscored the potential of dibutyl maleate in improving combustion characteristics. Similarly, Opuz *et al.* [30] investigated the addition of metallic nanoparticles (quantum dots) to canola oil biodiesel, reporting that Specific Fuel Consumption (SFC) was reduced by 17.69%, 8.70%, and 3.08% when using D80TCB20C150, D80TCB20C100, and D80TCB20C50, respectively, compared to D80TCB20. However, CO and NOx emissions were observed to increase with the addition of these nanoparticles. El-Adawy [1] examined the effects of zinc oxide (ZnO) nanoparticles in diesel/biodiesel mixtures, concluding that ZnO improved performance and combustion characteristics, with B0ZnO, B20ZnO, and B40ZnO showing higher torque by 3.69%, 4.9%, and 6.74%, respectively, compared to B40, B20, and B0 at 2300 rpm. Razzag *et al.* [31] demonstrated that titanium dioxide (TiO_2) nanoparticles improved Brake Thermal Efficiency (BTE) and reduced Brake-Specific Fuel Consumption (BSFC), with a B30+120 ppm biodiesel blend achieving minimum BSFC of 0.33994 kg/kWh and maximum BTE of 25.90%. These studies collectively suggest that nanoparticle additives can significantly enhance the performance and emission profiles of biodiesel blends, although results are highly dependent on factors such as nanoparticle type, concentration, and the composition of the biodiesel blend.

In addition to these studies, research has also shown that nanoparticles facilitate enhanced heat transfer within the fuel mixture, which contributes to more complete combustion. This property is particularly advantageous in biodiesel applications, where improved combustion efficiency is necessary to overcome the high viscosity and density of the fuel. For example, Ansari *et al.* [32] studied the effects of aluminum oxide (Al_2O_3) nanoparticles in a biodiesel blend containing Jatropha oil, finding that Al_2O_3 reduced BSFC while increasing BTE and combustion noise. Mostafa *et al.* [33] conducted a similar study using aluminum oxide and found substantial reductions in NO_x, HC, and CO emissions, with reductions measured at 32.28%, 21.74%, and 20%, respectively. Other researchers, such as Suhel *et al.* [34], have explored the use of zinc oxide (ZnO) with waste plastic oil, demonstrating that ZnO effectively reduced NOx, Unburned HydroCarbons (UHC), smoke, and CO emissions. These results highlight the versatility and effectiveness of nanoparticles as biodiesel additives, as well as the broad applicability of these additives across different biodiesel sources and blend ratios.

Building on the advancements in nanoparticle research, the current study investigates the effects of Carbon Quantum Dot (CQD) nanoparticles in a diesel/canola oil biodiesel fuel blend (B20) for CI engines. CQDs are particularly promising as biodiesel additives due to their excellent catalytic properties and high thermal conductivity, which can enhance heat transfer and facilitate more efficient combustion reactions. This study focuses on evaluating the diesel/canola oil biodiesel blend (B20) in a CI engine at multiple torque levels: 20.60, 15.10, 9.61, and 4.12 Nm. The effects of CQDs on various combustion variables including heat release rate, in-cylinder pressure, Ignition Delay (ID), Combustion Duration (CD), and CA50 (the crank angle at which 50% of total heat is released) are examined in detail. Additionally, key engine performance indicators such as SFC and emissions (HC, CO, CO_2, soot, and NO_x) are measured experimentally to provide a comprehensive assessment of the additive's impact on biodiesel performance. By investigating these parameters, this research aims to provide valuable insights into the role of CQDs in enhancing biodiesel compatibility with CI engines, supporting the development of cleaner and more efficient biodiesel-powered engines.Tabulated versions of the results of the studies in the literature are given in Table 1.

The innovation of this study lies in its use of CQDs to enhance the performance of biodiesel produced through microwave-assisted transesterification, a method that yields higher conversion efficiency but presents unique challenges in terms of fuel properties. Biodiesel produced in this way typically exhibits increased viscosity and density, which can hinder efficient combustion in CI engines. This study addresses these specific limitations by introducing CQDs, whose high thermal conductivity and catalytic properties are expected to improve combustion efficiency and emission outcomes in biodiesel applications. The choice of CQDs in this study is based on their unique catalytic, thermal, and reactive surface properties, making them an ideal additive to address the specific combustion and emission challenges of biodiesel in CI engines [40–44]. Unlike traditional nanoparticle additives, CQDs facilitate enhanced heat transfer and oxidation reactions, optimizing the atomization and combustion of biodiesel.

By examining CQDs in concentrations of 50 ppm and 150 ppm, this study explores both minimal and substantial catalytic effects, providing valuable insights into the potential of CQDs as a biodiesel additive. A comprehensive experimental evaluation is conducted across varied torque loads (4.12, 9.61, 15.10, and 20.60 Nm), measuring essential combustion variables such as in-cylinder pressure, heat release rate, ignition delay, and CA50 as well as SFC and emissions (HC, CO, CO_2, NOx, and soot). This detailed approach provides a holistic understanding of CQD effects on biodiesel performance, offering a novel pathway toward cleaner and more efficient biodiesel-powered engines suitable for CI applications. In summary, this research contributes to the broader effort to make biodiesel a more viable and environmentally friendly fuel for CI engines by addressing its fundamental challenges through innovative nanoparticle additives. By examining the effects of CQDs in a controlled experimental setting, this study aims to support the development of cleaner, more efficient biodiesel-powered engines that meet the stringent emission standards of today's regulatory landscape.

2 Experimental setup and procedures

The flow chart of the study is given in Figure 1. The fuels to be examined in the study were determined. The design of the experiments to be carried out with the determined fuels was carried out. Fuel production was carried out and tests were carried out depending on the experimental design. In the last stage, the experimental data were analyzed.

2.1 Test fuels

Biodiesel production by transesterification occurs due to the reaction of vegetable or animal oils with alcohol in the presence of a catalyst [45, 46]. Alcohols such as methanol, ethanol, propanol, butanol, and amyl alcohol are used in the transesterification reaction [47–49]. Methanol is preferred due to its low cost and physical and chemical advantages [47]. The transesterification reaction occurs with or without a catalyst. Alkaline, acidic, and enzymatic catalysts are used in the catalyzed transesterification reaction [50]. An alternative heating method of the transesterification reaction is microwave irradiation [51]. Microwave irradiation increases the reaction rate, yield, and purity of the products [52].

Biodiesel was produced from canola oil using the microwave-assisted transesterification method. The biodiesel production system consists of a modified household-type microwave (Samsung ME711K), glass reactor (a flat- bottomed glass flask with a volume of 250 mL), reflux condenser, magnetic stirrer, and temperature sensor. Figure 2 shows the biodiesel production system.

Table 1. Effects of blended fuels and nanofuels on engine performance, combustion and emissions.

Fuel mixtures and additives	Changes in combustion, performance and emission results		References
	Increase	Decrease	
Diesel + canola biodiesel	BSFC, CO_2, NO_2	BTE, CO, HC, smoke	[35]
Diesel + waste plastic oil + ZnO	–	BSFC, EGT, UHC, CO, NO_x, smoke	[34]
Diesel + AL_2O_3	BSFC, NO_x, HC, EGT	BTE, CO_2	[33]
Diesel + jatropha biodiesel + Al_2O_3	BTE	MPRR, SFC, pressure, EGT	[32]
Diesel + waste cooking oil biodiesel + TiO_2	BTE, NO_x	BSFC, CO, HC,	[31]
Tamanu methyl ester + multi walled carbon nanotube (MWCNT)	Pressure, BTE	SFC, HC, CO, NO_x, smoke	[36]
Diesel + grass limon oil + Al_3O_3	BTE, pressure	BSFC, HC, CO, smoke, NO_x	[37]
Ziziphus biodiesel + Al_2O_3	BTE, NO_x	BSFC, smoke, HC, CO	[38]
Diesel + waste cooking oil	BSFC, BSEC, HC, smoke, CO_2	BTE, NO_x	[39]

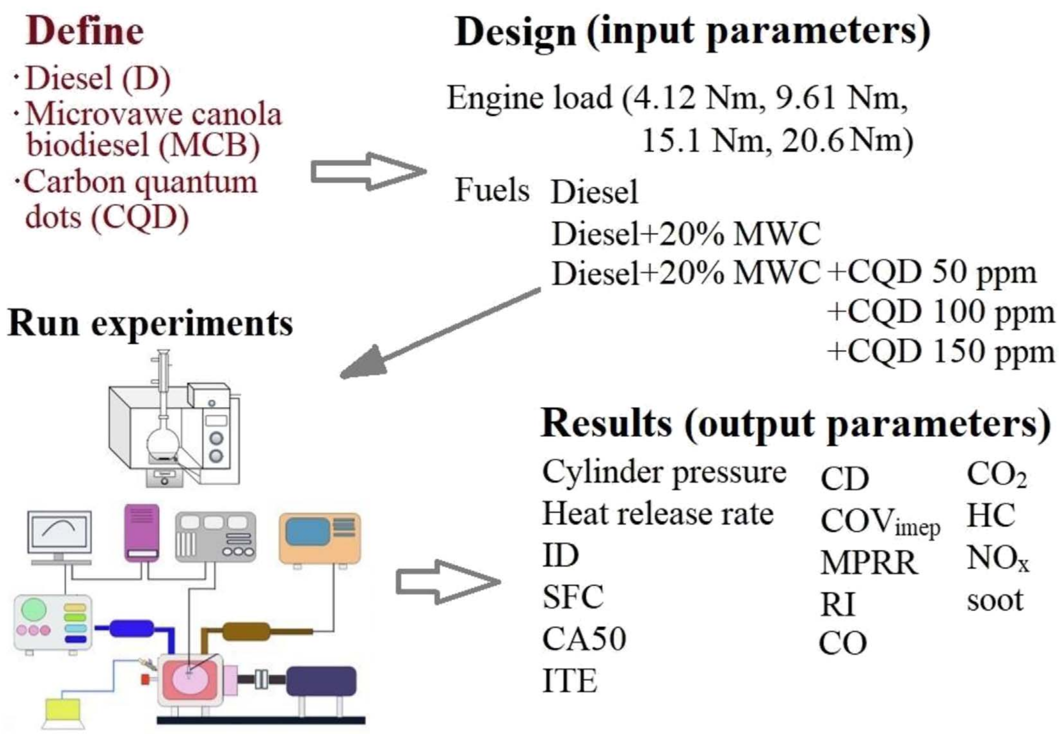

Fig. 1. Flow chart of the study.

The microwave-assisted transesterification reaction used canola oil, 0.5 wt% NaOH, and 25 wt% methanol. Canola oil was heated to 60 °C in the reactor. A methyl alcohol catalyst mixture was added to the canola oil. The reaction was carried out at 500 rpm, stirring speed 60 °C temperature, 100 W microwave output power, and 10 min reaction time. The mixture was transferred to the separation funnel at the end of the reaction. After separating the glycerin layer, the biodiesel was washed five times with pure water at 90 °C. The water and alcohol remaining in the biodiesel were evaporated by heating. The preparation of CQD additives for this study involved carefully controlled steps to ensure a stable and homogeneous blend with the B20 biodiesel-diesel fuel mix. First, biodiesel was produced from canola oil using microwave-assisted transesterification, after which it was blended with diesel fuel in an 80:20 ratio by volume to form the B20 base fuel. Next, CQDs were added to this B20 blend in concentrations of

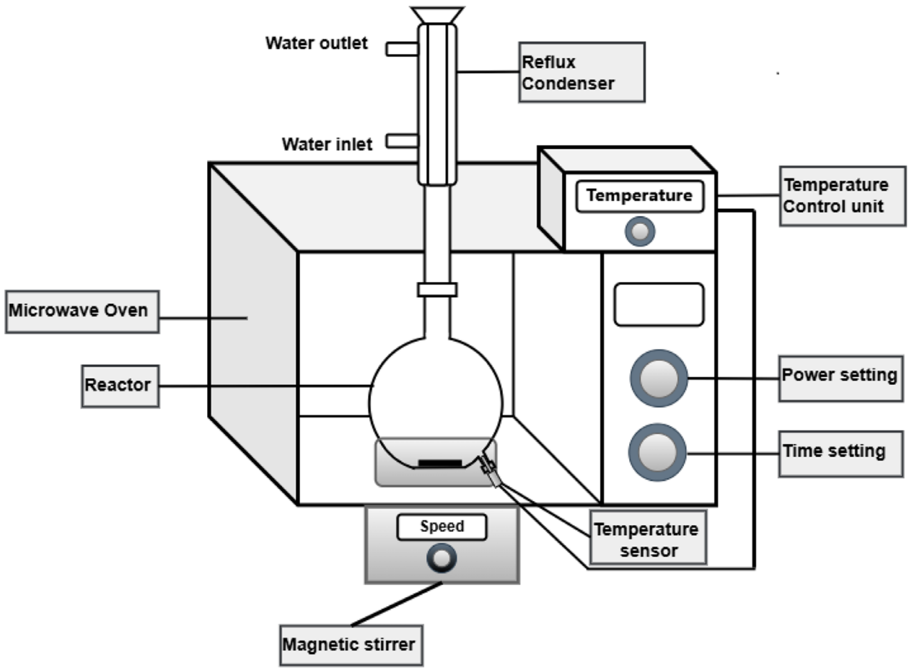

Fig. 2. Biodiesel production system.

Table 2. Test fuels properties.

	Diesel	B20
Density [kg/m^3 @ 15 °C]	831.88	841.48
Kinematic viscosity [mm^2/sn @40 °C]	3.09	3.49
Water content (wt.%)	0.0033	0.0077
Flash point [°C]	60	63
Calorific energy [kJ/kg]	44890	43740

50 ppm, 100 ppm, and 150 ppm to enable a comparative analysis of their effects at different dosages. To ensure even dispersion and prevent agglomeration of the CQDs within the fuel, an ultrasonic mixer was used for homogenization. Eventually, B20 and B20CQD 50 ppm, B20CQD 100 ppm and B20CQD 150 ppm test fuels were obtained. Test fuel properties are shown in Table 2.

2.2 Engine performance, combustion and emissions analysis

This paper focuses on the experimental investigation of the influences of nanoparticle addition into canola oil biodiesel. For this purpose, the engine test bed that is given in Figure 3 was installed at Afyon Kocatepe University, Technology Faculty in Internal Combustion Engine Laboratory. Antor AD510 BS CI engine was used in the tests. Engine properties were given in Table 3. Kemsan regenerative dynamometer was mounted with the engine that can absorb 20 HP. The tests were performed at 2200 rpm and 4.12, 9.61, 15.10 and 20.60 Nm engine loads. Fuel consumption in this study was measured by placing a calibrated scale under the fuel tank to monitor the change in fuel weight over a specified period of 2 min. The weight of the fuel was recorded at the beginning and end of each 2-minute interval. Measurements were taken at various engine loads (4.12, 9.61, 15.10, and 20.60 Nm) to evaluate fuel consumption under different operating conditions. To ensure consistency, the engine was warmed up prior to each measurement to achieve stable operating conditions.

HC, CO, CO_2, soot and NO_x emissions were determined using Bosch BEA 350 gas analyzer. The properties of the exhaust gas analyzer are shown in Table 4.

AVL QC34C in-cylinder pressure sensor was utilized for cylinder pressure measuring. It measured in-cylinder pressure with an interval of 0.36 °CA. Determined in-cylinder pressure data were then amplified using Kistler 5018A amplifier. National instrument 6351 data acquisition card was used to obtain analog data from digital data. In addition, the temperature of engine surface was determined using TFA ST-490 infrared thermometer. The uncertainties of the devices were calculated using method from literature [53]. The uncertainties of the encoder, precision balance and pressure sensor are 0.10, 0.001 and 0.5 respectively. The total uncertainties were determined as 0.72% by the method followed in the literature [54]. After taking the in-cylinder pressure data, heat release rate was computed using equation (1). To specify the total heat release, equation (1) was obtained dependent on the first law of thermodynamics. Heat transfer to the cylinder wall also includes as seen. Heat transfer can also be computed with equation (2) [55–58].

$$\frac{dQ_{gr}}{d\theta} = \frac{k}{k-1} P \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dP}{d\theta} + \frac{dQ_{heat}}{d\theta}. \quad (1)$$

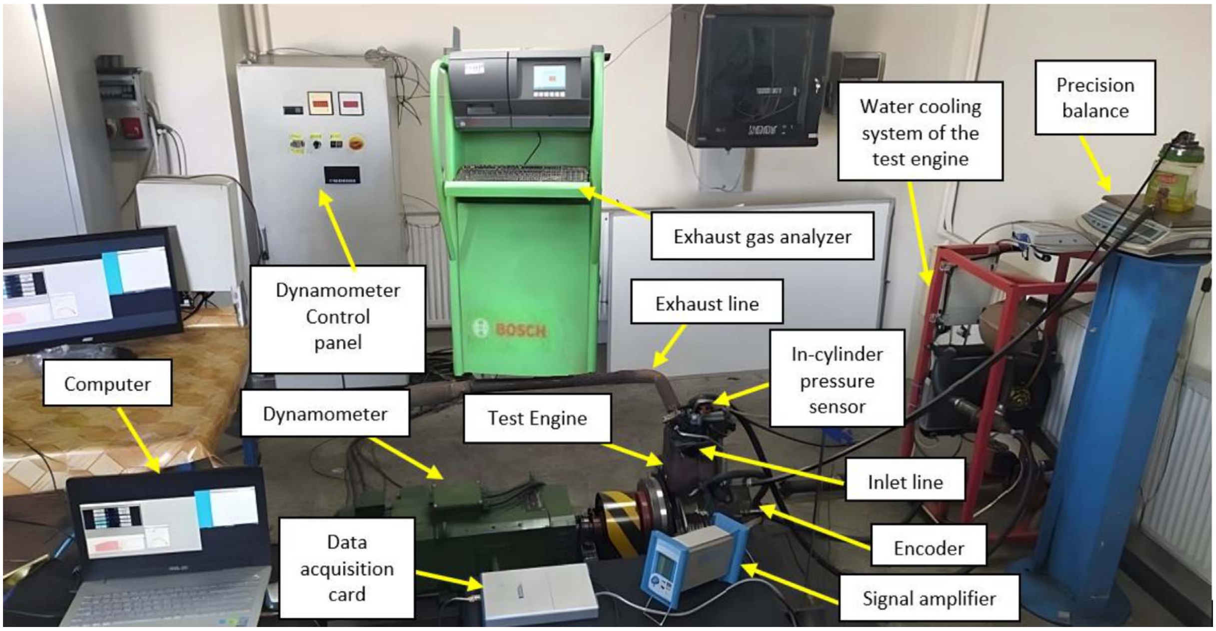

Fig. 3. Engine test setup.

Table 3. Test engine specifications.

Number of cylinders	1
Cylinder volume [cm^3]	510
Stroke x Bore [mm]	90 × 85 mm
Power output [HP]	12
Compression ratio	17.5:1
Maximum engine torque [Nm, at 1800 rpm]	32.8

Table 4. The technical properties of exhaust gas analyzer.

	Operating range	Uncertainty (%)	Sensitivity
CO_2 [%vol.]	0–18	0.056	0.01
CO [%vol.]	0–10	0.01	0.001
O_2 [%vol.]	0–22	0.045	0.01
HC [ppm]	0–9999	0.01	1
NO [ppm]	0–5000	0.02	1
Lambda	0.5–9.999	0.01	0.001

$$\frac{dQ_{heat}}{d\theta} = \frac{1}{6n} A_2 h_c \left(T_g - T_w \right). \tag{2}$$

In equation (2) T_w, T_g, h_c, A_2, n define the in-cylinder wall temperature, averaged in-cylinder gas temperature, heat transfer coefficient, heat transfer surface area and engine speed respectively

Q_{LHV}, W_{net} and m_f refer to calorific energy of the test fuel, net work and consumption of fuel respectively. Cyclic variations that are critical parameter for stable operation of the test engine were determined using equation 3 as mentioned below [55–58].

$$COV_{imep} = \frac{\sigma_{imep}}{\bar{X}} \times 100. \tag{3}$$

3 Results and discussion

In this study, the effects of adding CQDs to a B20 biodiesel-diesel blend (produced with 80% diesel and 20% canola biodiesel) were evaluated across combustion, performance, and emissions characteristics. CQDs were tested at concentrations of 50 ppm, 100 ppm, and 150 ppm. Key parameters, including in-cylinder pressure, heat release rate, and ignition delay, were analyzed to understand the catalytic role of CQDs in enhancing biodiesel performance.

As shown in Figure 4, the highest in-cylinder pressure was observed with pure diesel fuel, with a noticeable reduction in pressure for the B20 biodiesel blend. This reduction aligns with the lower calorific value of biodiesel, which limits energy release during combustion. However, the addition of CQDs to the B20 blend resulted in a slight increase in maximum cylinder pressure, indicating improved combustion efficiency due to the catalytic effect of CQDs [55–70]. This result aligns with findings from El-Fakharany *et al.*, who observed that adding cerium oxide nanoparticles to biodiesel improved peak pressures by enhancing combustion reactions through catalytic effects [71]. Furthermore, the heat release rate demonstrated an increase with CQD addition, particularly at the higher 150 ppm concentration, suggesting enhanced combustion intensity facilitated by the CQDs' high thermal conductivity, as supported by Zheng *et al.*, who documented similar results with metal-based nanoparticles in biodiesel blends [72].

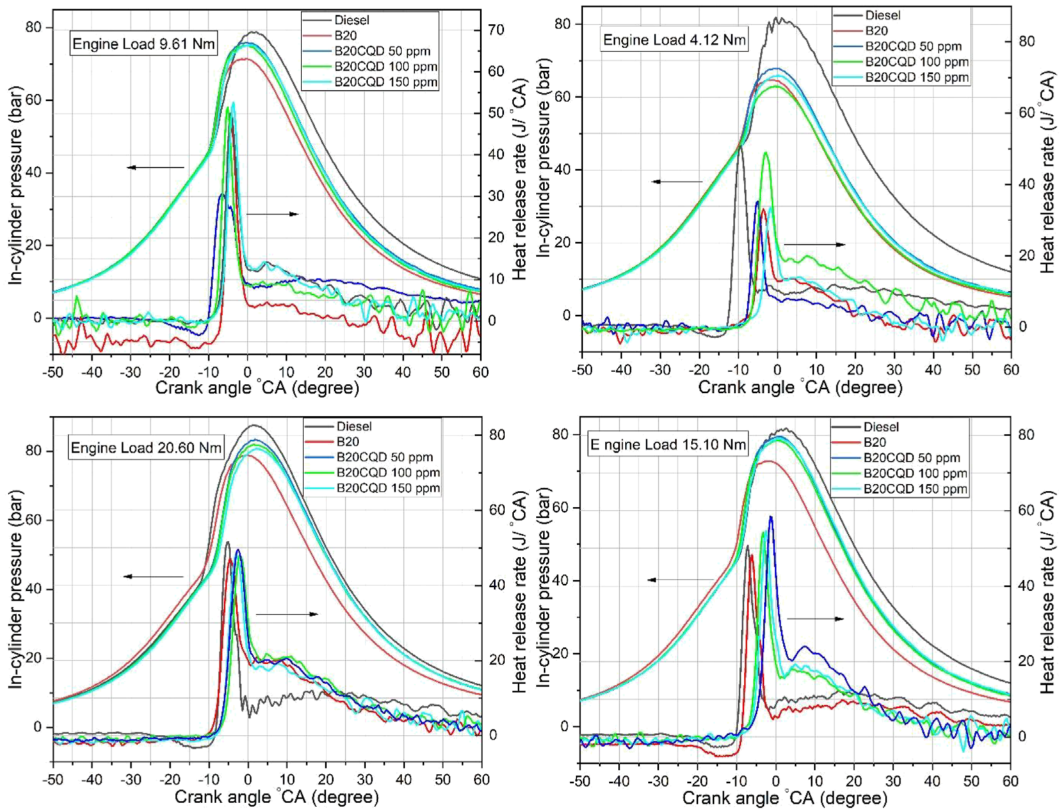

Fig. 4. The influences of carbon quantum dot nanoparticle material addition on heat release rate and cylinder pressure.

Figure 5 displays the ignition delay (ID) variations for different CQD concentrations under increasing load conditions. In general, ID decreased as engine load increased, likely due to higher temperatures that favour autoignition [55–65]. The B20 blend exhibited a prolonged ID, attributed to its higher viscosity and density, which slowed fuel pulverization and vaporization [55–70, 73, 74]. However, with CQD addition, ID was significantly shortened, especially in the B20CQD 150 ppm blend, indicating that the CQDs' oxygen content and catalytic properties facilitated quicker ignition. These results corroborate those of Dhanarasu *et al.*, who observed that oxygenated nanoparticles in biodiesel improved ignition characteristics by accelerating fuel-air mixing and ignition [75].

As depicted in Figure 6, SFC decreases up to an engine load of 15.10 Nm across all test fuels, achieving the lowest SFC at this load. This trend is attributed to reduced heat losses and gas leakages at lower loads, allowing for more complete fuel oxidation [63, 76–79]. However, beyond 15.10 Nm (at 20.60 Nm), SFC values increase due to inadequate oxygen availability, which slows down combustion reactions, requiring more fuel to maintain power output. This observation aligns with findings from Ansari *et al.*, who reported that higher loads in biodiesel-diesel blends can lead to increased SFC due to similar limitations in oxygen supply and heat retention [32].

Biodiesel's higher viscosity and density, as well as its lower calorific value, contribute to increased fuel consumption [76–83]. Biodiesel-diesel blends generally result in higher SFC because more fuel volume must be injected to achieve comparable energy output, consistent with the findings of Sharifianjazi *et al.*, who noted that biodiesel's fuel economy is inherently limited due to these physical properties [84]. The addition of CQDs notably decreases SFC compared to the B20 blend without CQDs. The CQD nanoparticles, with their high oxygen content, help improve the combustion process by enhancing oxygen availability and facilitating chemical reactions within the combustion chamber. This catalytic effect reduces the fuel required for complete combustion. For instance, SFC increased by 2.03%, 4.83%, 4.40%, and 1.69% with B20, B20CQD 50 ppm, B20CQD 100 ppm, and B20CQD 150 ppm, respectively, compared to pure diesel at 15.10 Nm. This improvement is supported by recent studies such as those by Lv *et al.*, who found that oxygenated nanoparticles in biodiesel effectively reduce SFC by improving combustion kinetics [85]. Higher CQD concentrations (such as 100 ppm and 150 ppm) demonstrated further reductions in SFC compared to lower concentrations, indicating an incremental benefit in fuel efficiency with increased nanoparticle concentration. These findings align with research by Sharifianjazi *et al.*, who observed that increasing nanoparticle concentration in biodiesel improves combustion efficiency, as evidenced by reduced fuel consumption [84].

As shown in Figure 7, CA50 occurred slightly after Top Dead Center (TDC) for the B20 blend compared to diesel, indicating a slight delay in combustion phasing due to biodiesel's higher viscosity and density, which affects

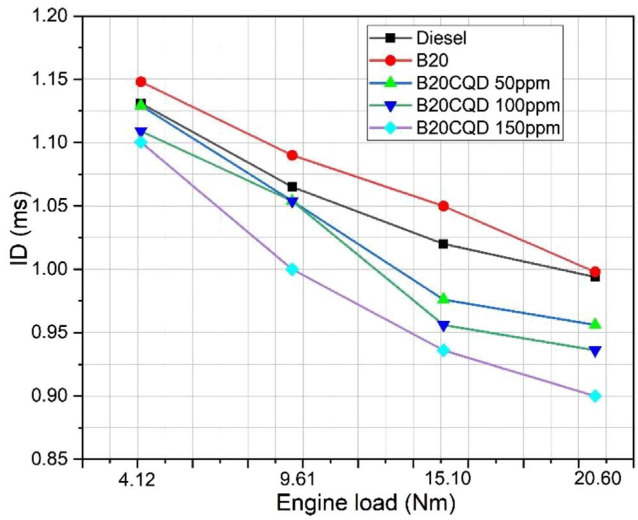

Fig. 5. ID variations.

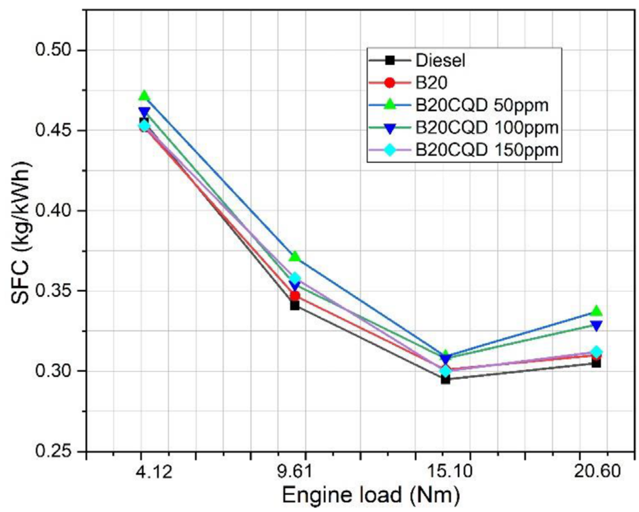

Fig. 6. The variations of SFC.

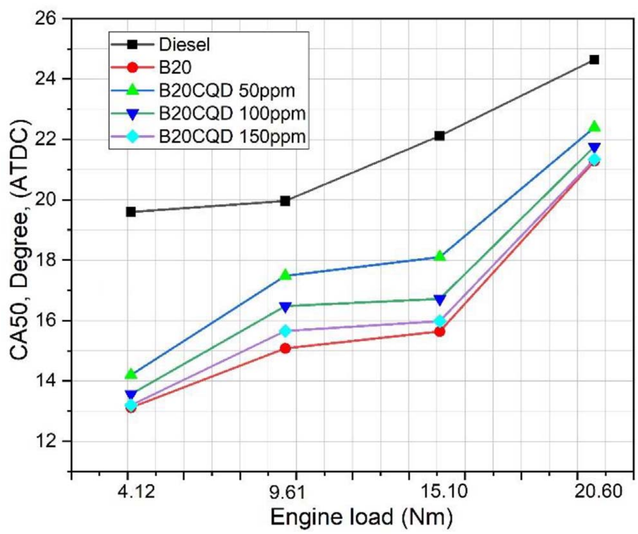

Fig. 7. The variations of CA50.

atomization and ignition properties. The later CA50 for B20 correlates with findings from Sirinivasan *et al.*, who reported that biodiesel's lower volatility and increased viscosity generally lead to delayed combustion phasing [86].

When CQDs were added to the B20 blend, CA50 was further retarded, suggesting that the presence of CQDs affects the combustion timeline, potentially due to improved oxygen availability and catalytic support for combustion reactions. Strong relationship between CA50 and thermal efficiency is seen. CA50 shifts with increasing CQD concentration, indicating slower energy release rates. There is a clear relationship between CA50 and thermal efficiency, as thermal efficiency typically peaks when CA50 occurs near TDC [55–58, 67–73]. In this study, thermal efficiency was highest for diesel, with a slight reduction in B20 due to the inherent properties of biodiesel. The addition of CQDs did not significantly impact thermal efficiency but helped to stabilize combustion. Sai *et al.* observed that oxygenated nanoparticles like CQDs support thermal efficiency by enhancing combustion completeness, despite slight shifts in CA50 [87].

Higher CQD concentrations, such as 100 ppm and 150 ppm, exhibited more pronounced effects on CA50 timing, shifting it further from TDC. Although this shift can slightly decrease thermal efficiency, it also improves combustion stability and reduces emissions by allowing more thorough oxidation reactions. This trade-off between CA50 timing and thermal efficiency aligns with results from Ilyas *et al.*, who reported that metal oxide nanoparticles in biodiesel blends can stabilize combustion even with slight efficiency reductions due to delayed CA50 [88].

Figure 8 illustrates the changes of CD. The end of combustion has been determined as 90% of the mixture complemented to ignite dependent versus crank angle. Maximum CD was obtained in case of diesel usage. Shorter CD was obtained with B20 according to diesel. But CD increased with nanoparticle additive [77–83]. In addition, CD is shortened with the rise of nanoparticle fraction in the fuel mixtures. It can be mentioned that quantum dot showed catalyst effect and caused to increase combustion velocity. Besides, CD is shortened.

Cyclic variation is a significant variable in view of stable engine operation. Cyclic variation of imep decreases are seen with the rise of load as shown in Figure 9. Cyclic differences show how regularly the engine operates. Charge mixture that enters the cylinder and gas temperature increase in case of engine load rise. This situation improves the combustion conditions and reduces cyclic variations. COV_{imep} declined with the rise of engine load for each test fuel. It was also realized that cyclic variations increased with the CQD nanoparticle additive. It can be explained that oxidation reactions are improved and combustion was partially accelerated [58–66, 73–81]. Operation that is more irregular was observed with the addition of nanoparticles compared to pure diesel and B20. Maximum cyclic variations were computed with B20CQD 150 ppm.

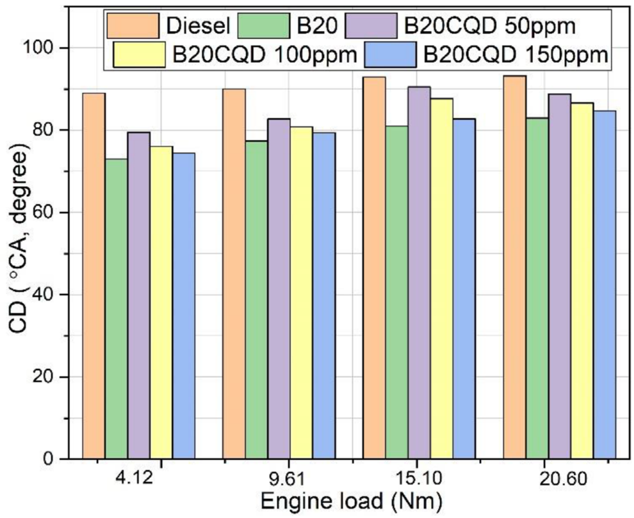

Fig. 8. The variations of CD.

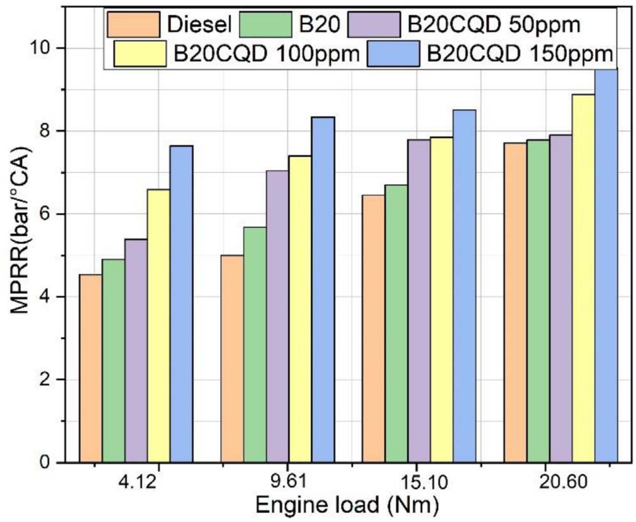

Fig. 10. The variations of MPRR.

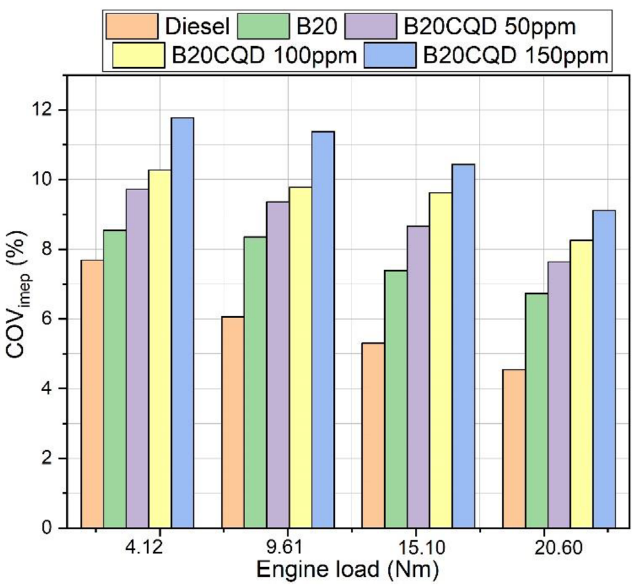

Fig. 9. Cyclic variations of imep.

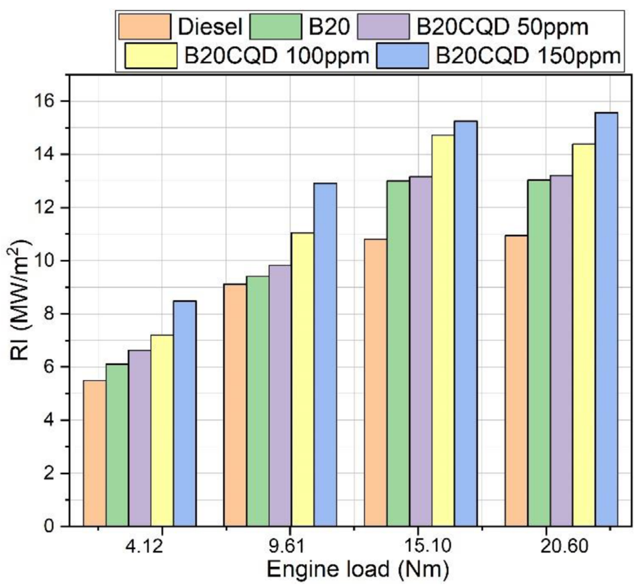

Fig. 11. The changes of RI.

The pressure at the end of combustion has shown a sudden increased tendency in CI engines because of the auto ignition approach [55–58]. If in-cylinder pressure that is applied to the piston increases too much, a knocking tendency is seen. Figure 10 defines the Maximum Pressure Rise Rates (MPRR). As seen in Figure 10, MPRR values increased with fuel blends. It was also seen that MPRR rose with the addition of nanoparticle. Nanoparticle material supported to occur sudden oxidation reactions and pressure force that is applied to crankshaft increased suddenly [76–83]. The highest MPRR was computed with B20CQD 150 ppm.

Figure 11 represents the changes of computed Ringing Intensity (RI) with the test fuels. RI raised with the rise of engine load like MPRR. In-cylinder pressure and knocking tendency raise when the charge mixture taken into cylinder is increased. Nanoparticle addition showed a reactivation effect on oxidation reactions, ignition and combustion characteristics were improved [55–62, 69–83]. Maximum RI was obtained with B20CQD 150 ppm at 20.60 Nm engine load.

Figure 12 represents the changes of CO and CO_2. It can be claimed that oxygen concentration decreases in case engine load increases. In the meantime, oxidation reactions are deteriorated between fuel and oxygen molecules. Thus, CO formation is accelerated. In Figure 12a, CO raises with D80MCB20 compared to diesel. The tendency of obtain a homogeneous charge mixture is badly influenced using biodiesel because of higher density and viscosity. So, combustion is worsened, and lower in-cylinder gas temperature

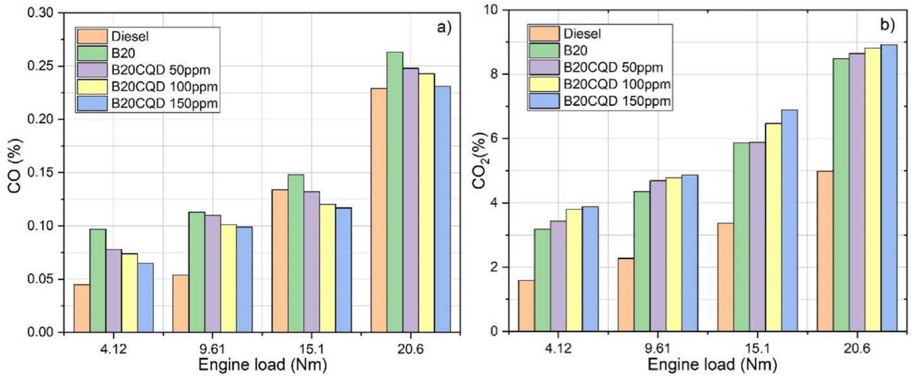

Fig. 12. CO and CO_2 emissions. a) CO emissions; b) CO2 emissions.

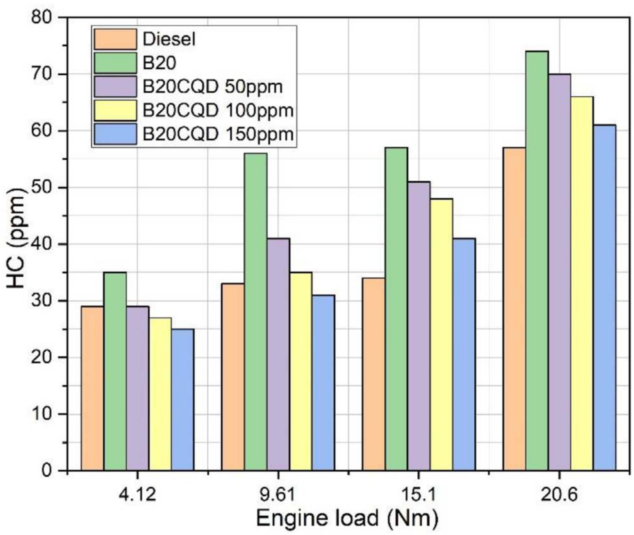

Fig. 13. HC emissions.

is obtained. Consequently, CO is generated owing to insufficient gas temperature. Reaction rate increases with nanoparticle additive and CO formation decreases. Moreover, the rise of nanoparticle additives in the fuel mixtures caused to reduce CO emissions. CO was reduced by 5.70%, 7.60% and 12.16% using B20CQD 50 ppm, B20CQD 100 ppm and B20CQD 150 ppm according to B20 respectively, at 20.60 Nm engine load. When Figure 12b was examined, it was found that CO_2 showed the opposite change compared to CO. CO_2 increased with the increase of nanoparticle addition. Improved combustion characteristics were obtained using nanoparticles. Thermal properties of nanoparticle cause to increase reaction rate. In the end, CO_2 increase was seen.

Figure 13 shows the influences of nanoparticle addition on HC emissions. HC raised with B20 compared to diesel. The possibility of obtaining homogeneous charge mixture decreases due to the physical properties and poor injection properties of biodiesel. Homogeneous fuel and oxygen mixture can not be obtained. This phenomenon causes to form rich mixture regions in cylinder. So, oxidation reactions slow down on the piston and ring edges and cavities. Nevertheless, HC formation is reduced with quantum dot nanoparticle addition. Nanoparticle material acts as an energy-carrying catalyst and improves the chemical combustion reactions. Consequently, HC emissions reduce. It was presented that HC reduced by about 5.40%, 10.81% and 17.56% with B20 compared to B20CQD 50 ppm, B20CQD 100 ppm and B20CQD 150 ppm test fuels, respectively at 20.60 Nm.

The changes of NO_x and soot emissions are shown in Figure 14. NO_x raised with the rise of engine load as given in Figure 14a. Higher NO_x was measured with B20 according to diesel. ID period is prolonged owing to higher viscosity and density of biodiesel. Hence, all mixture would like to ignite immediately to towards to the end of the compression process. This case leads to sudden combustion and increases in-cylinder pressure and temperature too much. Nitrogen and oxygen molecules can react with each other at high in-cylinder gas temperatures. Hence, NO_x is formed. Furthermore, nanoparticle addition to B20 provided more chemical reactivation. This situation was accelerated NO_x formation mechanisms. On the other hand, Figure 14b presents the variations of soot emissions. It was realized that maximum soot was obtained using diesel. Soot emissions were significantly reduced with fuel mixtures. It was attributed that the oxygen content and high reaction energy of biodiesel and nanoparticle prevented the soot formation. Minimum soot was determined with B20CQD 150 ppm at 20.60 Nm.

4 Conclusion

This research provides a comprehensive experimental evaluation of the effects of CQDs as an additive in a diesel/canola oil biodiesel blend (B20) on combustion characteristics, engine performance, and emissions in a single-cylinder CI engine. By utilizing microwave-assisted transesterification, a method known for increasing conversion efficiency but resulting in higher viscosity and density, this study addresses the specific challenges associated with biodiesel use in diesel engines.

The experimental results demonstrated that adding CQDs to the B20 blend significantly influences both

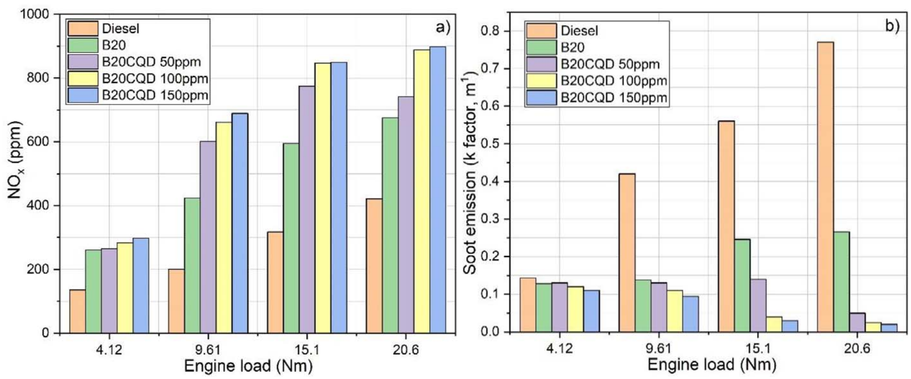

Fig. 14. The variations of NO_x and soot emissions. a) The variations of NOx emissions; b) The variations of soot emissions.

combustion and emission parameters. Specifically, the heat release rate and in-cylinder pressure were observed to decrease for the B20 and B20-CQD fuel blends compared to pure diesel, attributed to the lower calorific value of biodiesel. However, CQD addition shortened the ID period, enhancing combustion stability and ignition quality. At a load of 15.10 Nm, SFC increased by 2.03%, 4.83%, 4.40%, and 1.69% for B20, B20CQD 50 ppm, B20CQD 100 ppm, and B20CQD 150 ppm, respectively, compared to diesel. This rise in SFC is consistent with the higher viscosity and lower heating value of biodiesel blends.

In terms of emissions, the study found significant reductions in both CO and HC emissions with increasing CQD concentrations. CO emissions decreased by 5.70%, 7.60%, and 12.16%, and HC emissions were reduced by 5.40%, 10.81%, and 17.56% for B20CQD 50 ppm, B20CQD 100 ppm, and B20CQD 150 ppm, respectively, at full load. This improvement is attributed to the catalytic properties of CQDs, which enhance oxidation reactions, resulting in more complete combustion. Additionally, the nanoparticle additive effectively reduced soot emissions, with the lowest soot levels observed in the B20CQD 150 ppm blend at 20.60 Nm. However, an increase in NOx emissions was noted with the use of CQD blends, likely due to elevated combustion temperatures and enhanced reactivity from the additive.

Moreover, the MPRR and RI were found to increase with CQD addition, suggesting that while CQDs improve combustion efficiency, they also introduce a greater propensity for knocking at higher concentrations. These findings underline the dual role of CQDs as both a combustion enhancer and an emissions reducer, though careful optimization is required to balance performance gains with potential increases in NOx.

In conclusion, this study illustrates that CQDs are a promising additive for improving biodiesel combustion efficiency and emission profiles. The results support the potential of CQDs to enhance biodiesel's viability in diesel engines by addressing critical limitations. Future studies could focus on optimizing CQD concentration to achieve a more favorable balance between enhanced combustion and minimized emissions, contributing to the development of cleaner, more efficient biodiesel-powered engines. In addition, future studies can modify the fuel injection timing to reduce the NO_x increase caused by CQDs.

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References

1 El-Adawy M. (2023) Effects of diesel-biodiesel fuel blends doped with zinc oxide nanoparticles on performance and combustion attributes of a diesel engine, *Alexandria Eng. J.* **80**, 269–281.

2 Ooi J.B., Ismail H.M., Tan B.T., Wang X. (2018) Effects of graphite oxide and single walled carbon nanotubes as diesel additives on the performance, combustion, and emission characteristics of a light-duty diesel engine, *Energy* **161**, 70–80.

3 Yana S., Nizar M., Mulyati D. (2022) Biomass waste as a renewable energy in developing bio-based economies in Indonesia: a review, *Renew. Sustain. Energy Rev.* **160**, 112268.

4 Sharma A., Singh Y., Singh N.K., Singla A., Ong H.C., Chen W.H. (2020) Effective utilization of tobacco (Nicotiana Tabaccum) for biodiesel production and its application on diesel engine using response surface methodology approach, *Fuel* **273**, 117793.

5 Maawa W.N., Mamat R., Najafi G., De Goey L.P.H. (2020) Performance, combustion, and emission characteristics of a CI engine fueled with emulsified diesel-biodiesel blends at different water contents, *Fuel* **267**, 117265.

6 Yılmaz N., Atmanlı A., Hall M.J., Vigil F.M. (2022) Determination of the optimum blend ratio of diesel, waste oil derived biodiesel and 1-pentanol using the response surface method, *Energies* **15**, 14, 5144.

7 Yaashikaa P.R., Kumar P.S., Karishma S. (2022) Bio-derived catalysts for production of biodiesel: a review on feedstock, oil extraction methodologies, reactors and lifecycle assessment of biodiesel, *Fuel* **316**, 123379.

8 Jain A., Bora B.J., Kumar R., Sharma P., Deepanraj B., Irshad K., Ravikiran C. (2023) Application of hybrid Taguchi L16 and desirability for model prediction and optimization in assessment of the performance of a novel Water Hyacinth biodiesel run diesel engine, *Fuel* **339**, 127377.

9 Ashok A., Gugulothu S.K., Reddy R.V., Gurel A.E., Deepanraj B. (2022) Prediction-optimization of the influence of 1-pentanol/jatropha oil blends on RCCI engine characteristics using multi-objective response surface methodology, *Renew. Energy Focus* **42**, 8–23.

10 Solmaz H., Sürer E., Yılmaz E., Calam A., İpci D. (2023) Investigation of the effect of carbon nanotube addition to diesel-biodiesel blend on engine performance and exhaust emissions, *J. Faculty Eng. Archit. Gazi Univ.* **38**, 2, 1055–1064.

11 Solmaz H., Calam A., Yılmaz E., Şahin F., Ardebili S.M.S., Aksoy F. (2023) Evaluation of MWCNT as fuel additive to diesel-biodiesel blend in a direct injection diesel engine, *Biofuels-UK* **14**, 2, 147–156.

12 Shekofteh M., Gundoshmian T.M., Jahanbakhshi A., Heidari-Maleni A. (2020) Performance and emission characteristics of a diesel engine fueled with functionalized multi-wall carbon nanotubes (MWCNTs-OH) and diesel–biodiesel–bioethanol blends, *Energy Rep.* **6**, 1438–1447.

13 Heidari-Maleni A., Gundoshmian T.M., Jahanbakhshi A., Ghobadian B. (2020) Performance improvement and exhaust emissions reduction in diesel engine through the use of graphene quantum dot (GQD) nanoparticles ethanol-biodiesel blends, *Fuel* **267**, 117116.

14 Hoseini S.S., Najafi G., Ghobadian B., Ebadi M.T., Mamat R., Yusaf T. (2020) Biodiesels from three feedstock: the effect of graphene oxide (GO) nanoparticles diesel engine parameters fuelled with biodiesel, *Renew. Energy* **145**, 190–201.

15 Solmaz H., Ardebili S.M.S., Calam A., Yılmaz E., İpci D. (2021) Prediction of performance and exhaust emissions of a CI engine fueled with multi-wall carbon nanotube doped biodiesel-diesel blends using response surface method, *Energy* **227**, 120518.

16 Heydari-Maleney K., Taghizadeh-Alisaraei A., Ghobadian B., Abbaszadeh-Mayvan A. (2017) Analyzing and evaluation of carbon nanotubes additives to diesohol-B2 fuels on performance and emission of diesel engines, *Fuel* **196**, 110–123.

17 Shaafi T., Sairam K., Gopinath A., Kumaresan G., Velraj R. (2015) Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends– A review, *Renew. Sustain. Energy Rev.* **49**, 563–573.

18 Selvan V.A.M., Anand R.B., Udayakumar M. (2014) Effect of cerium oxide nanoparticles and carbon nanotubes as fuel-borne additives in diesterol blends on the performance, combustion and emission characteristics of a variable compression ratio engine, *Fuel* **130**, 160–167.

19 El-Seesy A.I., Abdel-Rahman A.K., Bady M., Ookawara S. (2017) Performance, combustion, and emission characteristics of a diesel engine fueled by biodiesel-diesel mixtures with multi-walled carbon nanotubes additives, *Energy Convers. Manag.* **135**, 373e93.

20 Lai C.M., Loo D.L., Teoh Y.H., How H.G., Le T.D., Nguyen H.T., Ghfar A.A., Sher F. (2023) Optimization and performance characteristics of diesel engine using green fuel blends with nanoparticles additives, *Fuel* **347**, 128462.

21 Laad M., Jatti V.K.S. (2018) Titanium oxide nanoparticles as additives in engine oil, *J. King Saud. Univ. Eng. Sci.* **30**, 116–122.

22 Uflyand I.E., Zhinzhilo V.A., Burlakova V.E. (2019) Metal-containing nanomaterials as lubricant additives: state-of-the-art and future development, *Friction* **7**, 93–116.

23 Ghanbari M., Mozafari-Vanani L., Dehghani-Soufi M., Jahanbakhshi A. (2021) Effect of alumina nanoparticles as additive with diesel–biodiesel blends on performance and emission characteristic of a six-cylinder diesel engine using response surface methodology (RSM), *Energy Convers. Manag. X* **11**, 100091.

24 Tyagi H., Phelan P. E., Prasher R., Peck R., Lee T., Pacheco J.R., Arentzen P. (2008) Increased hot-plate ignition probability for nanoparticle-laden diesel fuel, *Nano Lett.* **8**, 5, 1410–1416.

25 Günaydın S., Uyumaz A., Kocakulak T., Coşman S., Solmaz H., Aksoy F. (2024) Evaluation of dibutyl maleate/diesel blends on combustion, performance and emissions in a DI diesel engine, *Appl. Ther. Eng.* **236**, 121520.

26 Sarma C.J., Sharma P., Bora B.J., Bora D.K., Senthilkumar N., Balakrishnan D., Ayesh A.I. (2023) Improving the combustion and emission performance of a diesel engine powered with mahua biodiesel and TiO_2 nanoparticles additive, *Alexandria Eng. J.* **72**, 387–398.

27 Alex Y., Earnest J., Raghavan A., Roy R.G., Koshy C.P. (2022) Study of engine performance and emission characteristics of diesel engine using cerium oxide nanoparticles blended orange peel oil methyl ester, *Energy Nexus* **8**, 100150.

28 Bitire S.O., Jen T.C. (2022) The role of a novel green synthesized nanoparticles added parsley biodiesel blend on the performance-emission characteristics of a diesel engine, *South Afr. J. Chem. Eng.* **41**, 1, 161–175.

29 Kumar S., Dinesha P., Bran I. (2017) Influence of nanoparticles on the performance and emission characteristics of a biodiesel fuelled engine: an experimental analysis, *Energy* **140**, 98–105.

30 Opuz M., Uyumaz A., Babagiray M., Solmaz H., Calam A., Aksoy F. (2023) The effects of metallic fuel addition into canola oil biodiesel on combustion, engine performance and exhaust emissions, *J. Energy Inst.* **111**, 101390.

31 Razzaq L., Abbas M. M., Waseem A., Jauhar T. A., Fayaz H., Kalam M. A., Soudagar M. E. M., Silitonga A S, Samr-Ul-Husnain, Ishtiaq U. (2023) Influence of varying concentrations of TiO_2 nanoparticles and engine speed on the performance and emissions of diesel engine operated on waste cooking oil biodiesel blends using response surface methodology, *Heliyon* **9**, 7, e17758.

32 Ansari A.M., Memon L.A., Ghannam M.T., Selim M.Y. (2023) Impact of biodiesel blended fuel with nanoparticles on performance and noise emission in compression ignition engine, *Int. J. Thermofluids* **19**, 100390.

33 Mostafa A., Mourad M., Mustafa A., Youssef I. (2023) Influence of aluminum oxide nanoparticles addition with diesel fuel on emissions and performance of engine generator set using response surface methodology, *Energy Convers. Manag. X* **19**, 100389.

34 Suhel A., Rahim N.A., Rahman M.R.A., Ahmad K.A.B., Khan U., Teoh Y.H., Abidin N.Z. (2023) Impact of ZnO nanoparticles as additive on performance and emission characteristics of a diesel engine fueled with waste plastic oil, *Heliyon* **9**, 4, e14782.

35 Simsek S. (2020) Effects of biodiesel obtained from Canola, sefflower oils and waste oils on the engine performance and exhaust emissions, *Fuel* **265**, 117026.

36 Nachippan N.M., Parthasarathy M., Elumalai P.V., Backiyaraj A., Balasubramanian D., Hoang A.T. (2022) Experimental assessment on characteristics of premixed charge compression ignition engine fueled with multi-walled carbon nanotube-included Tamanu methyl ester, *Fuel* **323**, 124415.

37 Balasubramanian D., Venugopal I.P., Viswanathan K. (2019) Characteristics investigation on Di diesel engine with nano-particles as an additive in lemon grass oil, *SAE Technical Paper No. 2019-28-0081*

38 Aalam C.S., Saravanan C.G., Kannan M. (2015) Experimental investigations on a CRDI system assisted diesel engine fuelled with aluminium oxide nanoparticles blended biodiesel, *Alex. Eng. J.* **54**, 3, 351–358.
39 Balasubramanian D., Inbanaathan P.V., Gugulothu S.K., Noga M. (2021) Characterization of single-cylinder di diesel engine fueled with waste cooking oil biofuel/diesel blends, in: *Alternative fuels and advanced combustion techniques as sustainable solutions for internal combustion engines*, Springer Singapore, Singapore, pp. 173–196.
40 Xie J., Li X., Hu Y. (2023) Catalytic properties of carbon quantum dots in biodiesel applications, *J. Renew. Energy.*
41 Wang F., Ma L., Shi Y. (2022) Thermal properties and catalytic effects of carbon quantum dots on biodiesel combustion, *Int. J. Green Energy.*
42 Zhang W., Liu H., Zhao T. (2023) Impact of carbon quantum dots on heat transfer and emission characteristics of biodiesel, *J. Clean Prod.*
43 Chen Z., *et al.* (2021) Microwave-assisted biodiesel synthesis and the role of carbon quantum dots, *Renew. Energy Rev.*
44 Lin M., Zhou Y., Tang J. (2024) Emission control using carbon quantum dots as fuel additives in CI engines, *Molecules.* Available at: https://www.mdpi.com/1420-3049/29/9/2002.
45 Isah A.G., Faruk A.A., Musa U., Garba U.M., Alhassan M., Abdullahi U.B., Damian A.T. (2022) Oxidation stability and cold flow properties of biodiesel synthesized from castor oil: influence of alkaline catalysts type and purification techniques, *Mater. Today Proc.* **57**, 748–752.
46 Gopi R., Thangarasu V., Ramanathan A. (2022) A critical review of recent advancements in continuous flow reactors and prominent integrated microreactors for biodiesel production, *Renew. Sustain. Energy Rev.* **154**, 111869.
47 Fukuda H., Kondo A., Noda H. (2001) Biodiesel fuel production by transesterification of oils, *J. Biosci. Bioeng.* **92**, 5, 405–416.
48 Ghaly A.E., Dave D., Brooks M.S., Budge S. (2010) Production of biodiesel by enzymatic transesterification, *Am. J. Biochem. Biotechnol.* **6**, 2, 54–76.
49 Lourenço V.A., Nadaleti W.C., Vieira B.M., Li H. (2021) Investigation of ethyl biodiesel via transesterification of rice bran oil: bioenergy from residual biomass in Pelotas, Rio Grande do Sul-Brazil, *Renew. Sustain. Energy Rev.* **144**, 111016.
50 Aksoy L. (2011) Opium poppy (Papaver somniferum L.) oil for preparation of biodiesel: optimization of conditions, *Appl. Energy* **88**, 12, 4713–4718.
51 Hsiao M.C., Lin C.C., Chang Y.H., Chen L.C. (2010) Ultrasonic mixing and closed microwave irradiation-assisted transesterification of soybean oil, *Fuel* **89**, 12, 3618–3622.
52 Athar M., Imdad S., Zaidi S., Yusuf M., Kamyab H., Klemeš J.J., Chelliapan S. (2022) Biodiesel production by single-step acid-catalysed transesterification of Jatropha oil under microwave heating with modelling and optimisation using response surface methodology, *Fuel* **322**, 124205.
53 Taheri-Garavand A., Heidari-Maleni A., Mesri-Gundoshmian T., Samuel O.D. (2022) Application of artificial neural networks for the prediction of performance and exhaust emissions in IC engine using biodiesel-diesel blends containing quantum dot based on carbon doped, *Energy Convers. Manag. X* **16**, 100304.
54 Mary L.L.G., Manivel S., Garg S., Nagam V.B., Garse K., Mali R., Baig R.U. (2023) Exploring the impact of Al_2O_3 additives in gasoline on HCCI-DI engine performance: an experimental, neural network, and regression analysis approach*ACS Omega* **8**, 50, 47701–47713.
55 Heywood J.B. (1988) *Internal combustion engines fundamentals.* USA: McGraw-Hill.
56 Zhao H. (2007) *HCCI and CAI engines for the automotive industry.* Cambridge, UK: Woodhead Publishing Ltd.
57 Stone R. (1999) *Introduction to internal combustion engines,* Macmillan Press Ltd, pp. 295–300. ISBN 0-333-74013-0, Tesseraux, I.;Toxicoll, Lett., 2004, 149.
58 Eng J.A. (2022) *Characterization of pressure waves in HCCI combustion*, SAE Paper 2002-01-2859.
59 Polat S., Kannan K., Shahbakhti M., Uyumaz A., Yücesu H.S. (2015) An experimental study for the effects of supercharging on performance and combustion of an early direct injection HCCI engine, in: 2nd International Conference On Science, Technology, Engineering And Management, 3–4 July, Dubai.
60 Tsurushima T. (2009) A newskeletal PRF kinetic model for HCCI combustion, *Proc. Combust. Inst.* **32**, 2835–2841.
61 Amano T., Morimoto S., Kawabata Y. (2001) Modeling of the effect of air/fuel ratio and temperature distribution on HCCI engines, *SAE Technical Paper 2001-01-1024.*
62 Sjöberg M., Edling L., Eliassen T., Magnusson L., Angstrm H. (2002) GDI HCCI: effects of injection timing and air swirl on fuel stratification, combustion and emissions formation, *SAE Technical Paper 2002-01-0106.*
63 Wildman C., Scaringe R.J., Cheng W. (2009) On the maximum pressure rise rate in boosted HCCI operation, *SAE* **2009**.
64 Razzaq L., Mujtaba M. A., Soudagar M. E. M., Ahmed W., Fayaz H., Bashir S., Fattah I. M. R., Ong H. C., Shahapurkar K., Afzal A., Wageh S., Al-Ghamdi A., Ali M. S., El-Seesy A. I. (2021) Engine performance and emission characteristics of palm biodiesel blends with graphene oxide nanoplatelets and dimethyl carbonate additives, *J. Environ. Manag.* **282**, 111917.
65 Qian W., Huang H., Pan M., Huang R., Tong C., Guo X., Yin J. (2020) Effects of 2-ethylhexyl nitrate and post-injection strategy on combustion and emission characterizes in a dimethyl carbonate/diesel blending engine, *Fuel* **263**, 116687.
66 Pan M., Qian W., Zheng Z., Huang R., Zhou X., Huang H., Li M. (2019) The potential of dimethyl carbonate (DMC) as an alternative fuel for compression ignition engines with different EGR rates, *Fuel* **257**, 115920.
67 Wang X., Cheung C.S., Di Y., Huang Z. (2012) Diesel engine gaseous and particle emissions fueled with diesel–oxygenate blends, *Fuel* **94**, 317–323.
68 Barrientos E.J., Lapuerta M., Boehman A.L. (2013) Group additivity in soot formation for the example of C-5 oxygenated hydrocarbon fuels, *Combust. Flame* **160**, 8, 1484–1498.
69 Singh S., Kumar A., Mahla S.K., Batth G.S. (2013) Experimental study on emission analysis of oxygenated fuels dimethyl carbonate (DMC) and dibutyl maleate (DBM) in a CI engine, *Int. J. Res. Eng. Technol.* **2**, 10, 158–162.
70 Cheung C.S., Zhu R., Huang Z. (2011) Investigation on the gaseous and particulate emissions of a compression ignition engine fueled with diesel-dimethyl carbonate blends, *Sci. Total Environ.* **409**, 3, 523–529.
71 El-Fakharany M.K., Abdelrazek A.S., Baz F.B., Gad M.S. (2024) Impact of nano-TiO_2 combination with biodiesel on diesel engine performance and emissions under fuel magnetism conditioning, *Arab. J. Sci. Eng.*, 1–16.
72 Zheng F., Cho H.M. (2024) The comprehensive effects of nano additives on biodiesel engines –a review, *Energies* **17**, 16, 4126.

73 Yelvington P., Green W. (2003) *Prediction of the knock limit and viable operating range for a homogeneous-charge compression-ignition (HCCI) engine*, SAE Technical paper 2003-01-1092.
74 Kumar N., Varun Chauhan S.R. (2013) Performance and emission characteristics of biodiesel from different origins: a review, *Renew. Sustain. Energy Rev.* **21**, 633–658.
75 Dhanarasu M., Ramesh Kumar K.A., Maadeswaran P. (2022) Recent trends in role of nanoadditives with diesel–biodiesel blend on performance, combustion and emission in diesel engine: a review, *Int. J. Thermophys.* **43**, 11, 171.
76 Devarajan Y. (2019) Experimental evaluation of combustion, emission and performance of research diesel engine fuelled Di-methyl-carbonate and biodiesel blends, *Atmos. Pollut. Res.* **10**, 3, 795–801.
77 Zhang J., Niu S., Zhang Y., Tang C., Jiang X., Hu E., Huang Z. (2013) Experimental and modeling study of the auto-ignition of n-heptane/n-butanol mixtures, *Combust. Flame* **160**, 1, 31–39.
78 Chen G., Shen Y., Zhang Q., Yao M., Zheng Z., Liu H. (2013) Experimental study on combustion and emission characteristics of a diesel engine fueled with 2, 5-dimethylfuran–diesel, n-butanol–diesel and gasoline–diesel blends, *Energy* **54**, 333–342.
79 Glaude P.A., Pitz W.I., Thomson M.J. (2005) Chemical kinetic modeling of dimethyl carbonate in an opposed-flow diffusion flame, *Proc. Combust. Inst.* **30**, 1111–1118.
80 Sun W., Yang B., Hansen N., Westbrook C.K., Zhang F., Wang G., Moshammer K., Law C.K. (2016) An experimental and kinetic modeling study on dimethyl carbonate (DMC) pyrolysis and combustion, *Combust. Flame* **164**, 224–238.
81 Soudagar M.E.M., Nik-Ghazali N.-N., Kalam M.A., Badruddin I., Banapurmath N., Akram N. (2018) The effect of nano-additives in diesel-biodiesel fuel blends: a comprehensive review on stability, engine performance and emission characteristics, *Energy Convers. Manag.* **178**, 146–177.
82 Lu X.C., Yang J.G., Zhang W.G., Huang Z. (2005) Improving the combustion and emissions of direct injection compression ignition engines using oxygenated fuel additives combined with a cetane number improver, *Energy Fuels* **19**, 1879–1888.
83 Zhao F., Yang W., Yu W., Li H., Sim Y.Y., Liu T., Tay K.L. (2018) Numerical study of soot particles from low temperature combustion of engine fueled with diesel fuel and unsaturation biodiesel fuels, *Appl. Energy* **211**, 187–193.
84 Sharifianjazi F., Esmaeilkhanian A., Karimi N., Horri B.A., Bazli L., Eskandarinezhad S., Ahmadi E. (2023) A review of combustion properties, performance, and emission characteristics of diesel engine fueled with Al2O3 nanoparticle-containing biodiesel, *Clean Technol. Environ. Policy* 1–23.
85 Lv J., Wang S., Meng B. (2022) The effects of nano-additives added to diesel-biodiesel fuel blends on combustion and emission characteristics of diesel engine: a review, *Energies* **15**, 3, 1032.
86 Srinivasan S.K., Kuppusamy R., Krishnan P. (2021) Effect of nanoparticle-blended biodiesel mixtures on diesel engine performance, emission, and combustion characteristics*Environ. Sci. Pollut. Res. Int.* **28**, 29, 39210–39226.
87 Sai Roshita B., Annapurna B., Sai Kumari Ch., Guna Deep E., Manoj Kumar B., Kumar Mohith B., Chiranjeeva R.S. (2023) Diesel engine performance: a study on biodiesel blends and nano-enhanced fuel additives, *Int. J. Res. Publ. Rev.* **4**, 10, 1210–1214.
88 Ilyas H., Pawar S.S., Chopra M.K. (2022) Nanoparticles as fuel additives in biodiesel: a review, *Int. J. Innov. Res. Sci. Eng. Technol.* **7**, 4, 4–10.