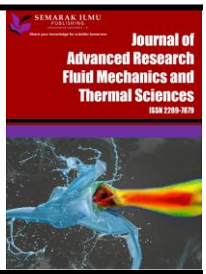
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Waste Cooking Oil Biodiesel and Their Nanobiodiesel Blends Infused with Reduced Graphene Oxide (RGO) Nanoparticles for Diesel Engine Applications

Sumana Yajaman Belludi[1], Nagaraj Ramalingayya Banapurmath[2,*], Sadasivappa Suresh[1], Hiresadarahalli Bommappa Aravinda[1], Sushrut Shashidhar Halewadimath[3], Lakshmaiah Ranganatha Swamy[4], Chandramouli Vadlamudi[5], Sanjay Krishnappa[5], Nagesh Sampige Basavaraju[6]

[1] Department of Civil Engineering, Bapuji Institute of Engineering and Technology, Davangere, India
[2] Centre of Excellence in Material Science, School of Mechanical Engineering, KLE Technological University, Hubballi-580031, Karnataka, India
[3] Department of Mechanical Engineering, KLE Institute of Technology, Hubballi-580027, Karnataka, India
[4] Department of Mechanical Engineering, BGSIT, Adichunchanagiri University, Mandya, India
[5] Aerospace Integration Engineer, Aerosapien Technologies, Daytona Beach, FL 32114, United States
[6] Department of Mechanical Engineering, Channabasaveshwara Institute of Technology, Gubbi, India

ARTICLE INFO

Article history:
Received 5 October 2023
Received in revised form 15 January 2024
Accepted 28 January 2024
Available online 29 February 2024

Keywords:
Waste cooking oil biodiesel; reduced graphene oxide; zeta potential

ABSTRACT

This work focusses on the potential application of waste cooking oil (WCO) as alternative to diesel as it is abundantly, locally available. The oil is subsequently converted into its biodiesel called waste cooking biodiesel (WCOBD). GCMS studies of the waste cooking oil and its biodiesel is carried out to determine the fatty acid composition. Further WCOBD is blended with diesel to produce its WCOBD B20 blend. The physio-chemical properties of the WCO, WCOBD, WCOBD B20 and their nano-biodiesel blends were determined and were compared with diesel. These properties of WCOBD B20 are in good agreement with diesel. This B20 blend can successfully provide 20% substitute to fossil diesel and save foreign exchange besides providing energy security to India. The fuel properties of the WCOBD B20 blends are further modified by adding carbon derived nanoparticles of reduced graphene oxide (RGO) to prepare nano-biodiesel blends. The percentage of RGO nanoparticles were varied from 20% to 100 % by volume insteps of 20% using suitable SDS surfactants. The stability of these nano-biodiesel blends is determined by using zeta potential method. The stability of decreased with increase in the nano-particle dosage in base biodiesel blends. Accordingly, the blends with dosage beyond 80% showed lower stability in terms of lower zeta potential values. The nano-biodiesel blends showed improvement in calorific value and self-ignition temperature compared to the B20 biodiesel blend. Among the Nano-biodiesel blends considered WCOME B20 RGO80 showed comparatively higher BTE (11.67%), reduced emissions of smoke opacity (14.63%), HC (21.42%), CO (16.67%), ID (10%), CD (16.67%) and increased NO_x (2.5%), and PP (15.38%) respectively when compared to the WCOBD B20 blend.

* *Corresponding author.*
E-mail address: nr_banapurmath@kletech.ac.in

https://doi.org/10.37934/arfmts.114.2.1531

1. Introduction

Research activities to find alternative and renewable fuels for internal combustion engines has gained interest in recent years, owing to depleting oil reserves and climate concerns. High demand for fossil fuels in transport sector put burden on exchequer. India's energy security focusing on renewable fuels is essential. Biodiesel produced indigenously at a much lesser cost addresses the problems of fossil fuel usage. Government is promoting blending of biodiesel with diesel for power traction.

India aims to blend 5% biodiesel by 2030 as per Biofuel policy 2018. At present dismal 0.16% biodiesel is being used as per United States Department of Agriculture report, 2020. India uses 102 billion liters of diesel annually. 5 billion liters of biodiesel per year is essential to meet blending targets. Usage of several organic raw materials to produce biodiesel and Used Cooking Oil (UCO) is one of them. Biodiesel produced from UCO can be blended with diesel for automotive traction. 1.1 billion liters can be obtained from Used Cooking Oil (UCO) itself. Indian oil companies procured 105 million liters of biodiesel in 2019-20 which is 10% of the potential. Biodiesel and their blends produced from discarded UCO are tested for comparative engine performance and engine emission [1].

Vegetable oils such as palm, sunflower, coconut, peanut, soybean, corn, cottonseed, canola, and safflower are commonly used for frying food items. Oil undergoes different processes such as hydrolysis, polymerization, and thermal degradation. Hydrolysis occurs since food items contains moisture in it and there is an increase observed free fatty acids in the used cooking oil. Further, the oil gets thermally degraded alike autoxidation [2]. For 20% WCO with copper oxide nanoparticles in diesel engine BTE 29.6761%, exhaust gas temperature (EGT) 250.20°C, carbon monoxide (CO) 0.0128%, hydrocarbon (HC) 13.7117 ppm, carbon dioxide (CO_2) 2.2643%, nitrogen oxide (NO_x) 169.0098 ppm, smoke emission 10.0252 HSU are observed at given engine parameters [3]. At all engine loads, DF80-WCOB20 the BTE was higher than that of DF70-WCOB30, DF60-WCOB40, and DF50-WCOB50. BSFC for compression ratio (CR) increased (16.5, 17.5, and 18.5) at all engine loads when waste cooking oil biodiesel was mixed with diesel fuel compared to diesel fuel. Cooking oil biodiesel blends showed lower CO and HC emissions, with higher NO_x emissions than diesel [4]. W50A50DB20 showed maximum peak cylinder pressure and peak heat release rate of 6.37% and 13.81% higher waste cooking biodiesel blends. BTE of biodiesel blend W50A50DB20 was 3.49% higher compared to WCDB20. NO_x was maximum for WCDB30 and minimum for W50A50DB20 at 100% load. Lower greenhouse gas emission is reported for W50A50DB20 among tested fuels [5]. Nanoparticles addition in biodiesel blends enhance engine performance and reduce the emission. Interaction of the metal oxide particles with the molecules of water to form hydroxyl ions during the combustion process are reported [6]. The B20TNP50 blend showed enhanced performance and emission characteristics of 325.862 g/kWh, 28.021%, 5.008 MJ/kW, 0.021 g/kWh, 327.725 g/kWh, 0.0013 g/kWh, and 1.760 g/kWh for BSFC, BTE, BSEC, HC, CO_2, CO, and NO_x respectively. Furthermore, when B20TNP50 was compared to pure diesel, BTE and BSEC were increased by 5.7% and 4.62% while BSFC, HC, CO_2, CO, and NO_x were reduced by 7.82%, 4.74%, 23.88%, 29.42%, and 21.19%, respectively. Hence, biodiesel made from parsley (B20) with a nano additive (TNP50) can be utilized for a green environment condition [7]. A maximum BTE of 32% was achieved by adding 75 ppm nanoparticle to the biodiesel fuel blend with some counter effect on NO_x emission at maximum load. The optimized outcomes were 58% engine load, 1800 rpm engine speed and 75 ppm nano-particles (NP) concentration (B20W10NP75) [8]. The result of amalgamating the fuel with alumina and ceria nanoparticles has given encouraging BSFC results, compared to diesel fuel POME20 at CR20 and 6% of EGR added with 100 ppm of Al2O3 and CeO2 nanoparticles was less than 15.15% and

6.06% [9]. By using graphene oxide (GO), power and EGT significantly increase. Furthermore, by using GO nano-particles, significant reductions in CO and HC were observed. However, under similar conditions, a slight increase in CO_2 and NO_x emissions observed. Nano-graphene oxide can be introduced as a suitable alternative fuel additive for Oenothera lamarckiana biodiesel blends [10].

From the literature survey it is desirable to enhance the combustion characteristics of diesel engine fueled with biodiesels with different nanoparticles. Dispersion of higher dosage of nano-particles into liquid biodiesel is still a challenge as agglomeration of the same may result into inferior diesel engine performance with higher emissions when powered with these nano-biodiesel blends.

In view of this WCO B20 blend is infused with RGO nanoparticles with higher dosage of 80 to 100% and combustion characteristics of the diesel engine powered with these nano-biodiesel blends were determined. Further the stability of the nano-biodiesel blends was ascertained using zeta potential technique.

2. Methodology

This section discusses the potential availability of WCO. Further analysis of WCO biodiesel and its Nano-biodiesel blends are also discussed.

2.1 Potential Availability of WCO in India

India annually uses about 27 billion liters of cooking oil, of which 1.4 billion liters UCO can be collected from bulk food operators alone to make 1.1 billion liters of biodiesel. Indiscriminate disposal of such oil leads to environmental problems and can be recycled for biodiesel production.

In the present work WCO is used as raw material for biodiesel preparation and is collected from different sources such as hotels, restaurants, canteen, and cafeterias. The oil is filtered to remove solid food contents and other impurities. WCO is converted into its biodiesel (BDF) using conventional transesterification process. The set up used for biodiesel production is shown in Figure 1 and the schematic diagram of waste cooking oil biodiesel production is shown in Figure 2 respectively.

Fig. 1. Biodiesel production unit

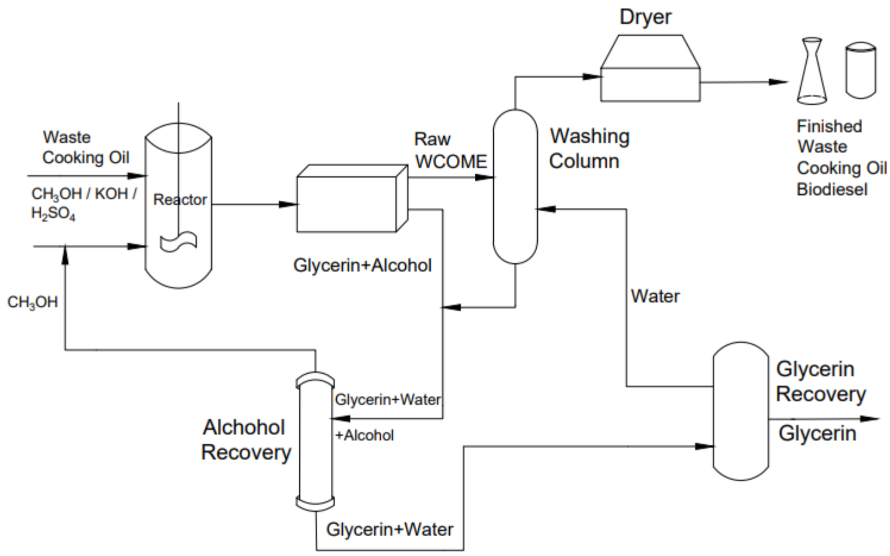


Fig. 2. Schematic diagram of biodiesel production from waste cooking oil

2.2 Analysis of Waste Cooking Oil Biodiesel and its Nano-Biodiesel Blends

2.2.1 GCMS of waste cooking oil biodiesel

GC-MS chromatogram of the biodiesel is determined using a QP 2020 Gas chromatograph Mass Spectrometer (m/z range: 45–550) and GC-MS device (SHIMADZU). For carrier gas Helium, 2.02 mL/min (flow rate) is utilized. Temperatures of column are maintained from 50^{o}C to 240^{o}C at 10^{o}C/min. The injector temperature is maintained at 240^{o}C, while methanol is used on sample bases in split flow (100 mL/min) being injected. In GC-MS analysis of waste cooking oil biodiesel, 11 compounds are detected as shown in Figure 3. The molecular formula, molecular weight, and peak area are used to identify the compounds in line with ASTM D6584 criteria. Table 1 shows fatty acid composition of biodiesel derived from waste cooking oil.

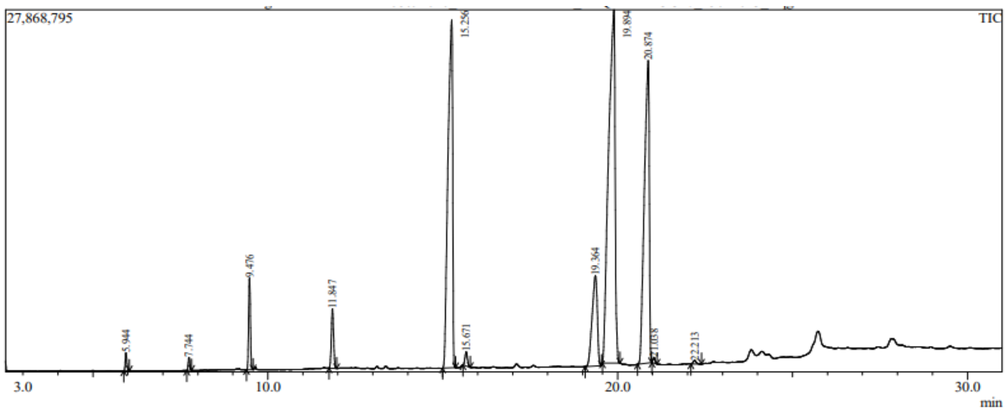


Fig. 3. Chromotograph of waste cooking oil biodiesel

Table 1
Fatty acid composition of biodiesel

Fatty acids	WCOME Biodiesel (Vol%)
Palmitic C16:0	25.72
Stearic C18:0	7.45
Oleic C18:1	36.75
Linoleic C18:2	23.61
Linoleic C18:3	0.16

Blends of waste cooking-oil biodiesel are prepared in varied percentages by volume 5,10,15 and 20% to obtain blends of B5, B10, B15 and B20 respectively. The samples are stored at room temperature. Important fuel properties of waste cooking-oil biodiesel and their blends such as density, viscosity, flash point, acid value and water content are determined according to D128, D445, D94, D664 and D2709 test methods as shown in Table 2. The samples are stored at room temperature. Important fuel properties of diesel, waste cooking-oil biodiesel, and its B20 blend are tabulated in Table 3.

Table 2
Properties of waste cooking oil, and its diesel blends

Fuel type	Density ($g/cm^{3)}$	Kinematic Viscosity (cSt)	Flash point (°C)	Fire point (°C)	Acid value (mgKOH/g)	Water content (%)
Diesel	0.840	3	70	80	0.168	0
WCO	0.8987	7.73	180	200	0.869	0
WCO5	0.8214	1.37	90	100	0.140	0
WCO10	0.8228	1.67	95	110	0.145	0
WCO15	0.8309	1.84	100	120	0.148	0
WCO20	0.8329	2.51	110	125	0.150	0

Table 3
Properties of Diesel, WCOME B20 and its blends with Ethanol

Properties	Diesel	WCOME B100	WCOME B20
Density (kg/m^3) @15 ºC	840	900	860
Flashpoint (°C)	70	176	60
Calorific value (kJ/kg)	43,000	39,600	40,900
Kinematic Viscosity, @40°C cSt	2-3	5.2	4.5
Cetane Number	45-55	--	--
Pour Point °C	0.845	-6.0	0.858
Cloud point, °C		9	--

Nano biodiesel blends are prepared using B20 blend of WCO infused with varied proportions of RGO from 20 to 120 mg and optimized SDS surfactant to ensure stability of the blends prepared. Figure 4 shows the RGO nanoparticle based nano biodiesel blends of WCOME B20. Table 4 the properties of Diesel, WCOME B20 and its blends with RGO respectively.

Fig. 4. Diesel, WCOME B20 and its blends with RGO nanoparticle

Table 4
Properties of Diesel, WCOME B20 and its blends with RGO

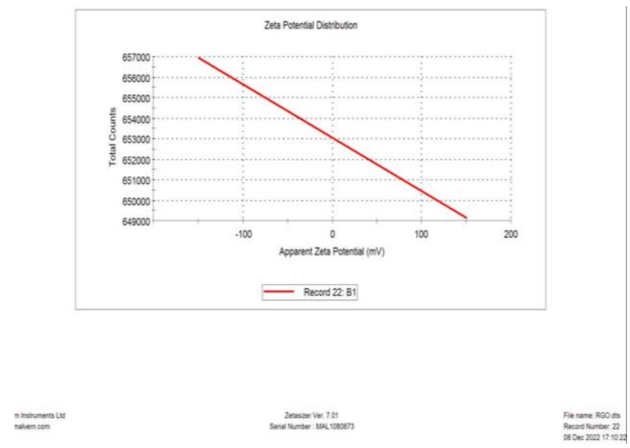
Properties	WCOME B20 RGO20	WCOME B20 RGO40	WCOME B20 RGO60	WCOME B20 RGO80	WCOME B20 RGO100	WCOME B20 RGO120
Density, kg/m^3	860	865	875	885	897	905
Kinematic Viscosity, @40^{o}C cSt	4.62	4.76	4.88	5.12	5.25	5.45
Flashpoint (^{o}C)	54.5	53.5	54.5	54.5	52.5	51.5
Calorific value (kJ/kg)	40,900	41,280	41,565	41,878	42,090	42,211
Oil-Type (Non-Edible:N-E)	N-E	N-E	N-E	N-E	N-E	N-E

2.3 Effect of Ultra Sonication Time on the Stability of Nano fluids

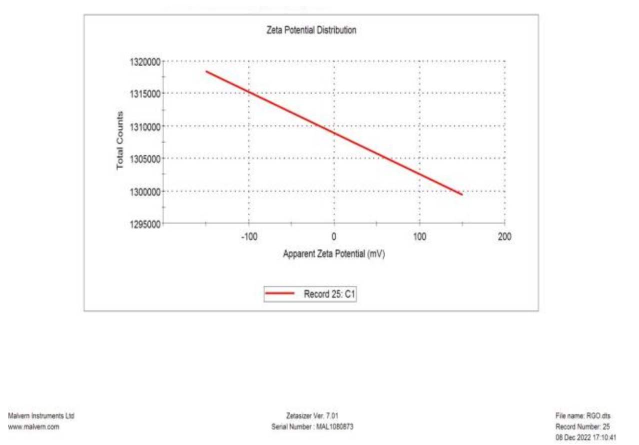
Ultra-sonication affects stability of nano-fluids. Increased ultra-sonication provides improved stability. Decreased cluster size obtained with increased sonication time, changes the thermo-physical property of nano-fluids.

2.3.1 Stability analysis by sedimentation and zeta potential method

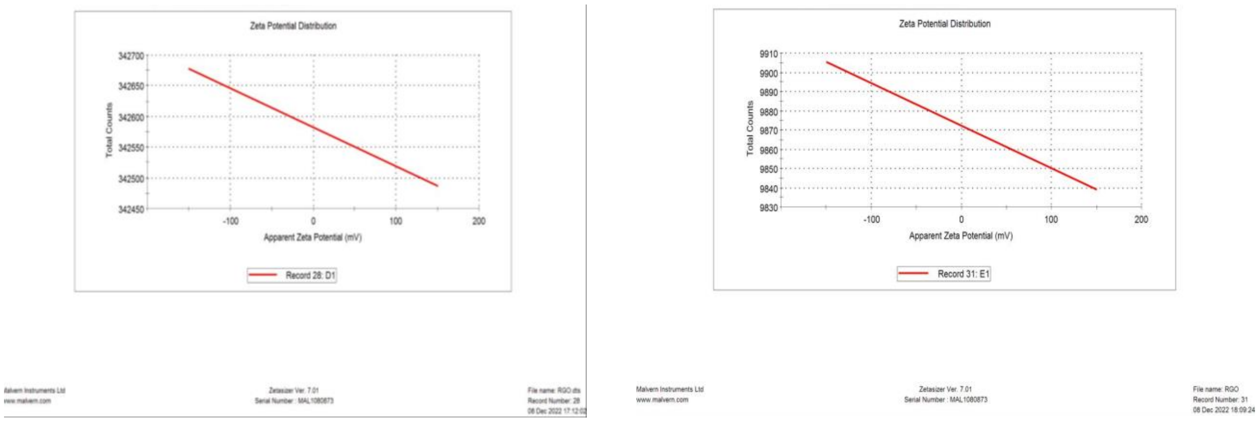
Stability of RGO nano-biodiesel blends, are done using Zeta potential. Magnitude of Zeta potential of nanofluids tested are anticipated to be lower than -30mv or higher than +30mv for solid-liquid suspension to authenticate their steadiness aspects. The stability of nanofluids is visually inspected for 6 samples with different mixtures of WCOME20 and RGO nanoparticles at 20:20, 20:40, 20:60, 20:80, 20:100 and 20:120, respectively. The samples are analyzed for zeta potential measurement. Degree of repulsion between similarly charged particles indicates stability of colloidal dispersions in the fluid. For Zeta potential of the dispersant with high value of 40-60mv, then degree of repulsion enhances, which intend leads to good stability. Table 5 and Figure 5 shows the zeta potential values of RGO based nano biodiesel blends. Higher dosage of nanoparticles in the B20 blends showed lower zeta potential values indicating lower stability of the nano-biodiesel blends.



(a) B20R40



(b) B20R60



(c) B20R80 (d) B20R100

Fig. 5. Zeta potential values of RGO based nano biodiesel blends

Table 5
Zeta potential values of RGO based nano biodiesel blends

Sample Name	Sample Description	Actual Zeta Potential (mv)
A1	B20R20	-44.4
B1	B20R40	39.67
C1	B20R60	37.7
D1	B20R80	35.0
E1	B20R100	31.8
F1	B20R120	-29.8

3. Results and Discussion

Experiments are conducted to evaluate performance, emission and combustion characteristics of diesel engine fuelled with waste cooking biodiesel and its nano-biodiesel at 1500 rpm speed, injection timing of 23^{o}BTDC, injection pressure of 240 bars, CR of 17.5 and 6-hole injector having 0.2mm diameter.

The following section discusses performance, emission and combustion characteristics of diesel engine fuelled with waste cooking biodiesel nano-biodiesel blends.

3.1 Performance Parameters
3.1.1 Brake thermal efficiency

Variations of BTE with respect to BP at different loads for diesel and waste cooking oil methyl ester (WCOME B20) blended with different dosage levels of reduced graphene oxide (RGO) nanoparticles (NPs) is illustrated in Figure 6. Among the different blends tested, WCOME B20 fuel blend operation in diesel engine exhibited inferior BTE due to its lower calorific value, poorer atomization of fuel droplets associated with its higher viscosity. Fuel-spray pattern of WCOME (B20) fuel could have led to higher ID period and thereby promoting higher dilution in the pre-flame region and more fuel burns in the diffusion combustion phase [11].

Nano-biodiesel blends of WCOME showed improved engine performance and could be due to higher Heat Release Rates (HRR) exhibiting increased premixed combustion at different loads [12]. Nanoparticle in emulsion with large surface to volume ratio leads to rapid evaporation and better atomization [13]. As dosage of RGO NPs increased, improvement in the BTE of the engine obtained. At full load conditions, the BTE observed for WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 was 28%, 29, and 28.5% respectively. Increase in convective heat transfer coefficient and the combustion characteristics of nano-biodiesel fuels resulted with the addition of RGO NPs, due to their higher thermal conductivity [14]. This reduces ignition delay (ID), and combustion duration (CD) thereby accelerating thermal exchange process, with rapid, improved, and enhanced combustion of fuel blends. Improved homogenization of A:F mixing in the presence of RGO NPs led to enhanced combustion characteristics.

BTE of the diesel engine reduces when the dosage level of RGO NPs was increased to 100 ppm. This could be due to agglomeration of the NPs in the biodiesel blends, resulting into rise in the viscosity which affect the fuel atomization with higher rate of fuel consumption. Diesel has shown enhanced BTE due to its higher calorific value and lower viscosity compared to biodiesel and nano-biodiesel blends. However, the engine performance with nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

BTE of the diesel engine fueled with nano-fuel blends with higher dosage of nanoparticles WCOME B20RGO80 increased by 11.67% respectively when compared with WCOME B20 at maximum loading conditions. The BTE with diesel operation is found to be 30%.

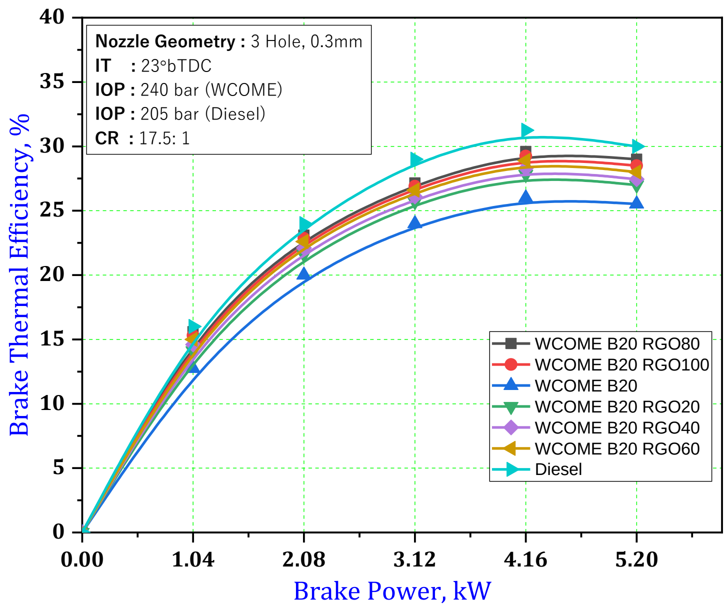


Fig. 6. Variation of BTE with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.2 Emission Parameters
3.2.1 Smoke opacity

Smoke opacity is a measurement of the concentration of soot particles in exhaust emissions. It is primarily associated with fuel rich zones resulting in non-homogeneous fuel-air mixtures with higher smoke emissions and is more pronounced at higher engine loads. The variations of smoke emission with BP for WCOME B20 biodiesel and its nano-fuel blends are shown in Figure 7. Increase in smoke emission is observed with an increase in the loading conditions. WCOME B20 exhibits a significant higher smoke emission due to partial combustion at full load engine operation. WCOME nano-biodiesel blends infused with RGO NPs showed lower smoke emissions. The catalytic effect of the nanoparticle and higher surface to volume ratio results, in an improved combustion, minimizing the smoke formation [15]. This is because RGO NPs act as oxygenated additives which improve fuel properties. The smoke emissions reported for WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 fuel blends are 73 HSU, 68 HSU, and 70 HSU respectively at full load. As the percentage of RGO NPs in the fuel blend increased, the smoke emissions are reduced by 27.84% for WCOME B20RGO80 when compared with WCOME B20 at full load engine operation. Reduced formation of soot particles and enhanced reactant mixture occurs because of the effects of enhanced secondary atomization and increased spray momentum [14]. Also, addition of SDS surfactant for fuel blend stabilization reduces the viscosity and facilitates better atomization of fuel droplets, thus increasing the BTE. The smoke emission with diesel operation is found to be 66 ppm. Diesel has shown lowest smoke emissions due to lower viscosity resulting into uniform air-fuel mixing compared to heavier molecular structure of biodiesel and nano-biodiesel blends. However, the smoke emission patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

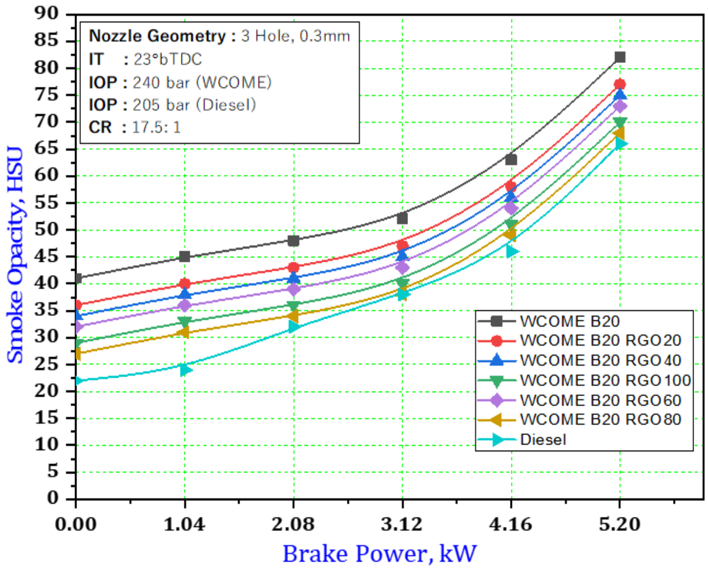


Fig. 7. Variation of Smoke opacity with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.2.2 HC emissions

Unburned hydrocarbons (HC) refers to partial combustion of fuel occurring inside the combustion chamber. Variation of HC emissions with BP for the fuel blends is illustrated in Figure 8. Higher cetane number of fuel blends facilitate ignition process and lower HC emissions [16]. Improved fuel atomization forms uniform air-fuel mixtures ensuring complete combustion of the fuel blends with lower ignition delay periods thereby reducing the HC emissions. For WCOME(B20), higher unburned hydrocarbon emissions are obtained at full engine load operation. Higher viscosity, poor atomization of WCOME B20 leads to incomplete combustion with higher HC emissions. However, WCOME B20 infused with NPs showed comparatively lower HC emissions. Increase in the concentration of RGO nanoparticles from 20 ppm to 80 ppm result in continual decrease in HC emissions. Relative air-fuel mixture and higher cetane number reduces the ignition delay, hence the concentration of HC emission decreases [17]. HC emissions were lower for the higher dosage levels of RGO NPs added to the WCOME B20. A minimum value of HC emission is observed for the WCOME2080 fuel blend which emitted 66 ppm of HC at 5.2 kW (around 21.42% reduction) when compared with WCOME B20. The HC emissions of the nano-fuel blends were comparable with diesel fuel. Addition of NPs beyond 100 ppm results into higher HC emissions due to agglomeration of NPs in the WCOME B20 blend. The HC emission with diesel operation is found to be 52 ppm. Diesel has shown lowest HC emissions due to its lower wall wetting phenomenon with improved combustion compared to heavier molecular structure of biodiesel and nano-biodiesel blends. However, the HC emissions patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

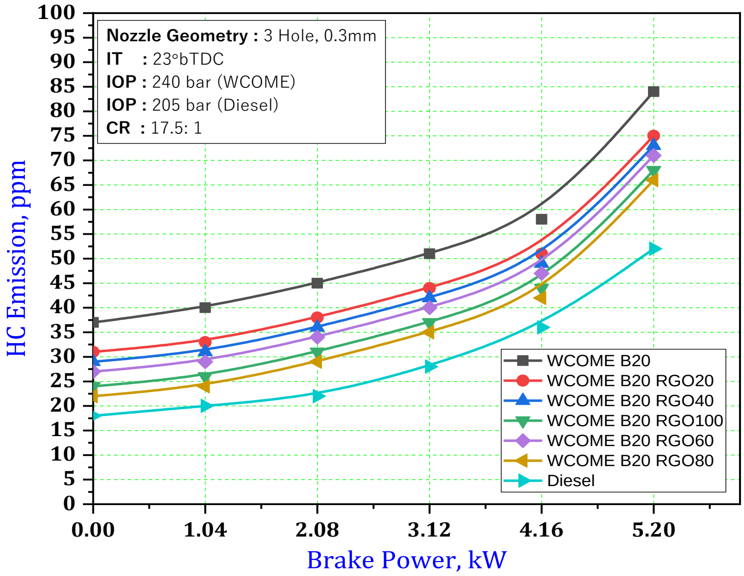


Fig. 8. Variation of HC Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.2.3 Carbon monoxide

Carbon monoxide and HC emissions occurs mainly due to incomplete combustion when oxygen unavailability results during combustion process. Factors like wall quenching, fuel injection quality, and spray penetration affect CO formation [18].

Effect of CO with BP for different fuel blends is shown in Figure 9. Large quantity of oxygen content and higher viscosity of WCOME(B20) leads to higher oxidation reaction and poor atomization. This increases the CO formation in engine cylinder. The rise in the engine loads increases the CO emission for all fuel blends. These may be due to richer F:A ratio, which increases with increase in engine load as more pilot fuel is injected inside engine cylinder. The CO emitted for WCOME(B20) fuel blend is 0.25% vol. at full load engine operation. Carbon monoxide emission reduces for WCOME B20 blend infused with NPs of RGO. As the percentage of RGO in the B20 blend increases the CO decreases and this is observed till 80% of NPs addition. WCOME B20RGO80 illustrated lower CO emissions compared with other fuel blends. The CO is reduced by 16.67% for WCOME2080 in contrast with the B20 fuel. CO emission for WCOME B20RGO80 and WCOME B20RGO100 nano fuel blends at maximum loads were 0.2% vol. and 0.22% vol. The fuel blend WCOME2080 illustrates lowest CO emission, compared with B20 blend. The viscosity reduces with addition of surfactants that led to improved atomization of the fuel droplets. This assisted in the complete combustion of fuel, hence reducing the CO emissions. The CO emission increased for WCOME20100, and the reason may be due to an increase in density, non-uniform distribution of the NPs in the base fluid. The CO emission with diesel operation is found to be 0.18%. Diesel has shown lowest CO emissions due to improved combustion compared to higher viscosity of biodiesel and nano-biodiesel blends. However, the CO emissions patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

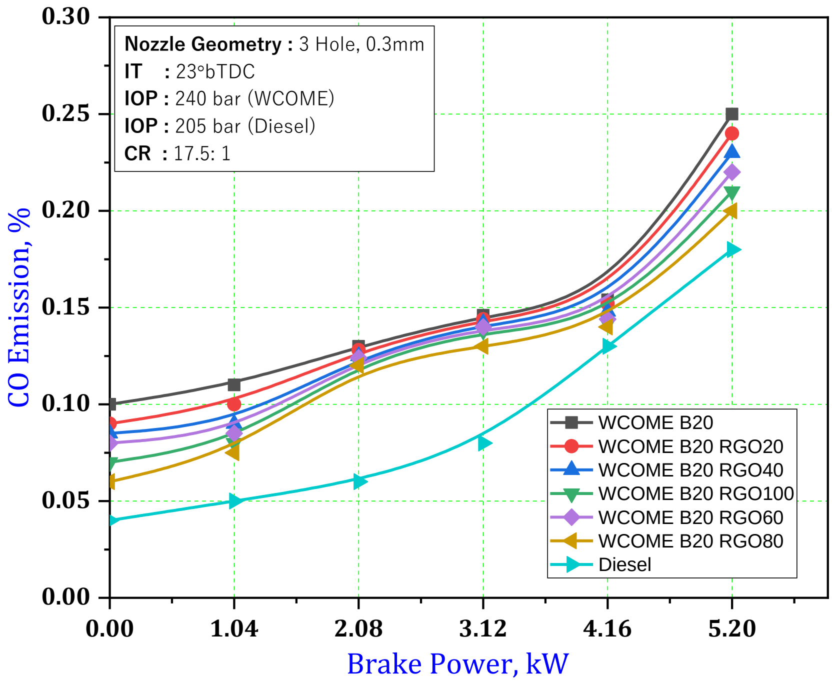


Fig. 9. Variation of CO Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.2.4 NO_X emission

The variation of NO_x emission with BP is shown in Figure 10. Numerous researchers stated that presence of oxygen, higher in-cylinder temperature and residual time affect NO_x [19]. NO_x emission for WCOME(B20) at the full load is the lowest amongst all the fuel blends. At maximum load conditions, higher NO_x is recorded. While a slight increase of 25 ppm of NO_x emission is observed for WCOME2020. There was 2.5% rise in the NO_x emission for the WCOME(B20) compared to diesel. For the fuel blends WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 the increase in NO_x is around 1190, 1198, and 1194 ppm emission respectively, compared with B20. An increase in RGO NPs concentration in the fuel blends increases the NO_x emissions. This might be due to the increase in oxygen level in the base fuel. Ntrogen oxide relies on the peak and flame temperature in the combustion chamber (CC), and residence time [20]. The lowest nitrogen oxide emission is observed for B20 fuel blend without the addition of nanoparticles, while the highest NO_x emitted was observed for WCOME B20RGO80. A similar trend is observed for higher engine load operation. The nano-blends of WCOME showed comparatively higher NO_x emissions. Decreasing the flame temperature and CD and using Exhaust Gas Recirculation (EGR) can effectively control NO_x during post combustion process. The NO_x emission with diesel operation is found to be 1220 ppm. Diesel has shown highest NO_x emissions due to improved combustion with increased in-cylinder temperature, peak pressure and heat release rate compared to higher viscosity of biodiesel and nano-biodiesel blends. However, nano-biodiesel blends WCOME B20RGO80 showed lower NO_x compared to diesel operation.

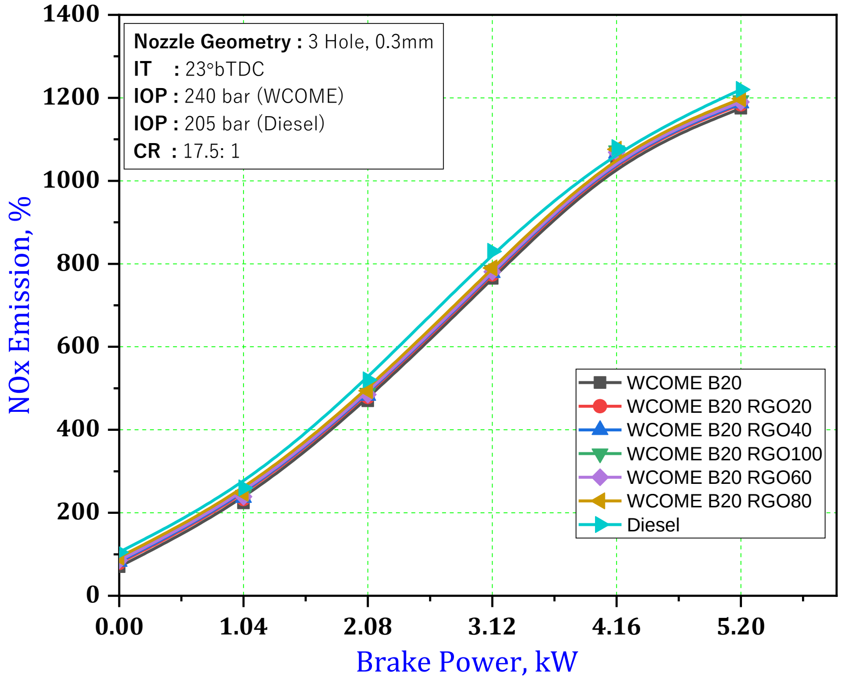


Fig. 10. Variation of NO_x Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.3 Combustion Parameters

3.3.1 Peak pressure

The variation of peak pressure with BP for different fuel blends is shown in Figure 11. WCOME B20 blend showed lower peak pressure compared to nano-blends of WCOME. The addition of NPs to biodiesel led to an improved rate of fuel droplets evaporation, thereby resulting in higher pressure rise [14].

At full load engine operation, the peak pressure for the WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 fuel are 72 bar, 75 bar and 73 bar respectively. The highest peak pressure is observed for 80 ppm of RGO NPs in WCOME B20. Advanced heat transfer rates are observed for nano-biodiesel WCOME(B20) blends as NPs have higher surface-area-to-volume ratio and act like catalyst in aiding combustion process. This dosing of NPs enhances in-cylinder combustion characteristics which increase the peak pressure (PP) and reduces the combustion duration (CD). The PP with diesel operation is found to be 84 bar and is higher compared to biodiesel and nano-biodiesel blends. However, the PP patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

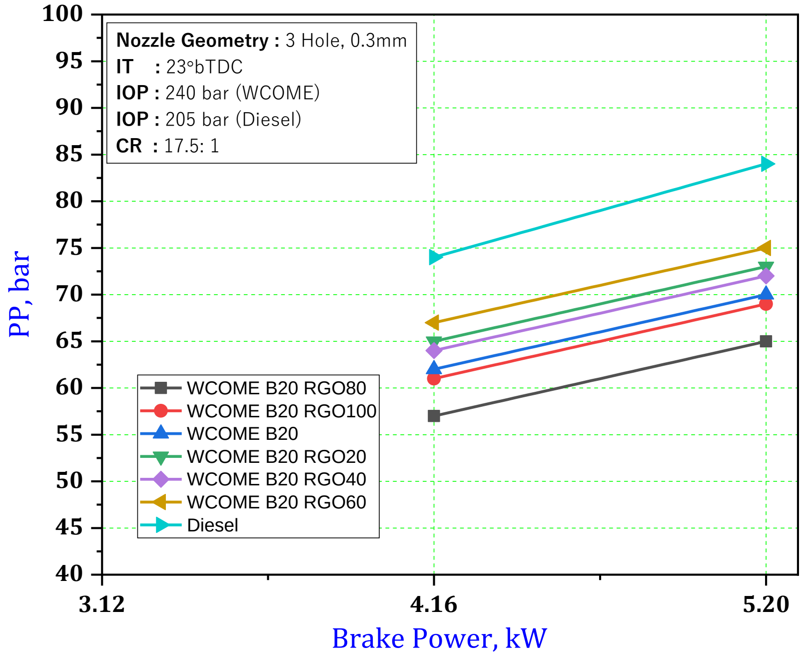


Fig. 11. Variation of PP Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.3.2 Ignition delay

The variations of ID with respect to BP for different fuel blends are shown in Figure 12. ID indicates the period between start of injection to start of combustion. RGO nanoparticles possess a very high thermal conductivity and it enhances the combustion phenomenon by increasing the convective heat transfer coefficient [20]. Accelerated, thermal exchange process decreases ID, and promoting rapid, improved, and complete combustion. Nano-blends of WCOME B20 exhibited lower IDs compared to that without NPs addition. At maximum load conditions, the ID for the WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 fuel are 9.2°CA, 9°CA, and 9.1 °CA. The ID with diesel operation is found to be 8.9°CA due to its higher cetane number and is lower compared to biodiesel and nano-biodiesel blends. However, the ID patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

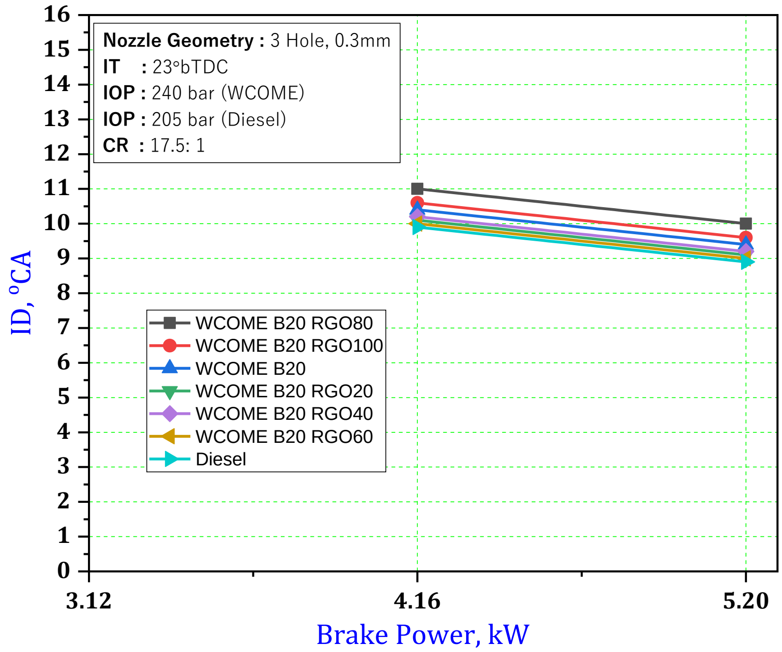


Fig. 12. Variation of ID Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.3.3 Combustion duration

Figure 13 illustrates variations of CD with BP for different Nano-biodiesel fuel blends. Addition of nanoparticles results in a micro-explosion of the fuel droplets and enhances fuel evaporation and air mixing, thereby reducing the combustion duration. A reduced CD is observed for the fuel blends WCOME B20RGO80, followed by WCOME B20RGO100, a maximum CD was reported for the WCOME (B20) fuel blend. At maximum loading condition, the combustion duration for the WCOME B20RGO60, WCOME B20RGO80 and WCOME B20RGO100 fuel is 49°CA, 45°CA and 47°CA respectively. The CD with diesel operation is found to be 43 °CA and is lower due to more fuel burning in pre-mixed combustion compared to biodiesel and nano-biodiesel blends. However, the CD patterns of nano-biodiesel blends WCOME B20RGO80 are comparable to diesel operation.

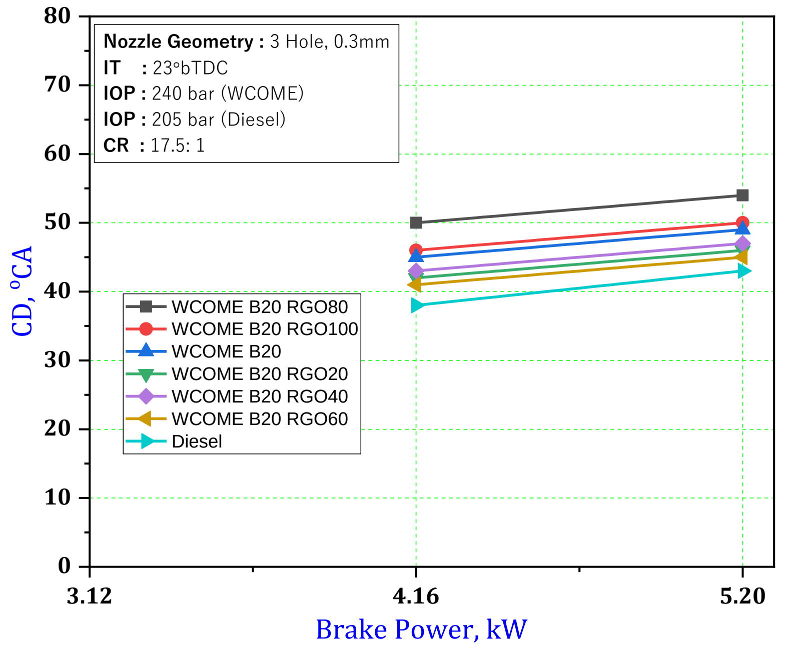


Fig. 13. Variation of CD Emission with brake power for WCOME B20 - reduced graphene oxide based nano-biodiesel blends

3.3.4 Pressure and heat release rate variation with crank angle

Figure 14 and Figure 15 show the variation of in-cylinder pressure and heat release rate (HRR) with crank angle. Around 100 cycles of pressure crank angle history were acquired and the averaged out in-cylinder pressures at each crank angle were used to determine the heat release rate. WCOME B20 showed lower peak pressure and HRR compared to its Nano bio-diesel blend. This is due to the latter showing high premixed combustion compared to diffusion combustion phase. Addition of RGO enhanced combustion activity thereby increasing the peak pressure as well as higher HRR. RGO nanoparticles dispersed in the base biodiesel B20 blend provided ignition enhancing facilitators thereby improving the combustion greatly.

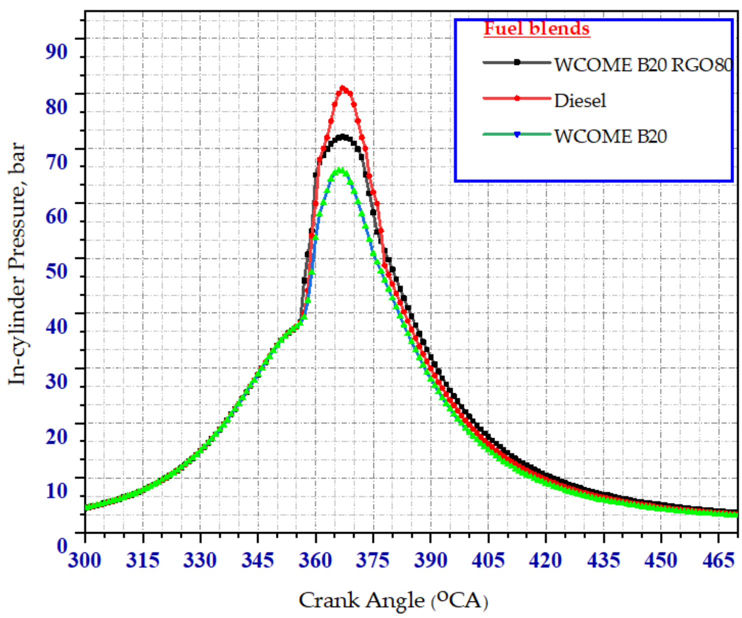


Fig. 14. Variation of In-cylinder pressure with crank angle for WCOME fuelled blends

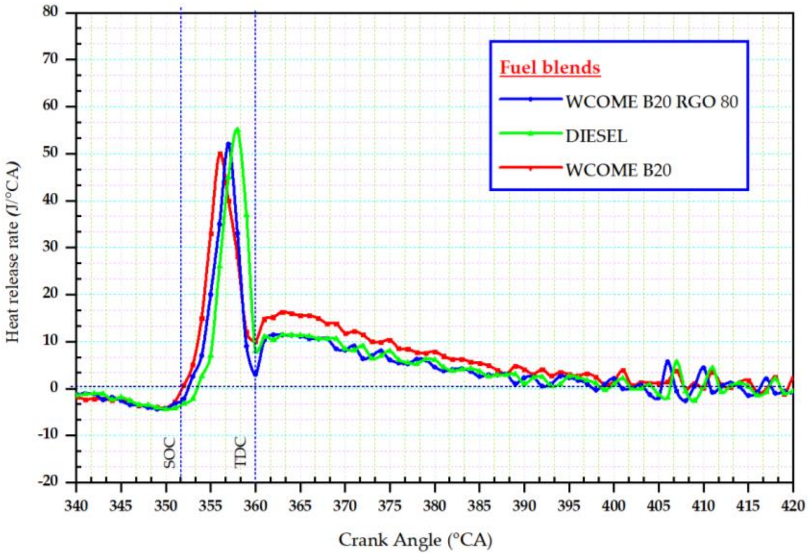


Fig. 15. Variation of HRR with crank angle for WCOME fuelled blends

4. Conclusions

Physiochemical properties of biodiesel derived from waste cooking oil and its B20 nano-blends infused with RGO are determined and compared with diesel to study their suitability for diesel engine applications. Stability of the nano-biodiesel B20 blends infused with varied RGO percentage are determined using Zeta potential method. Higher dosage of nanoparticles in WCO B20 blends beyond 80% resulted into lowering of the Zeta potential values making the nano-fluids unstable. Among the blends tested B20RGO80 showed improved diesel engine performance with reduced emissions significantly compared with WCOME B20.

At full load engine operation, WCOME B20 RGO80 showed comparatively higher BTE (11.67%), reduced emissions of smoke opacity (14.63%), HC (21.42%), CO (16.67%), ID (10%), CD (16.55%) and increased NO_x (2.5%), and PP (15.38%) respectively when compared to the WCOBD B20 blend. Higher dosage of RGO infused biodiesel exhibited higher peak pressures as well as higher heat release rates.

Acknowledgement
The authors extend their appreciation to the KLE Technological University for the testing facility provided for the present research work.

References

[1] Adhikesavan, C., D. Ganesh, and V. Charles Augustin. "Effect of quality of waste cooking oil on the properties of biodiesel, engine performance and emissions." *Cleaner Chemical Engineering* 4 (2022): 100070. https://doi.org/10.1016/j.clce.2022.100070

[2] Choe, E., and D. B. Min. "Chemistry of deep-fat frying oils." *Journal of Food Science* 72, no. 5 (2007): R77-R86. https://doi.org/10.1111/j.1750-3841.2007.00352.x

[3] Chatur, Madhuri G., Anil Maheshwari, and Nand Jee Kanu. "Comprehensive analysis of the behavior of waste cooking oil biodiesel in CI Engines modified using CuO nanoparticles with varying fuel injection pressure." *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.03.620

[4] Rajak, Upendra, Thokchom Subhaschandra Singh, Tikendra Nath Verma, Prem Kumar Chaurasiya, Saboor Shaik, Asif Afzal, Erdem Cuce, Ali A. Rajhi, and C. Ahamed Saleel. "Experimental and parametric studies on the effect of waste cooking oil methyl ester with diesel fuel in compression ignition engine." *Sustainable Energy Technologies and Assessments* 53 (2022): 102705. https://doi.org/10.1016/j.seta.2022.102705

[5] Kukana, Rajendra, and Om Prakash Jakhar. "Performance, combustion and emission characteristics of a diesel engine using composite biodiesel from waste cooking oil-Hibiscus Cannabinus oil." *Journal of Cleaner Production* 372 (2022): 133503. https://doi.org/10.1016/j.jclepro.2022.133503

[6] Akram, Naveed, Rad Sadri, S. N. Kazi, S. M. Ahmed, M. N. M. Zubir, Mohd Ridha, Manzoore Soudagar, Waqar Ahmed, Mazdak Arzpeyma, and Goh Boon Tong. "An experimental investigation on the performance of a flat-plate solar collector using eco-friendly treated graphene nanoplatelets-water nanofluids." *Journal of Thermal Analysis and Calorimetry* 138 (2019): 609-621. https://doi.org/10.1007/s10973-019-08153-4

[7] Bitire, Sarah Oluwabunmi, and Tien-Chien Jen. "An optimization study on a biosynthesized nano-particle and its effect on the performance-emission characteristics of a diesel engine fueled with parsley biodiesel blend." *Energy Reports* 9 (2023): 2185-2200. https://doi.org/10.1016/j.egyr.2023.01.041

[8] Reddy, S. Rami, and Saroj Kumar Sarangi. "Optimizing the effect of using novel hydrogen enriched nano particles added emulsified waste mango seed biodiesel in diesel engine." *Fuel* 342 (2023): 127783. https://doi.org/10.1016/j.fuel.2023.127783

[9] Kumar, Perumalla Vijaya, B. Ashok, R. Vignesh, J. Pradeep Bhasker, and A. Naresh Kumar. "Evaluation of performance, emissions and combustion attributes of CI engine using palmyra biodiesel blend with distinct compression ratios, EGR rates and nano-particles." *Fuel* 321 (2022): 124092. https://doi.org/10.1016/j.fuel.2022.124092

[10] Hoseini, S. S., G. Najafi, B. Ghobadian, M. T. Ebadi, R. Mamat, and T. J. R. E. Yusaf. "Performance and emission characteristics of a CI engine using graphene oxide (GO) nano-particles additives in biodiesel-diesel blends." *Renewable Energy* 145 (2020): 458-465. https://doi.org/10.1016/j.renene.2019.06.006

[11] Soudagar, Manzoore Elahi M., Nik-Nazri Nik-Ghazali, Md Abul Kalam, Irfan Anjum Badruddin, N. R. Banapurmath, T. M. Yunus Khan, M. Nasir Bashir, Naveed Akram, Rijavan Farade, and Asif Afzal. "The effects of graphene oxide nanoparticle additive stably dispersed in dairy scum oil biodiesel-diesel fuel blend on CI engine: performance, emission and combustion characteristics." *Fuel* 257 (2019): 116015. https://doi.org/10.1016/j.fuel.2019.116015

[12] Soudagar, Manzoore Elahi M., Nik-Nazri Nik-Ghazali, Md Abul Kalam, I. A. Badruddin, N. R. Banapurmath, and Naveed Akram. "The effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance and emission characteristics." *Energy Conversion and Management* 178 (2018): 146-177. https://doi.org/10.1016/j.enconman.2018.10.019

[13] Annamalai, M., B. Dhinesh, K. Nanthagopal, P. SivaramaKrishnan, J. Isaac JoshuaRamesh Lalvani, M. Parthasarathy, and K. Annamalai. "An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel." *Energy Conversion and Management* 123 (2016): 372-380. https://doi.org/10.1016/j.enconman.2016.06.062

[14] El-Seesy, Ahmed I., Ali K. Abdel-Rahman, Mahmoud Bady, and S. J. E. C. Ookawara. "Performance, combustion, and emission characteristics of a diesel engine fueled by biodiesel-diesel mixtures with multi-walled carbon nanotubes additives." *Energy Conversion and Management* 135 (2017): 373-393. https://doi.org/10.1016/j.enconman.2016.12.090

[15] Raju, V. Dhana, P. S. Kishore, K. Nanthagopal, and B. Ashok. "An experimental study on the effect of nanoparticles with novel tamarind seed methyl ester for diesel engine applications." *Energy Conversion and Management* 164 (2018): 655-666. https://doi.org/10.1016/j.enconman.2018.03.032

[16] Vairamuthu, G., S. Sundarapandian, C. Kailasanathan, and B. Thangagiri. "Experimental investigation on the effects of cerium oxide nanoparticle on Calophyllum inophyllum (Punnai) biodiesel blended with diesel fuel in DI diesel engine modified by nozzle geometry." *Journal of the Energy Institute* 89, no. 4 (2016): 668-682. https://doi.org/10.1016/j.joei.2015.05.005

[17] Kumar, M. Vijay, A. Veeresh Babu, and P. Ravi Kumar. "The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine." *Alexandria Engineering Journal* 57, no. 1 (2018): 509-516. https://doi.org/10.1016/j.aej.2016.12.016

[18] Basha, Syed Ameer, and K. Raja Gopal. "A review of the effects of catalyst and additive on biodiesel production, performance, combustion and emission characteristics." *Renewable and Sustainable Energy Reviews* 16, no. 1 (2012): 711-717. https://doi.org/10.1016/j.rser.2011.08.036

[19] Mirzajanzadeh, Mehrdad, Meisam Tabatabaei, Mehdi Ardjmand, Alimorad Rashidi, Barat Ghobadian, Mohammad Barkhi, and Mohammad Pazouki. "A novel soluble nano-catalysts in diesel-biodiesel fuel blends to improve diesel engines performance and reduce exhaust emissions." *Fuel* 139 (2015): 374-382. https://doi.org/10.1016/j.fuel.2014.09.008

[20] Sivakumar, Muthusamy, Nallathambi Shanmuga Sundaram, and Mohamed Hussain Syed Thasthagir. "Effect of aluminium oxide nanoparticles blended pongamia methyl ester on performance, combustion and emission characteristics of diesel engine." *Renewable Energy* 116 (2018): 518-526. https://doi.org/10.1016/j.renene.2017.10.002